# SEVENTH INTERNATIONAL CONFERENCE ON STRUCTURES UNDER SHOCK AND IMPACT

# SUSI VII

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# Experiments on concrete under shock loading

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## Abstract

On detonations or hypervelocity impacts concrete structures are loaded with shockwaves. These shockwaves cause a steep increase in pressure within the wavefront which propagates at high velocity. For a numerical simulation of such process a constitutive material law $F = f(\varepsilon, \dot{\varepsilon}, T)$ is needed which adequately describes concrete under these conditions. As basis for such a constitutive law tests on concrete under explosive loads were performed and different material parameters were investigated.

We report our approach to measure material parameters during tests with different explosive charges on concrete and our model tests for demolition work.

We got first experience in using a new temperature sensor, called the atomic layer thermopile, to measure the temperature raise caused by the adiabatic compression. This sensor was developed for performance measurement of high energetic laser pulses. The mode of operation of this sensor is based on the temperature gradient between the sensor surface and the base of the device. Very fast response time is possible, because there is no need of getting a complete heat transfer from the ambient concrete temperature to the whole sensor. Responsible for the output voltage proportional to the temperature rise is the thermal Seebeck-effect which can be splitted in a longitudinal and a transversal component due to the orientation of the layers.

For stress measurement manganin gauges and for strain measurement ordinary strain gauges were used. For the application of these methods at high velocity loads in concrete special encapsulations are needed in order to save the functionality and to provide fast rise times of the output signals.

Results of the measurements will be shown and remaining problems will be discussed.

# 1 Introduction

In order to develop material models as many as possible data should be gained by performing tests. The measuring of data within concrete under shock loading during tests with contact charges is a challenge for the measuring technique because of the fast rise time of the signals. In the literature only a small number of publications can be found containing data for standard concrete under these condition.

Tests for measuring the volumetric pressure were made earlier at our institute and a material law by disregarding deviatoric stress and analytically discribing the adiabatic temperature rise within the concrete was developed. To describe the stress-state including the deviatoric part, it is necessary to measure the stresses in different directions, or minimally by measuring the hydrostatic pressure and the stress in one direction. To check the assumptions for the adiabatic heat a new attempt to measure the temperature rise was made.

# 2 Theory

Shockwaves in concrete are formed because of the nonlinearity of the volumetric stress-strain-relation. The propagation velocity c of the wave depends on the slope of the non-linear stress-strain-relation.

In the elastic range all parts of the wave propagate with the same velocity, so the original shape is only disturbed by the inhomogenity of the material. If the amplitude of the wave is higher, so that the plastic range of the stress-strain-relation is achieved, the pores are destroyed and the velocity for the plastic part of the wave is lower, the wave smoothes out. In the high pressure range, the material is highly volumetric compacted and the propagation velocity for the higher amplitudes increases, so that the wave profile steeps up to a sharp discontinuity in pressure named shockwave [1]. The description of a shock wave transition through a material is given by the Hugoniot-Equation. The Conservation-Equations for mass, momentum and energy for the material before and after the wave transition can be combined to the Hugoniot-Equation describing all possible states of the material loaded by a shockwave:

$$E_1 - E_0 = \frac{1}{2}(p_1 + p_0) \cdot (V_0 - V_1) \qquad \text{Hugoniot-Equation} \qquad (1)$$

The transition between the initial state and the final state is given by the Raleigh-Line, since the states in between are not run through:

$$\frac{p_1 - p_0}{V_0 - V_1} = \left(\frac{u_S}{V_0}\right)^2 \qquad \text{Raleigh-Line} \qquad (2)$$

The Hugoniot-Curve is generally a line lying in a plane representing the Equation of State (EOS) in the pressure-volume-energy-space. Many assumptions for the EOS were made. To gain more information on the best fitting EOS it is necessary to know the adiabatic part for the Hugoniot [9].

In Figure 1 the failure surface for concrete is shown. The pressure region up to 1000 MPa is known from static tests, but in the high pressure region only a few points on the hydrostatic axis have been measured. The development of the deviatoric part is not known. There are three possibilities for the shape of this part. The first possibility is that the deviatoric part of the failure state increases with the hydrostatic part because of the increasing of the friction between the destroyed material parts, the second possibility is that the deviatoric part comes to a constant value or thirdly it decreases due to the decrease of friction between the remaining particles of the material. To get some information on the shape of the deviatoric it is necessary to measure stress in different directions.

