Effects of Biaxial Loading on the High Temperature Behaviour of Concrete

K. KORDINA and C. EHM
Institut für Baustoffe, Massivbau und Brandschutz
Technische Universität Braunschweig
Beethovenstrasse 52, D-3300 Braunschweig, FRG

U. SCHNEIDER
Fachgebiet Baustoffkunde
Universität Gesamthochschule Kassel, FRG

ABSTRACT

Biaxial compression tests with ordinary 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 higher than the strength under uniaxial
compression. The volumetric strains increase with increasing stress
ratios and increasing temperatures. The failure temperature of spe-
cimens being biaxially loaded is higher than the one of specimens
that are uniaxially loaded. The modes of failure indicate that the
tensile deformation is vital for the failure mechanism of concrete.

INTRODUCTION

During fires in buildings, concrete structures are exposed to
mechanical and thermal stresses. With respect to mechanical stress
states, there are uniaxial stresses, for example in centrically
loaded columns, biaxial stresses, for example in beams, panels,
slabs and shells and triaxial stresses. Regarding the temperature
exposure, there are the ambient temperature, increasing and high
temperatures when the fire is burning and decreasing temperatures,
when the burning has gone out.
This paper deals with the behaviour of concrete under biaxial
stress states and steady or transient high temperatures.

Up to now, only little is known about the strength and the defor-
mation behaviour of concrete subjected to biaxial stresses at
elevated temperatures. Our current knowledge about high temperature
behaviour is mainly based on uniaxial experiments, see for example
/1/. The knowledge about concrete behaviour under biaxial loading
conditions is based on experiments being performed at ambient tem-
perature as it is presented in, for instance, /2/.

In the following, at first the test equipment which was especially
developed for these investigations will be presented and then some
results concerning the strength and deformation behaviour of con-
crete under complex loading and temperature conditions will be

discussed. The fracture behaviour under biaxial high temperature
stress was already clearly presented in /3/.

EXPERIMENTAL EQUIPMENT

Loading Equipment

The loading frame of the test equipment (fig. 1) is designed as a
welded steel construction of high stiffness. The mechanical loading
of the specimens is achieved by four stress rate or strain rate
controlled hydraulic cylinders each with a maximum force of 1000
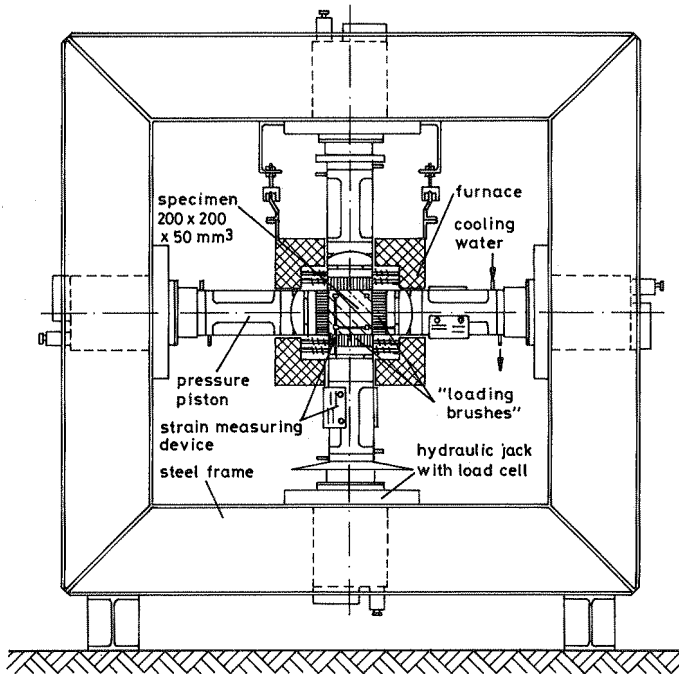kN. The heat resistant pressure pistons are cooled by water.

