Biaxial Testing of Reactor Concrete

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Abstract

Biaxial compression tests with concrete have been carried out under steady state and transient temperature conditions. The test results show that even small load levels in a second axis alter the mechanical properties of concrete significantly. The stress-strain relationships show a significant dependence on the temperature level and the stress ratio. The strength under biaxial compressive stress is greater than the strength under uniaxial compression. The volumetric strains increase with increasing stress ratios and increasing temperatures. The critical temperature is higher when the specimen is loaded biaxially, than the critical temperature, when the specimen is loaded uniaxially. The modes of failure indicate that tensile deformation is vital for the failure mechanisms of concrete.

1. Introduction

In many sections of reactor structures, e.g. in prestressed or reinforced concrete pressure vessels, plates and in various containment structures, concrete is exposed to biaxial stress conditions at elevated temperatures. Therefore it is important to have sufficient knowledge about the properties of concrete under these conditions. Practical design methods and theoretical analyses e.g. with finite elements and other advanced methods require a sufficient knowledge on the stress-strain behaviour and the fracture response of concrete under biaxial stress and elevated temperatures.

In order to provide basic data of this kind a comprehensive research program was initiated and performed.

2. Experimental Equipment

To carry out the experimental investigations a special test equipment was designed and constructed which allows the study of fracture and stress-strain behaviour of concrete subjected to biaxial stress and elevated temperatures. A detailed description of the equipment is given in /1/.

2.1 Loading Devices and Temperature Control

The loading frame of the testing equipment is built out of a steel construction of great stiffness. The loading of the specimens is done by four hydraulic cylinders with a maximum power of 1000 kN. Each cylinder has a separate stress and strain rate control circuit. The pressure pistons are cooled by water.

The construction of the loading device and the shape of the specimen have decisive effects on a defined and uniform state of stress in the specimen and therefore on the results of the experiments. With investigations of the mechanical properties of concrete under biaxial stress states at ambient temperature, it was found that the uniform, two dimensional state of stress can be established best in discshaped specimens.
The size of the specimens (200 x 200 x 50 mm^3), which are sawed out of cubes, results from concrete technological and experimental requirements.

Particular problems in biaxial testing arise especially at high temperatures due to the load application onto the specimens. Generally a nearly unrestrained load application is required and the test equipment must provide a defined and uniform state of stress in specimens. In order to minimize the restraining due to the friction between loading platens and specimens so-called "loading-brushes" were constructed. Each loading platen is divided into 190 parallel rods having a distance of about 0,1 mm from each other. These rods follow the deformations of the loaded specimen-surfaces and reduce the transverse strain inhibition to a minimum.
By comparing the uniaxial and biaxial high temperature strengths determined with brushes and with rigid steel platens the reduction of the strain inhibition by using loading brushes was proved. The strengths determinded with brushes were lower than the strengths determined with rigid platens. That means that an uniform twodimensional state of stress in the specimens is realized by using the "loading-brushes".

The control units of the loading equipment fulfil the following important requirements:
- different stress paths can be performed;
- an equal increase of the stresses in both axes corresponding to the chosen stress path is guaranteed;
- the given stress ratio $F_1:F_2$ remains constant during the whole test procedure;
- the geometric centre of the specimen is kept right in the center of the loading device during the test.

The two last points, constant stress ratio and stability of the centre point of the specimen, are of special importance for experiments under biaxial high temperature conditions. For that, the controls are put in a way that the deformations appearing during heating and loading are taken symmetrically synchronously by the loading units.

The heating and testing of the specimens is performed in an electric furnace. A 3- zone-PID controller is used to provide defined temperature procedures. The temperature of the specimen is measured with NiCr-Ni - thermocouples, which are applied on the surface of the specimen by means of a heat-resistant glue. A sufficiently long hold time period of 2 hours and a moderate temperature increase of 2 K/min guarantee an uniform temperature distribution in the specimen.

2.2 Measurement Devices

In order to measure the forces four load cells are used. The load cells are constructed in line between the cylinders and specimen. The application of two load cells per axis gives an additional possibility to test the correct fixture of the specimens and to discover mistakes in the system.

The deformations of the test specimens in the three axes are measured by means of a specially developed high temperature - deformation measuring device. The deformations of the concrete specimen are transferred by means of transmitters with zero thermal expansion out of the hot furnace to inductive diplacement tranducers in the region of the ambient temperature. The deformation measuring system is built according to the principle of a dilatometer. For the measurements of the strains in the unstressed axis, a system is constructed according to a lateral extensometer.
All tests data are continously recorded and stored at certain time steps by a data logger connected to a computer system.