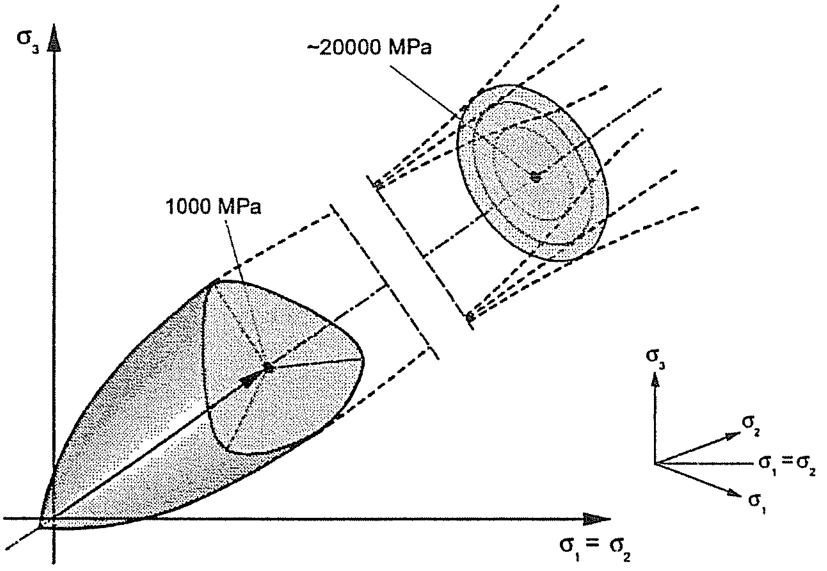

Figure 1: The known failure surface for concrete and the possibilities for the failure surface in the region above

## 3 Experiments

A series of 3 tests were performed on concrete slabs loaded with contact charges. In 2 cases the load was 2 kg TNT and in another case the load had a weight of 0.7 kg TNT. As charge a so-called plane-wave-generator and slabs with $a = 0.5$ m were used (Figure 2).

The outer part of this conical charge consists of Composition B, an explosive with a detonation velocity of 7900 m/s, the inner cone is made of TNT with a detonation velocity of 6800 m/s, so the detonation wave of the faster explosive holds the inner detonation wave within the cone. The base angle of the geometry of the charge depends on the detonation velocities and is responsible for the formation of a plane wave that loads the slab on the upper surface.

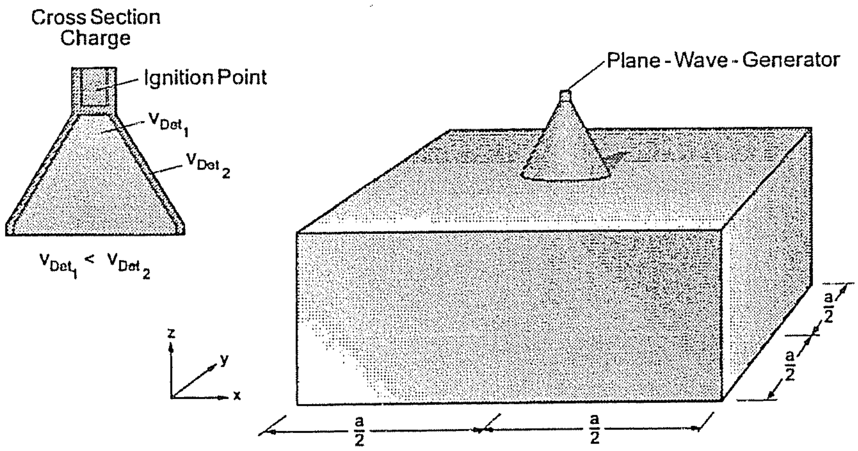

Figure 2: Test setup with plane-wave-generator

# 4 Measuring Technique

To collect the desired data a new measurement system was used and partially developed. For measuring the volumetric pressure p within the concrete carbon-resistors were used. At our institute a dimensionless calibration curve based on the results of many authors has been established [9]. The resistors are encapsulated by an epoxid-bonding-agent which is injected in a small casting form in which the resistors are positioned and connected by a coaxial cable. It is important that the connection wires pass the sensor on the opposite side to the load direction to avoid destruction of the sensor before it is hit by the pressure wave (Figure 3). In earlier tests at our institute only the method of the carbon-resistors was used to measure the volumetric pressure within the concrete and the deviatoric stress was neglected. In order to check the assumption that in the case of a slab loaded by a contact charge the stress state in the region directly under the charge is hydrostatic not only the volumetric pressure p should be measured.