Fig. 1 Test rig for biaxial high temperature concrete tests

Shape of Specimens and Load Application

Investigations of the mechanical properties of concrete under bi-
axial stress states at ambient temperature have shown that the uni-
form, two dimensional state of stress can best be achieved by the
use of a disc-shaped specimen. This type of a specimen was chosen
for the given investigations at high temperatures, too. The size of
the specimens which are sawed out of cubes, results from concrete
technological and experimental requirements. The optimum specimen
size we obtained after different pre-investigations is 200 x 200 x
50 mm³.

Particular problems in biaxial testing arise 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 homogeneous state of stress in the specimens. In order to minimize the restraining due to the friction between loading platens and the specimens' surfaces so-called "loading-brushes" were constructed as proposed by Hilsdorf /4/. Each load application steel 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 specimens' surfaces and therefore cause a considerable reduction of the transverse strain inhibition.

By comparing the uniaxial and biaxial high temperature compressive strength data determined with "loading-brushes" and with rigid steel platens, the reduction of the strain inhibition by using "loading-brushes" was proved. The strengths determined with brushes were more than 20 per cent lower than the strengths determined with rigid platens.

By additional experiments, it could clearly be proved that a defined uniaxial state of stress is achieved in the test specimens by using "loading-brushes". The measured compressive strength is the real uniaxial compressive strength.

Load Control

The control units of the test equipment fulfill the following important requirements:
- different types of loading and different stress paths can be realized;
- the central point of the specimen is in the centre of the loading during the whole test.

The last point especially apply to experimental conductions under biaxial high temperature conditions. For that the controls are put in the way that the deformations appearing during the heating and the loading of the specimen are synchronously accounted for by the loading units.

Load Measurements

In order to measure the forces in the specimens, four load cells are at disposal constructed between cylinders and the specimen. The application of two load cells per axis gives the possibility to control the correct installation of the specimens and to discover errors in the system.

Deformation Measurements

The deformation of the concrete specimens in the three axes are measured directly by means of a specially developed high temperature – deformation measuring device (fig. 2). With this device, the strains are transferred by transmitters out of the hot furnace regions. Inductive displacement transducers are installed in the region of ambient temperatures. The deformation measuring system for the determination of the deformations in the loaded axes is

designed according to the principle of a dilatometer, that means thermal strains of the transmitters are compensated by a special geometric arrangement. With the measurements of the strains in the unstressed axis, the system is conducted according to a lateral extensometer. The thermal strains of the transmitters separately determined by calibration tests must be taken into consideration.
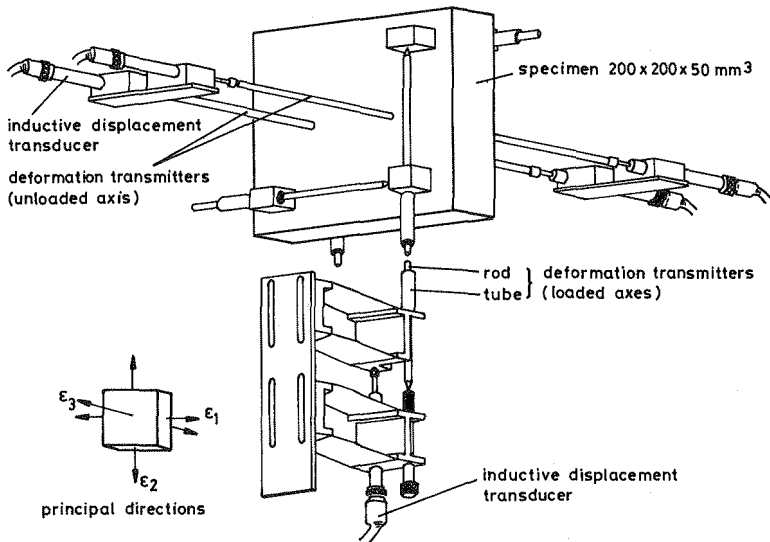

Fig. 2   High temperature deformation measuring system

Heating System and Temperature Measurements

The heating system consists of an electrical furnace and a 3- zone-PID programme controler regulating the heating and cooling of the specimens and the realization of prescribed temperature curves.

