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**Research Article / Araştırma Makalesi**

# EFFECTS OF THERMO-MECHANICAL STRESSES ON THE STRENGTH BEHAVIOR OF CONCRETE IN MACRO SPECIMENS IN FIRE CASE

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**Highlights**

- Non-steady state temperature development in large specimens in case of ISO834 fire
- Experimental research for the determination of behavior of large scale concrete specimens
- Development of Restraint forces in large scale specimens under fire action

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**Abstract**

Rheological research works investigate for fire case the material behavior of small specimens and derive from the test results material laws to determine the behavior of structural elements due to fire exposure. However, as it is known, the heat and mass transport processes can significantly happen in different phases in macro concrete elements. Besides, in case of a fire, different heating rates occur in the cross section of structural elements. The validity of the transferred test results from small test specimens to the material behavior of structural elements indicates a phenomenon, which has not been investigated up to now. Such a research work has been done for the first time through close cooperation of subprojects A and B3 of SFB (**S**onder-**F**orschungs**B**ereich: A special fire research activity for structural elements in Braunschweig Technical University, 1971-1986). The results of the rheological investigations presented in this paper can lead to a new research conception about the determination of realistic fire behavior of concrete structures. By means of further purposive research work, it will be possible to reproduce the structural behavior in case of fire with simple but realistic mathematic-rheological relationships.

# YANGIN DURUMUNDA MAKRO BETON NUMUNELERDE MEYDANA GELEN TERMO-MEKANİK GERİLMELERİN BETON DAYANIMINA ETKİSİ

**Makale Bilgileri**

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**Anahtar Kelimeler:**

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betonarme;
makro numuneler;
yangın dayanımı;
sünme;
reoloji.

**Öz**

Reolojik araştırma çalışmaları, yangın durumunda, malzeme davranışını belirlemek için küçük boyutlu numuneler kullanmakta ve deney sonuçlarından yapı elemanlarının yangın davranışını belirlemede kullanılacak malzeme davranış kanunlarını saptamaktadır. Bununla beraber, bilindiği üzere, beton makro elemanlarda ısı ve kütle taşınımları önemli ölçüde farklı fazlarda meydana gelmektedir. Küçük numunelerden elde edilmiş olan deney sonuçlarının, yapı elemanlarına tatbikinin geçerliliği, şimdiye kadar araştırılmamış bir fenomen teşkil etmektedir. Böyle bir araştırma çalışması ilk defa SFB ye ait (Özel Araştırma Alanı : Braunschweig Teknik Üniversitesi'nde yapı elemanlarının yangın davranışı üzerine özel araştırma aktivitesi) A ve B3 alt araştırma projelerinin yakın çalışması sonucunda gerçekleştirilmiştir. Bu çalışmada ortaya konan reolojik araştırma sonuçları, beton yapı elemanlarının gerçekçi yangın durumunu belirlemede yeni bir araştırma kavramına öncelik edebilir. İleride amaca yönelik araştırma çalışmalarında yangın durumunda yapı elemanlarının gerçek davranışını, basit matematik-reolojik bağıntılarla belirlemek mümkün olacaktır.

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## 1. Introduction

Research work on macro concrete specimens under elevated temperatures are rare, almost there are no systematically investigations to determine the behavior of such kind specimens. The all previous and new main concerning research works, which are published, inform however that in the tests small scale specimens were used. In the following chapters it will be shown that the macro specimens behave very differently, especially, in case of re-straining, which proves that material laws derived from small scale tests must be substantially new taken into account in order to predict the fire behavior of structural elements.

### *1.1. Literature review*

The effect of strain rate on the compressive behavior of high-strength concrete (HSC) is experimentally investigated by (Jianzhuang et al., 2016), in exposure to elevated temperatures. They used 45 (HSC) prisms, which are heated up to 20, 200, 400, 600 and 800ΔK. The pre-heated prisms are then axially loaded at quasi-static strain rate of $10^{-5}$ $s^{-1}$ as well as two aftershock dynamic strain rates of $10^{-3}$ and $67.10^{-3}$ $s^{-1}$, respectively. The test results indicate that the higher the temperature and strain rate are, the larger the number of cracks and fragments will be. Finally, the stress–strain relationship and dynamic increase factor (DIF) of (HSC) after exposure to elevated temperatures are proposed.