3. Concrete properties at constant temperatures

3.1 Compressive strength

For the given investigations the specimens were stored at least six months at 20°C/65 % r.h. They were unsealed during the tests as temperatures up to 750°C were employed.
The biaxial compressive strengths of a quartzitic normal concrete are presented on fig. 1. They are plotted in the plane of the principal stresses and they are related to the uniaxial compressive strength at ambient temperature β_o.
For different temperatures the failure envelopes of the concrete were established. The plane within the failure envelope is the region in which the specimen does not fail during a short time test with all biaxial compressive stress ratios. The failure envelope, itself, represents the limiting failure condition.

Concerning the biaxial high temperature compressive strength, the following findings were made:

1. The biaxial compressive strength of concrete is higher than the uniaxial compressive strength at all temperatures and under all stress ratios. The increase of the biaxial strength compared to the uniaxial strength occurs even with very small stresses in the second axis.

2. The biaxial compressive strength increases considerably with increasing stresses in the second axis. Thereby the stress can also be increased in the first axis without a failure of the specimen. The maximum influence of the stress in the second axis achieves its greatest effectiveness at a certain stress ratio which depends on the temperature. A further increase of the stress in the second axis has the consequence that the stress in the first axis must be decreased if no failure is accounted for.

3) The relative increase of the strength under biaxial stresses is greater at higher temperatures than at ambient temperature. At ambient temperature, the maximum increase of the strength is 20 to 40% at a stress ratio of $\sigma_1 : \sigma_2 = 0,5$. At 750°C peek values of for instance 200% with $\sigma_1 : \sigma_2 = 1,0$ were obtained. This means the maximum of the increase of the strength under biaxial stress is shifted with increasing test temperatures to higher stress ratios.

3.2 Deformations

The load depending deformations ε_1, ε_2 and ε_3 at constant temperatures and under symmetrically biaxial loading are presented on fig. 2.

Generally one can say that the deformations in all of the three directions increase with increasing loads. At high stress levels, the deformations indicate non-linear relations with respect to the largest principal stress.
With increasing temperatures the development of $\sigma - \varepsilon$ – curves shows the decrease of the strength and the modulus of elasticity under the influence of higher temperatures. The ultimate strains for all of the three axes are shifted to larger values with increasing temperatures. A particulary increase of the deformations is observed from 600°C onward. At higher temperatures, the $\sigma - \varepsilon$ – curves indicate softening, i.e. the concrete changes its brittle behaviour, which becomes quite obvious near the failure point.
The strains in the unstressed axis, ε_3, reach extreme values under the influence of high temperatures and large stress ratios. This deformations arise vertically to the stress directions due to the expansion of cracks. Therefore the maximum deformation in the load absent axis appears with the stress ratio $\sigma_1 : \sigma_2 = 1,0$.

4. Concrete behaviour at transient temperatures

4.1 Total deformations during heating

With transient high temperature creep tests, total deformations of unsealed specimens are recorded under a constant stress level and a defined temperature increase. The total deformations consist of temperature depending deformations and of load depending deformations. From the deformation behaviour near the failure point, a "critical concrete temperature", can be derived. For the tests the specimens are loaded corresponding to the chosen stress level in % of the uniaxial strength and to the chosen stress ratio F_1 : F_2 at ambient temperature. The stress level and the stress ratio are kept constant during the following heating period (2 K/min). The specimens are heated up until failure occurs. Simultaneously the deformations are measured in the three main axes.
The results of the deformation measurements in the biaxial case for different stress levels are presented on fig. 3. Stress levels up to 70 % of the uniaxial strength restrain nearly any thermal expansion in direction of the loaded axis i.e. in such cases only slight expansions can be achieved. Stress rates above 70% lead to a failure of the specimen just at low temperatures of about 120°C up to 130°C. The failure of a specimen is generaly initiated by a rapid increase of the lateral strains in the non-loaded axis.

4.2 Restraining stresses

Restraining forces arise in concrete specimens under transient temperature if the mechanically or thermally initiated expansions are restraint. In the tests the specimens were heated up with a constant heating rate (2 K/min). The expansions in the two stress axes were completely suppressed by external forces. The restraining forces were recorded at any time. The development of the restraining forces is shown on fig. 4. Up to 120°C, they rise considerably for a normally stored concrete (20°C/65 % r.h.). After that the main part of mixing water escapes accompanied by shrinkage effects between 120°C and 200°C. During this period, the restraining forces decrease. After passing a minimum at 200°C, the restraining forces increase again with increasing temperature and reach maximum values at 300°C to 350°C. These values are around 50 to 70 % of the failure load at ambient temperature. Finally the restraining forces decrease continously.

The behaviour of specimens that were predried at 105°C is something different. At 200°C, a clear maximum appears. The restraining forces reach values between 70 to 90 % of the failure load at 20°C. Then restraining forces decrease quickly. A second maximum appears at 650°C.

The values of the thermal expansion and the creep deformations of the concrete have an essential influence on the development of the restraining forces at increasing temperatures. Vaporization and dehydration processes are of importance, too. The development of the restraining forces in predried and normally stored specimens in the temperature region of 20°C to 200°C shows this distinctly. The higher moisture content of the normally stored specimens leads to higher creep deformations so that there are considerably lower restraining forces in comparison with predried specimens.