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 a uniform temperature distribution in the specimen.
A more detailed description of the experimental equipment is given in /3/ and /5/.

RESULTS

Compressive Strength

In the investigations to determine the biaxial compressive strengths at high temperatures all specimens were stored at least six months at 20°C/65% r.h.. The specimens were made of ordinary concrete with a cube strength of 41,0 N/mm^2 after 28 days. The biaxial compressive strengths are presented in figure 3. They are
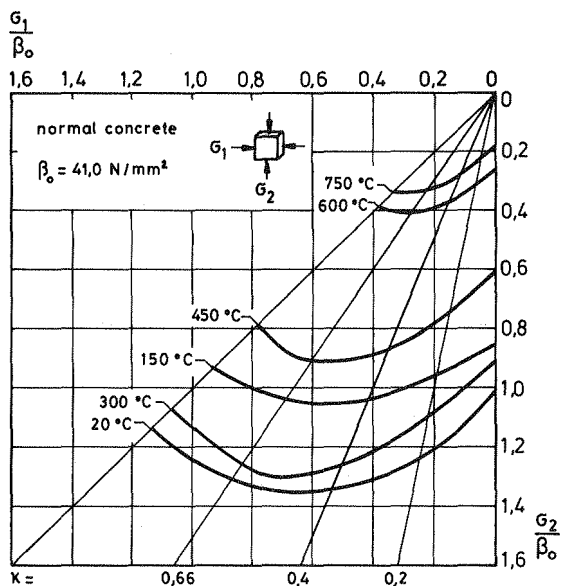
Fig. 3 Biaxial high temperature compressive strength of gravel
concrete related to the uniaxial strength at room temperature

related to the uniaxial compressive strength at ambient temperature
β_o at the time of testing.

For each particular temperature, the strengths were connected with
a failure envelope in the plane of principal stresses.

Concerning the biaxial high temperature compressive strength, the
following statements can be made:

1. The biaxial compressive strength of concrete is higher than the
uniaxial compressive strength. This comprises all temperatures and
all stress ratios κ . The increase of the strength compared to the
uniaxial strength is clear even with only small stress levels in
the second axis.

2. The biaxial compressive strength increases considerably with
increasing stresses in the second axis. The positive effect of the
stresses in the second axis obtains its greatest value with a
certain stress ratio which depends on the test temperature. A
further increase of the stress in the second axis beyond this point
consequently decreases the biaxial compressive strength.

3. The relativ increase of the strength under biaxial stress is
greater at higher temperatures than at ambient temperature. At
ambient temperature, the maximum increase of the strength comes to
20–40 per cent at a stress ratio of σ_1 : σ_2 = 0,5. At 750°C
this value is of the order of 200 per cent at σ_1 : σ_2 = 1,0.

This means that the maximum of the increase of the strength under
biaxial stress shifts with increasing test temperatures to higher
stress ratios. This is also valid for concretes with a higher cube

strength, as shown in /5/.

Mechanical strains

The mechanical strains ε_1, ε_2 and ε_3 at constant temperatures
are presented in the figures 4 and 5. The deformations depend on
the stress level, the stress ratio and the test temperature. The
deformations increase with increasing load in all three axes. At
high stress levels, they show a nonlinear relation in the direction
of the greatest principal stress.
With increasing temperatures, the development of $\sigma - \varepsilon -$ curves
indicates a decrease of the compressive strength. The decreasing
slope in the origin shows the decrease of the modulus of elasticity
at higher temperatures. The ultimate strains for all three axes are
shifted to greater values with increasing temperatures. A
particularly great increase of the deformations is observed from
600°C onward.
At higher temperatures, the $\sigma - \varepsilon -$ curves are highly non-linear: the
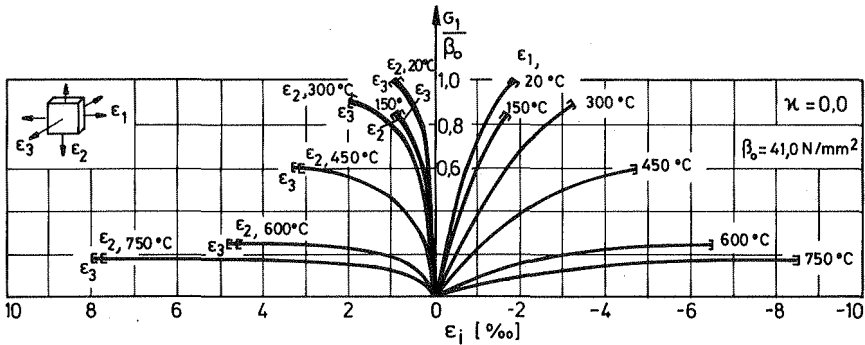concrete changes its brittle behaviour into a soft and plastic
behaviour.