Ordinary concrete samples made from the most common Type I Portland cement as well as some uncommon glossy-looking concrete lumps collected from a real fire scene are examined by Wei-Tun Chang, et al. (1994) by using thermo gravimetry (TG), differential thermal analysis (DTA), X-ray diffraction and scanning electron microscope/energy dispersive X-ray spectrometry (SEM/EDX) with the aid of an unsealed furnace. The study yields a rationalization of the interesting lump-formation phenomenon.

The effects of elevated temperatures on the concentric compressive behavior of confined concrete are presented by (K.A. Zaidi, et al., 2012). They designed an experimental program and carried out involving testing of hoop confined concrete cylindrical specimens exposed to elevated temperatures ranging from room [$T_r$] temperature to $T_c$ =800ΔK. The results indicated that the residual strength, strain corresponding to the peak stress and the post-peak strains of confined concrete are not affected significantly up to an exposure temperature of 400ΔK.

(Dwaikat and Kodur, 2008) presented a model to predict the influence of fire induced restraints on the fire resistance of reinforced concrete (RC) beams. The three stages, associated with the fire growth, thermal and structural analysis, for the calculation of fire resistance of the RC beams are explained. A simplified approach to account for spalling under fire conditions is incorporated into the model. The program is used to conduct two case studies to investigate the influence of both the rotational and the axial restraint on the fire response of the RC beams. Through these case studies, it is shown that the restraint, both rotational and axial, has significant influence on the fire resistance of the RC beams.

(Gernay and Franssen, 2012) showed that the stress–temperature experienced by structural concrete are varied and complicated and that concrete material models cannot handle properly these complex situations of unsteady temperatures and stresses without explicit consideration of transient creep. The first objective of this paper is as to show the capabilities and limitations of concrete uniaxial constitutive models at elevated temperatures for thermo-mechanical behavior modeling, depending on the creep strain in the model. It appears that one of the major limitations of implicit models concerns the unloading stiffness.

(Gustaferro and Lin, 1986) gave in their paper information for determining the fire endurance of certain concrete members based on heat transmission criteria. The paper contains information for determining the fire endurance of simply supported slabs and beams, continuous beams and slabs, floors and roofs in which restraint to thermal expansion occurs.

Research works presented above investigate the material behavior of small specimens and derive from the test results material laws to determine the behavior of structural elements in case of fire. However, as it is known, the heat and mass transport processes can significantly occur in different phases in macro concrete specimens. Besides, in case of a fire, steep heating rates are present in the cross section of macro specimens (see Figure 4). The transfer of the test results from small test specimens to describe the material behavior of structural elements presents therefor a complex problem, which is not analyzed and investigated up to now.

*1.2. Problem definition*

Determination of the influence of high temperature on the material properties of the concrete is often sufficient to carry out such kind of tests, which may be used to predict the behavior of the structural concrete elements in fire case. For the tests mainly such specimens are used, that the dimensions of them are very small with respect to the structural element. The tests are planned so that short- as well as long-term test data can be obtained under steady state as well as transient temperature conditions. This process may enable to obtain general statements on the material behavior of the concrete at high temperatures and to predict the deformations and the fire resistance of structural elements. The behavior of the concrete under thermal exposure is, of course, influenced by a variety of parameters, especially in concrete macro elements.

In the earlier research works of Subproject B3 of SFB 148, four different methods are used to determine these parameters by means of the developed own measurement techniques (Subproject B3 of SFB, 1981-1986). In view of the affectivity of these tests, the preparation of the specimens is carried out as concrete cylinders. It is known that, in mechanical-technological research work on concretes, the sample geometry plays a particular role. The collapse behavior of samples is, for example, determined very substantially by the friction conditions between the specimen's compression area and the pressure plates. It is determined that slenderness's ratio between two and five are the most appropriate values for material investigations. The smallest specimen size, however, is chosen according to the size of the aggregate. Due to technological reasons for concrete tests, the largest grain size was determined not below 16 mm, so that a sample diameter of 80 mm and the height 300 mm was decided for the investigations (Schneider, 1973, 1977).