The stress ratio influences the qualitative development of the restraining forces, too. The biaxial stresses initiate higher restraining forces compared to the uniaxial stresses.

5. References

/1/ Ehm,C.; Kordina,K.; Schneider,U.: The behaviour of concrete under biaxial conditions and high temperatures. RILEM International Conference on Concrete under Multiaxial Conditions. Toulouse 1984

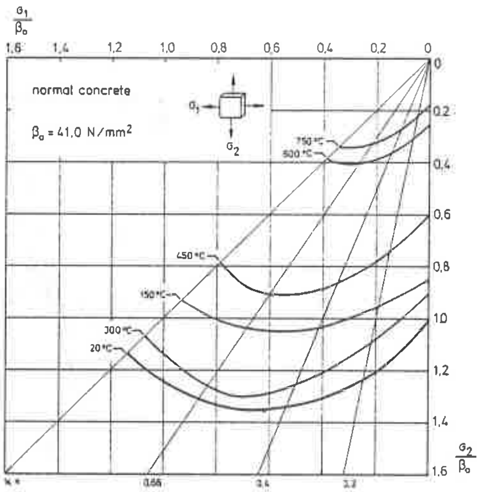

Fig. 1:

Biaxial high temperature compressive strength of normal concrete

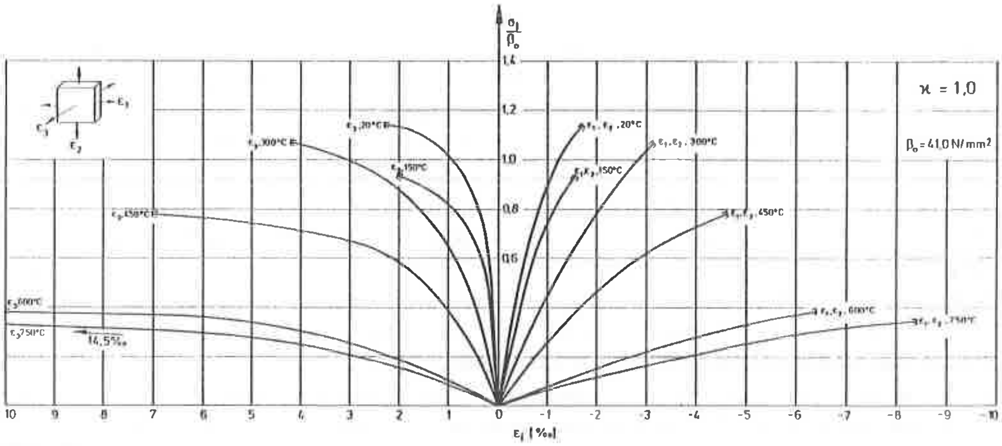

Fig. 2:

Stress-strain relation of normal concrete: $\sigma_1 : \sigma_2 = 1{,}0$

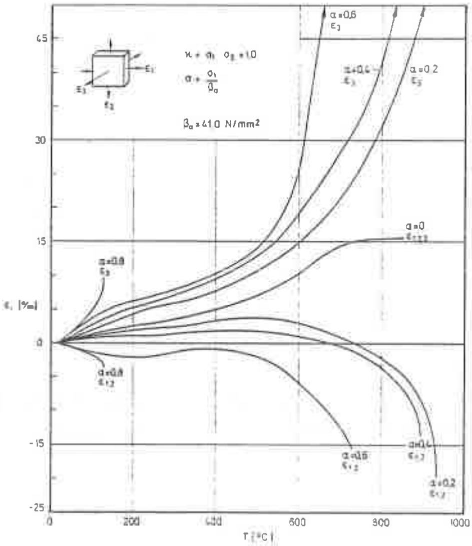

Fig. 3:

Total deformations of normal concrete during heating up

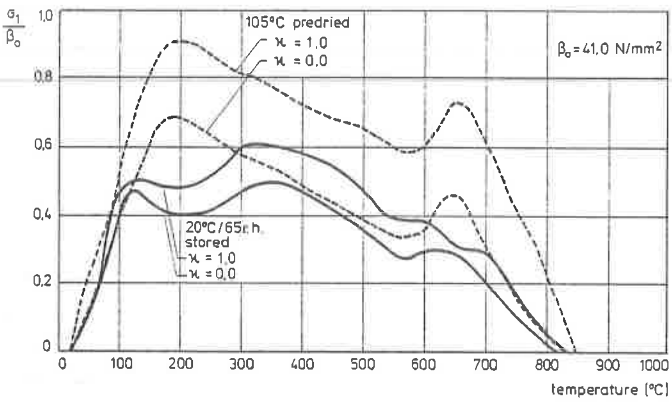

Fig. 4:

Restraining stresses of normal concrete during heating up