Fig. 4 Stress-strain relations of gravel concrete under uniaxial
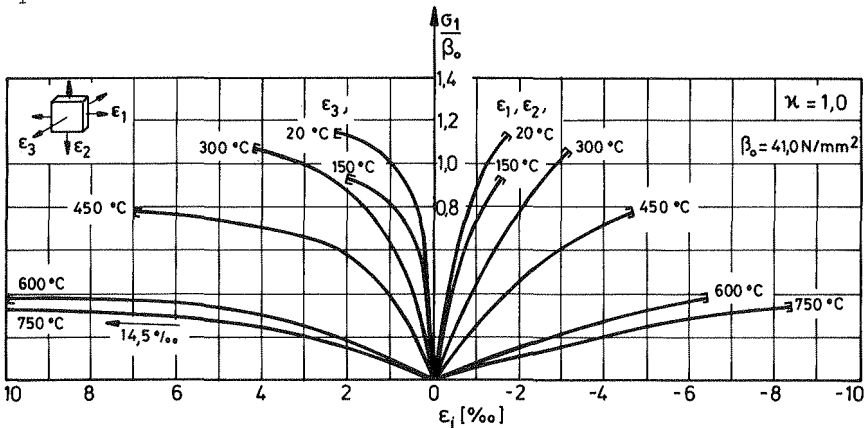compressive stresses

Fig. 5 Stress-strain relations of gravel concrete under
symmetrical biaxial compressive stresses

In the uniaxial case, figure 4, ε_2 and ε_3 are equal because of
equal Poisson's ratios.
In the biaxial case with $\sigma_1 : \sigma_2 = 0,4$ e.g., ε_2 has changed
and obtained positive values.
In the symmetrical biaxial case, $\sigma_1 : \sigma_2 = 1,0$ (figure 5)
ε_1 and ε_2 have the same value.
The strains in the unstressed axis, ε_3, reach extremely great
values at elevated temperatures and high stress ratios. The maximum
values of ε_3 appear with the stress ratio $\sigma_1 : \sigma_2 = 1,0$.

Total Deformations during Heating

With respect to the case of fire, it is important to investigate
the concrete behaviour at transient temperatures. Therefore high
temperature transient creep tests were performed.
In such tests, the total deformations of unsealed specimens are
measured under practical stress levels and defined non-steady tem-
perature exposures.

Results of the deformation measurements in the uniaxial case for
different stress levels are presented in figure 6. The elastic
deformations at ambient temperatures are neglected in that figure.
As a comparison curve, the curve with a zero stress level, i.e.
pure thermal expansion is shown in figure 6, too.

Stress levels of about 70 per cent of the uniaxial strength
restrain the thermal extension in the direction of the loaded axis.
In this case, only slight extensions can be observed. With
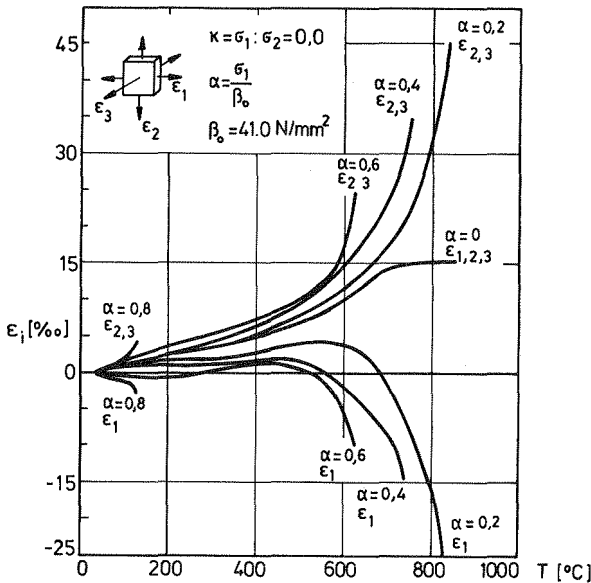continuously increasing temperatures comparatively great