The heating rate of the furnace hot gas temperature is controlled as $\dot{T}_g = 4\Delta\text{K/min}$, so, for the above selected sample dimensions a heating rate of $\max\dot{T}_c = 2\Delta\text{K/min}$ existed in the test specimens. This heating rate caused a radial temperature difference of approx. max. $T_v$=50ΔK/cm in the cross section, which is proven acceptable. The results of the investigations are presented in various periodical reports of subproject B3 (SFB148, 1970-1986).

Research results are obtained after type III tests in B3 of SFB148 (Determination of $\varepsilon_z$ and $\varepsilon_c$). In this type of tests, the deformations of the loaded specimens are obtained under a transient thermal condition. They have become known as *"warm creep tests"* (Schneider and Kordina, 1975). During the tests, the total uniaxial deformations of specimens, i.e. the sum of elastic and transient deformations, thermal expansions and shrinkage are measured. The thermal expansion of the concrete is determined by means of unloaded specimens. The difference between thermal expansion and the total deformation is caused due to the acting stress present and to the actual concrete temperature $T_c$ during the heating.

The material laws developed from this research program could be successfully used to determine the behavior of structural elements in case of a fire under *certain* test conditions (Kordina et al., 1975-1983, SFB). On the other hand, extensive computational investigations showed that the results of the warm creep tests could not be applied generally, if the structural element is subjected to a restraining condition during the fire (Haksever, 1978-1980 and 2017). The observed discrepancies between the calculation and the test results include the following reasons:

1. In case of a fire, generally rapid heating rates occur in the cross section of structural element
2. The heat and mass transport processes differ in macro concrete elements with respect to the small scale specimens, especially due to vapor pressure
3. The transfer of the test results from small test specimens with *low heating rates* to investigate the material behavior of structural elements indicates a complex problem, which has not yet been completely cleared and assessed for the fire case.

This research work aims at, as a *first step*, by appropriate planning of the experiments to find an answer to the above described question complex. The parameters are realized both by the dimensions of the test specimens as well as by the simulation of ISO834 fire in the furnace. A particular objective of the investigations is to enable the validity of the material laws evaluated from the tests for fire case.

### *1.3. Mechanical-technological investigations under elevated temperatures*

In order to determine the influence of the fire exposure on the material properties of the concrete, a test specimen with macro dimensions is planned. The sample cross-section is chosen with a width of 300 mm in square form. The height of the prismatic sample from 900 mm is almost 10 times the hydraulic radius of the cross section (Janko, 1972). The test sample thus formed a cut of a square bar-shaped structural element. Thus it is intended to obtain reliable information on the material behavior of the concrete as being construction sample.

Because the material-related investigation primarily focused on determining the material behavior of concrete, a weak reinforcement was selected for samples. The specimen was symmetrically and longitudinally reinforced with $\Sigma A_s$=8Φ8 and closed stirrups reinforcement is arranged as Φ6/15 cm from the reinforcing steel St420/500. The samples are planned to be cast with C20/25 concrete, which had however, a strength $f_{cm,c}$=45.6 N/mm$^2$ and reinforcing steel $f_y$=450 N/mm$^2$.

The experimental investigations for this research work have been carried out in a special high-temperature test furnace of which construction and equipment is described in (Meyer-Ottens, 1975). The Figure 1 illustrates the test specimen in the furnace before the fire exposure begins. Thick iron plates distribute the axial load into uniform pressure stress.

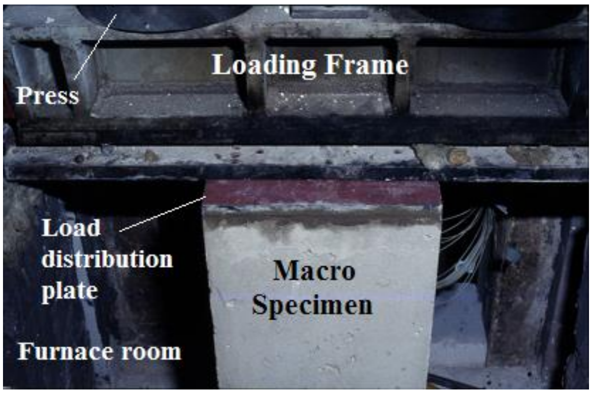


**Figure 1.** Built in macro specimen in the test furnace

The test furnace includes a combined load measuring and dilatation system. This arrangement allows deformation measurements to be carried out under steady state and transient thermal conditions up to almost $T_g$=1000ΔK by excluding the furnace deformations. The macro concrete specimens can be subjected to various load and temperature cycles. Figure 2 and 3 show the furnace structure and the arrangement of the measuring system (dilatometers D and thermo couples 1-6).

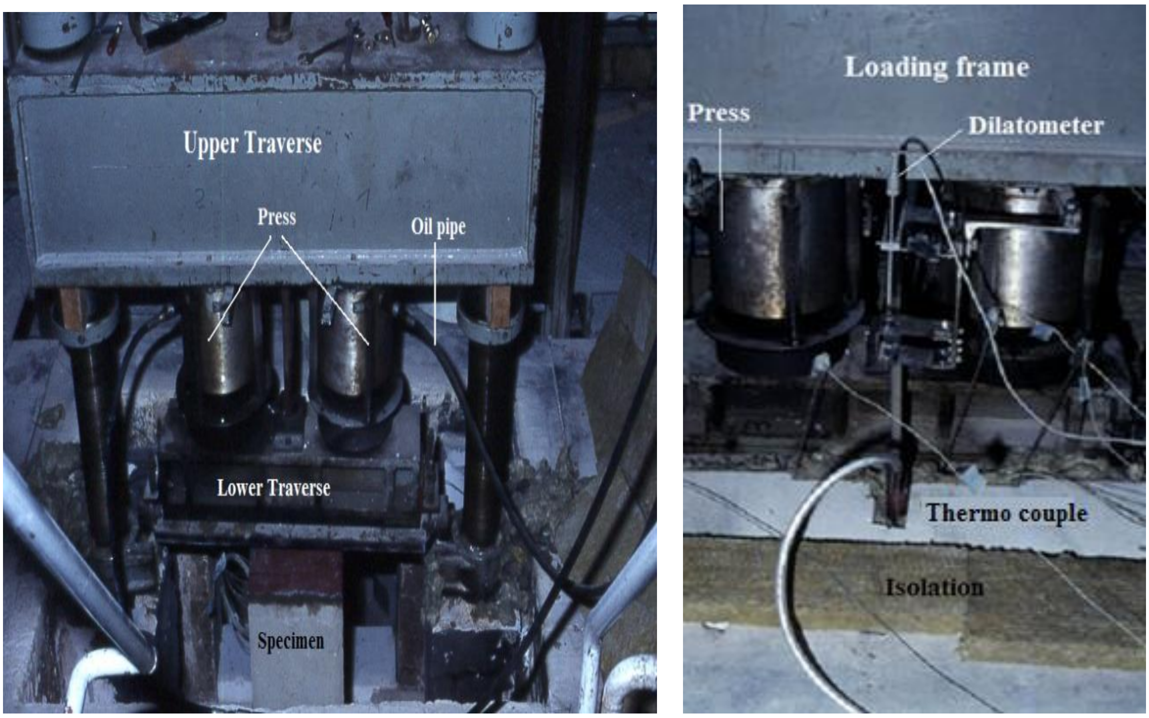


**Figure 2. Loading and dilatometer system of the test furnace**

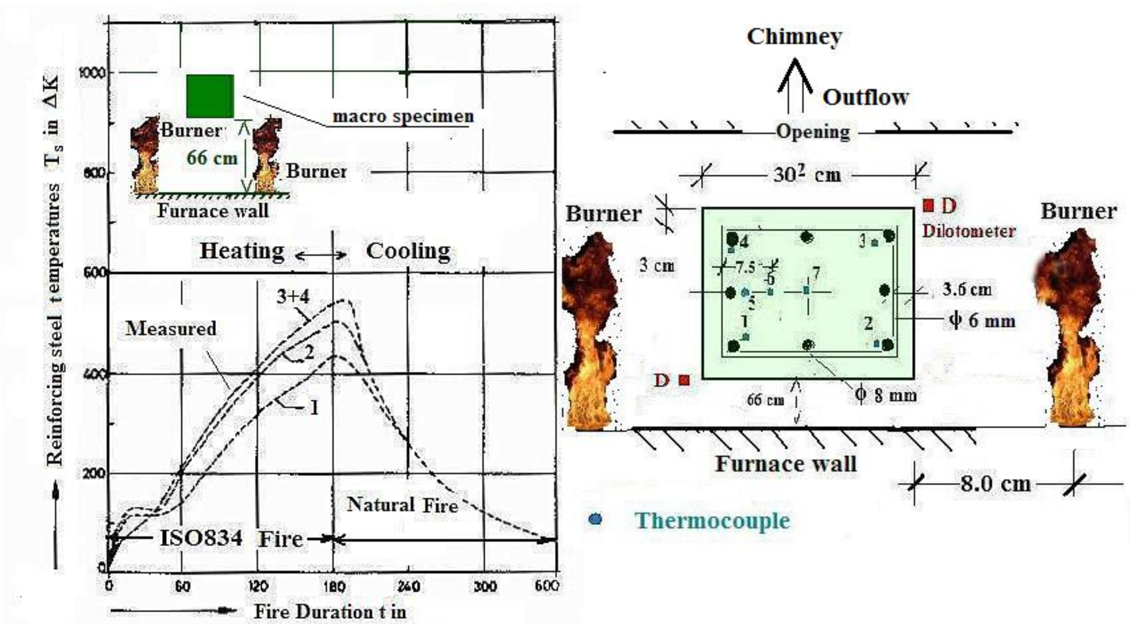


**Figure 3.** Temperature development of the measured corner reinforcements and the cross section of the macro specimen drawn with *no scale*.

In the tests furnace temperatures $T_g$ are controlled according to ISO834 (DIN 4102) fire curve. As a result of specimen dimensions high temperature differences and gradients developed in the cross sections of the macro samples (up to $T_c$≈900ΔK and $T_v$≈60ΔK/cm). Figure 4 shows the calculated temperature distribution in the 30/30 cross section. Consequently, rapid mass and heat transfer processes have been effective in the test specimen.