Fig. 6   Total deformations of gravel concrete during uniaxial
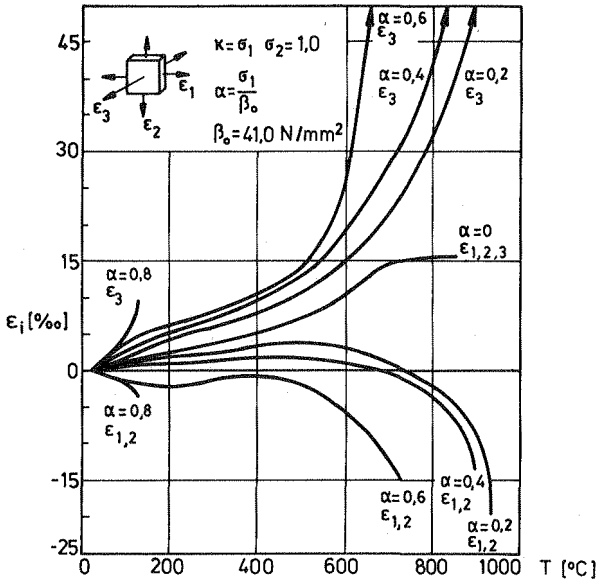transient creep tests

Fig. 7 Total deformations of gravel concrete during biaxial transient creep tests

compressive strains occur until the specimen fails. Stress levels above 70 per cent lead to a failure of the specimen at low temperatures of about 120°C to 130°C.

A fast increase of the lateral strains indicates the failure of the specimens. A symmetrical biaxial stress during heating (fig. 7) leads to extreme lateral strains in the free axis. The compressive strains in the stressed axes are not much greater than in the uniaxial case.

Failure Temperatures

In figure 8, the failure temperatures are presented. The individual stress ratios serve as a parameter in this graph. Three regions of failure can be distinguished: a stress level of 0 up to 70 per cent of the uniaxial compressive strength leads to failure temperatures above 600°C. Between 70 and 80 per cent, there is a very sensitive region with regard to the failure temperature. Only slight alterations in the stress level lead to failure temperatures that differ around several hundred centigrade. Stress ratios above 80 per cent consequently lead to failure at temperatures under 130°C. It has to be considered that in this region the time effect i.e. the duration of the stress exposure plays an important part in addition to the temperature effect.

With increasing stress ratios the failure temperatures increase. According to our tests, the optimum ratio is in the range of $\sigma_1 : \sigma_2 = 0,4$. The failure temperatures increase significantly in this case. In the region of high stress levels, this increase is of the order of several hundred centigrade.
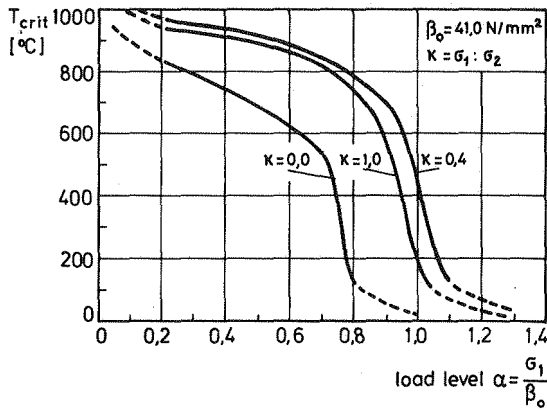
288