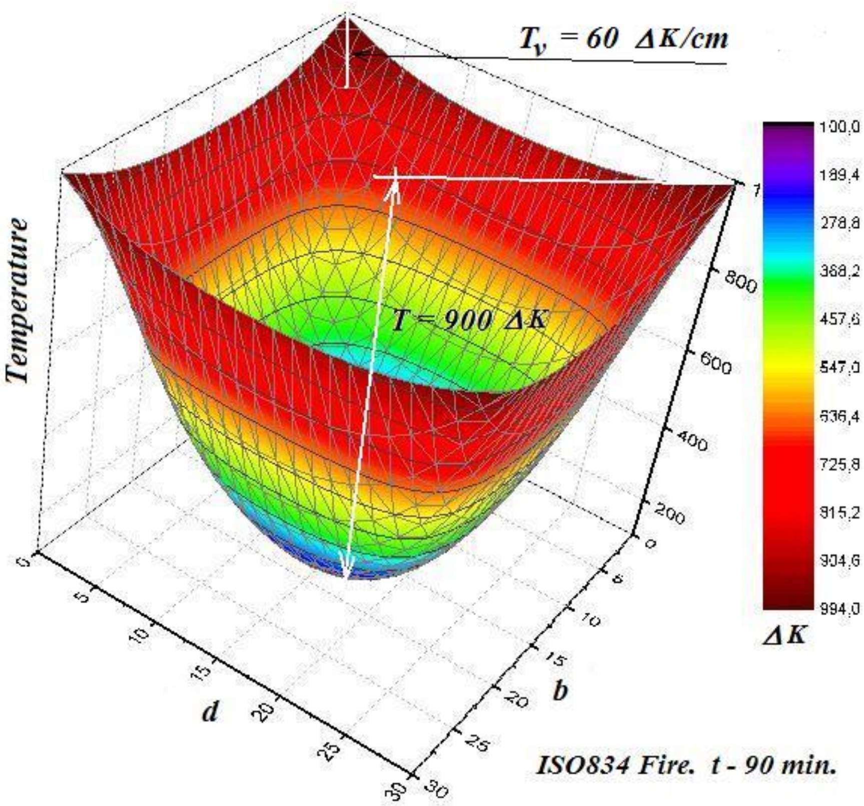


**Figure 4.** Temperature distribution in the specimen with $A_c$=300$^2$ mm$^2$ cross section

Totally seven thermo-couples were installed in each concrete sample. Besides, the steel temperatures $T_s$ measured are also illustrated in Figure 3. The results of the measurements show that the heating of the specimen is not completely symmetric during the test. The temperature differences are in the symmetrically arranged reinforcements up to $T_s$=50ΔK. It is mainly due to the arrangement and the flame direction of the burners as well as the location of the hot gas flow opening just at the opposite side of the furnace wall.

## 2. Total deformation of the macro specimen

The load-elongation development of reinforced concrete structures generally is very complex in case a fire. In a natural fire exposure, it can be dependent also on several of mutually influencing parameters. In order to avoid unnecessarily increasing the parameter number, an all-side fire exposure was chosen according to ISO834 for the tests and only the heating phase of the fire was taken into account and the cooling phase after switch off the furnace burners disregarded for the investigations. The total deformation of the macro-concrete specimens, which are dried at a temperature of $T_r$=20ΔK and a relative humidity of 65%, is shown for various load levels in Figure 5 for ISO fire case.

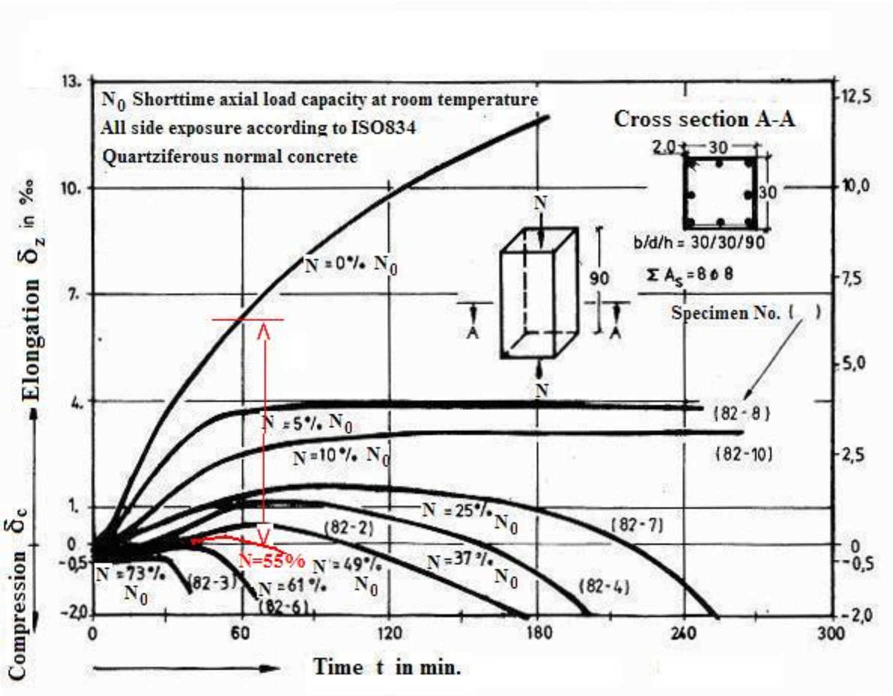


**Figure 5.** Total deformation of the heated macro-concrete specimens

With regard to the total deformation of the specimens under unsteady heating condition, the following results are obtained from the tests:

1. For the unloaded case of the specimen, a continuously increasing expansion is present as elongation (N = 0).
2. The gradient of the thermal elongation is permanently decreasing.
3. After a three-hour fire exposure, the thermal expansion has not decreased at any time during the fire, although thermal expansion decreases in case of small test specimens when approx. a temperature of $T_c$=700ΔK is reached.
4. A slight load increasing of the test specimens with 5% of the short-time load bearing capacity $N_0$ results in after one-hour fire duration a considerable stabilization in the elongation of the macro specimen (specimen 82-8).
5. Due to application of such low load level, the thermal elongation of the macro specimen is almost completely compensated after one hour exposure by the load dependent deformations.
6. However, the elongations remain almost constant even after 4 hour fire duration.
7. It can be seen from the picture that after one-hour fire duration considerable load-dependent deformations occur with the increasing load levels (specimen 82-7).

However, a similar observation can only be made with the small test specimens under a load of 45% $N_0$ with a heating rate of $\dot{T}_c$ =2ΔK/min. This effect in the macro specimens gives a clear indication of the differently developing relaxation forces compared to the small specimens. For example, Figure 5 indicates that after one hour fire exposure and in case of a total restraining, almost 55% restraint forces of $N_0$ develop in the macro specimen. The computational investigations carried out have shown that the application of the material laws, which base on hot creep tests with *small* concrete specimens cannot satisfactorily predict the deformation behavior of structural elements in the fire tests, especially in case of restraining the development of the restraint forces in concrete columns, if the *shape factor* is not taken into account.