Fig. 8 Failure temperatures of gravel concrete

Restraining Stresses during Heating

Restraining forces arise in concrete specimens under transient
temperatures if mechanically or thermally caused extensions are
restrained. The time dependent restraining forces of different
concrete specimens are shown in figure 9. Predried and normal cured
specimens are compared.
Up to 120°C, the restraining forces rise considerably for a
normally stored concrete (20°C/65 % r.h.). After that a phase of
shrinking follows between 120°C and 200°C. During this phase 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 per cent of the failure load at ambient temperature. Finally
the restraining forces decrease continuously.
The behaviour of specimens that were predried at 105°C is something
different. At 200°C, a distinct stress maximum appears. The
restraining forces reach values between 70 and 90 per cent of the
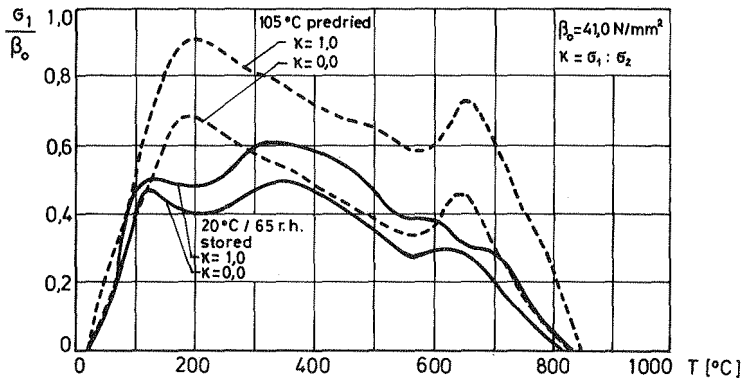failure load at 20°C.

Fig. 9 Restraining stresses of gravel concrete during heating

Thereafter the restraining forces decrease rapidly. 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 during heating. Vaporisation and dehydration processes are of importance. The development of 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 (20°C/65 % r.h.) in the cured specimens favours the creep of concrete so that there are considerably lower restraining forces in comparison with the predried specimens.

The stress ratio influences the quantitative development of the restraining forces, too. The biaxial stresses cause higher restraining forces of the order of 5 to 10 per cent compared to the uniaxial case.

CONCLUSIONS

Up to now, the experimental results can briefly be summarized as follows:
The biaxial high temperature tests have shown that even small load levels in the second axis alter the mechanical properties of concrete significantly. The strength under biaxial compression is higher than under uniaxial compression. This applies especially to higher temperatures. The strains increase with increasing stress ratios and with increasing temperatures.

The modes of failure indicate that tensile deformations are vital in the failure mechanism of concrete. The increase in strength and stiffness under biaxial compression is supposed to be due to the restraining of thermally induced and load induced microcracking. Studies on crack initiation and development will be performed to establish a theoretical background for the preliminary explanations.

Further experimental investigations are also necessary to proceed in the developing of analytical high temperature material models in order to describe the concrete behaviour as realistically as possible under extreme stresses and temperature conditions.

LITERATURE

/1/ Schneider,U.: Verhalten von Beton bei hohen Temperaturen.
    Heft 337 des DAfStB, Berlin 1982
/2/ Kupfer,H.: Das Verhalten des Betons unter mehrachsiger
    Kurzzeitbelastung unter besonderer Berücksichtigung der
    zweiachsigen Beanspruchung. Heft 229 des DAfStB, Berlin 1973
/3/ Ehm,C.; Schneider,U.; Kordina,K.: Fracture of Concrete
    under Biaxial High Temperature Tests. Proceedings of the 6th
    International Conference on Fracture, New Delhi 1984
/4/ Hilsdorf,H.: Die Bestimmung der zweiachsigen Festigkeit
    des Betons. Heft 173 des DAfStb, Berlin 1965
/5/ Ehm,C.; Kordina,K.; Schneider,U.: The Behaviour of Con-
    crete under Biaxial Conditions and High Temperatures.
    RILEM International Conference on Concrete under Multiaxial
    Conditions, Toulouse 1984