Up to 15% loading, no significant difference was observed between the fracture times of the specimens. Only beginning from a 25% $N_0$ loading the fire resistance times were differed. The *critical times* observed in the macro specimen-tests, correspond therefore to the *critical temperatures* at the small concrete cylinder-specimens at which the compression ends with fracture. Figure 5 shows clearly that after exceeding a 60% $N_0$ load level no significant elongation was observed in the specimen. On the other side, beginning from the 60% $N_0$ load level, fire resistance times of the specimens were considerably decreased (Figure 5: s. 82-3 and 82-6 specimens).

**3. Rheological relationships**

For the mathematical treatment of the fire behavior of concrete constructions, it is necessary to analyze and transform the results obtained from the tests in the form of mathematic-rheological relationships. In earlier research work of Subproject B3 of SFB it was pointed out that the total deformation of small concrete specimens under thermo-mechanical stress conditions is composed of at least five separate deformations **(Schneider, U., 1977)**. They are:

a) Thermal elongation
b) Shrinkage deformations
c) Spontaneous elastic deformations
d) Spontaneous plastic deformations
e) Creep deformations

The following types of deformation must be taken into account:

1. Load-dependent deformations (*c-e, see above*) and
2. Load-independent deformations (*a-b*).

The sum of the above-described deformation components *(a-e)* forms the total deformation of a concrete specimen in case of a steady state or transient temperature condition and under an acting load level. The warm creep tests described in section 2 can therefore be considered in this respect as representative for macro specimen deformation due to thermo-mechanical loading condition, so the corresponding rheological relationships can be obtained from the illustrated warm creep curves from Figure 5. While in the case of small test specimens for the temperature-strain relationships, the stress is used as share parameter, it is now being replaced by the load-share parameter for time-elongation relationship as shown in Figure 5.

In order to derive load and time-dependent deformations, working lines for concrete is developed by the help of warm-creep tests. Figure 6 shows the results of the analysis obtained by the help of Figure 5. It results in that; the well-known stress-strain relationship is also replaced by the compression-concrete loading in Figure 6 respectively. The duration of the fire is specified as share parameter by which the concerning specimen compression can be obtained for axial loading. In contrary to the tests by the small specimens, in Figure 6 strain [$\varepsilon_{c]}$ is replaced by the total compression [$\delta_{c]}$ and the stress [σ] by the axial load [N] for different fire durations [t] instead of specimen temperature [$T_c$] as it is the case for small specimens.

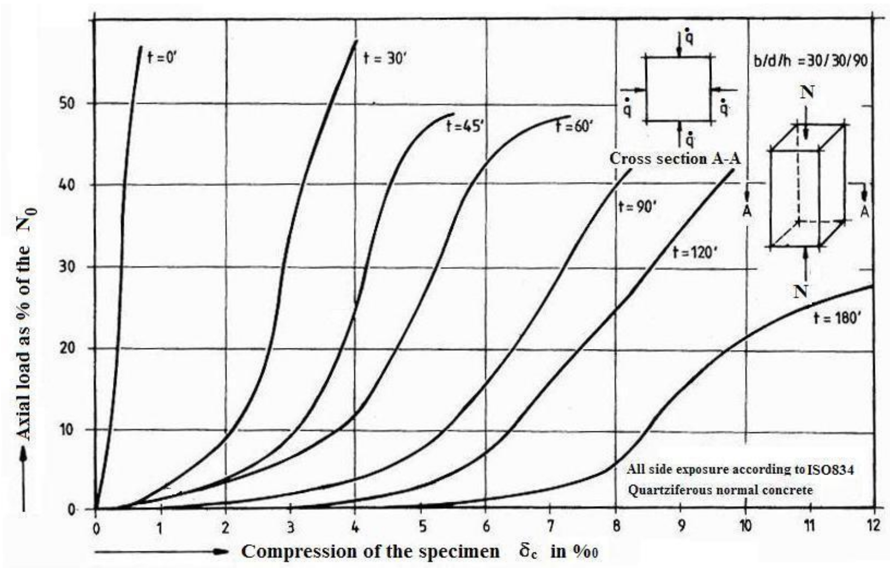


**Figure 6.** Axial load-compression relationship of macro specimens in case of ISO834 fire for different time durations due to eccentricity of $e_u=d/300$

Relationships in Figure 6 can thus be used to determine the load-dependent deformations of a macro concrete specimen for certain fire duration according to ISO834. The advantage of such a representation is that the behavior structural elements under standard fire case can be described with a single load-deformation illustration. It is therefore not necessary to obtain for certain fire duration temperature and stress distribution in the cross section of the structural element by means of complex calculation operations. Instead, the results of the load-compression calculations for a macro specimen can be directly taken from Figure 6.

Figure 6 also indicates that the curves of the load-compression relationships show a double curvature with the increasing fire duration. As the fire progress, a considerable increase in load-dependent compression deformations is to observe.

## 4. Conclusions and objectives

In this contribution, a new rheological relationship for normal concrete at elevated temperatures is presented. This relationship offers the possibility to determine the realistic fire behavior of concrete structural elements by means of simple load-deformation tests. In order to develop such a relationship, instead of the small test specimens, macro test specimens are used as a cut from a concrete structural element. The use of such a macro test specimen is advantageous, because the application problems of the material laws from the small test specimens can considerably be eliminated.

The presenting such rheological relationships for concrete material is, of course, only valid for a particular specimen shape, load eccentricity and fire case. However, the results of the computer investigations so far show that the transfer of the test results from a particular macro specimen shape to the similar macro test prisms, may be possible by some simple mathematical formulations (*i.e.* by relating the hydraulic radii of the specimens).

The results of the new rheological investigations in this paper can lead as a *first step* to a new research conception in order to determine the realistic behavior of concrete structures under fire exposure. By means of further purposive research, it will be possible to reproduce the structural behavior in case of fire, especially in case of restraining, with simple rheologic-mathematical relationships.

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**Notations:**

| | | |
|---|---|---|
| $A_c$ | Cross section area of the concrete specimen | [mm$^2$] |
| $A_s$ | Total reinforcing | [mm$^2$] |
| $b$ | Width of the cross section of macro specimen | [cm, mm] |
| $d$ | Depth of the cross section of macro specimen | [cm, mm] |
| $D$ | Dilatometer in Figure 3. | |
| $e_u$ | Unavoidable eccentricity; $e_u=s_k/300=0.15$ | [cm] |
| $h$ | Height of the macro specimen | [cm, mm] |
| $\Delta K$ | Kelvin difference | [°C] |
| $f_{cm,cube}$ $f_{cm.c}$ | Mean concrete compressive cube strength of 28 days | [N/mm$^2$] |
| $f_y$ | Yield strength of steel | [N/mm$^2$] |
| $N_0$ | Eccentric axial fracture load of concrete macro specimen at room temperatures due to $e_u$ | [kN] |
| $N$ | Axial load with an eccentricity of $e_u$ | [kN] |
| $\dot{q}$ | Heat flow direction | ← |
| $S$ | Distance | [cm] |
| $s_k$ | Buckling length | [cm] |
| $\sigma$ | Stress | [N/mm$^2$] |
| $T$ | Temperature | [$\Delta$K] |
| $T_c$ | Temperature of the specimen | [$\Delta$K] |
| $T_r$ | Room Temperature | [$\Delta$K] |
| $\dot{T}$ | Heating rate | [$\Delta$K/min] |
| $T_g$ | Hot-gas temperature in the furnace | [$\Delta$K] |
| $\dot{T}_g$ | Heating rate of the furnace | [$\Delta$K/min] |
| $T_s$ | Reinforcing steel temperatures | [$\Delta$K] |
| $T_v$ | Temperature gradient $\partial T/\partial s$ | [$\Delta$K/cm] |
| $t$ | Time | [min] |

**Additional Symbols:**

| | | |
|---|---|---|
| $\varepsilon_z$ | Elongation of the concrete small size specimen | [‰] |
| $\varepsilon_c$ | Compression of the concrete small size specimen | [‰] |
| $\delta_z$ | Elongation of the concrete macro specimen | [‰] |
| $\delta_c$ | Compression of the concrete macro specimen | [‰] |

The other notations are defined where they appear in the text

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