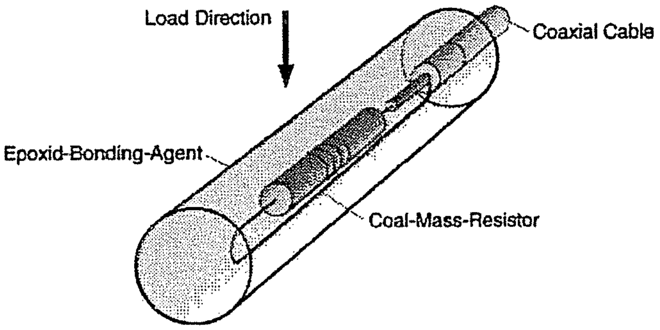

Figure 3: Encapsulation for carbon-resistor

One of the objectives of this study was to determine the deviatoric part of the stress state. Therefore it is necessary to record the stress in different directions or minimally to measure the volumetric pressure and stress in one direction. With the assumption $\sigma_{22} = \sigma_{33}$ one can calculate the deviatoric stress $\tau_0$ [3].

The tests were performed with manganin sensors which are thin foil-sensors measuring the stress perpendicular to the foil-plane. The sensors have a thickness of 13 μm and an area of (44.45 x 6.35) mm. As the foil itself and especially the connection wires are very sensitive they have been embedded in a sandwiched encapsulation made of aluminium (Figure 4). Aluminium was chosen because of the similar modulus of elasticity in comparison to the concrete. The wires were led to the opposite site of the load, to avoid a pre-event destruction [2].

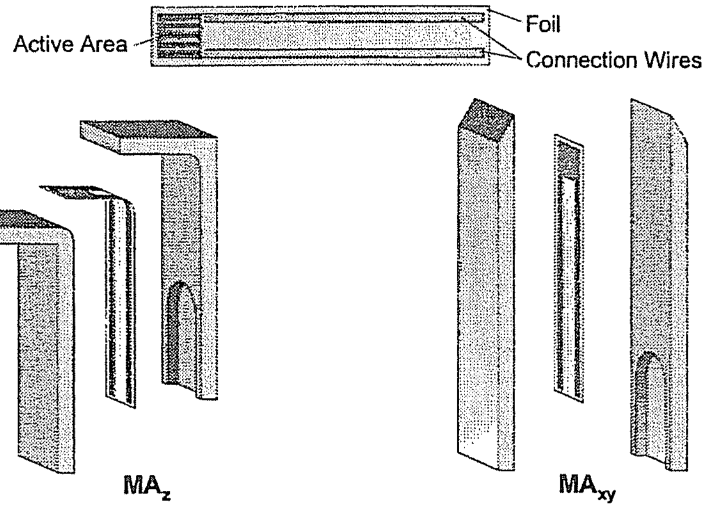

Figure 4: Encapsulation for manganin gauges

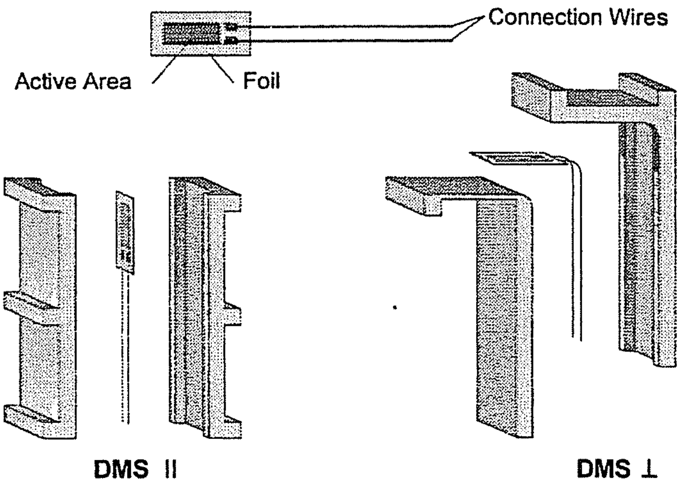

Figure 5: Encapsulation for strain gauges

For the strain measurement high performance strain gauges of a type that can measure strains up to 15 % were used (Figure 5). Similar to the manganin gauges they were bonded in an sandwiched aluminium encapsulation. In addition to the manganin-type encapsulation they have been ribbed in order to assure the bonding between the sensor and the concrete.

An innovative measurement system was developed to measure the temperature rise during the adiabatic compression. A sensor was used that is able to register a temperature rise in the time of nanoseconds when used in open form. This sensor called the atomic-layer thermopile was originally developed for power measurement of high energy lasers. The physical principle of this measurement is the Seebeck-Effect, well known as the principle of thermocouples [6].

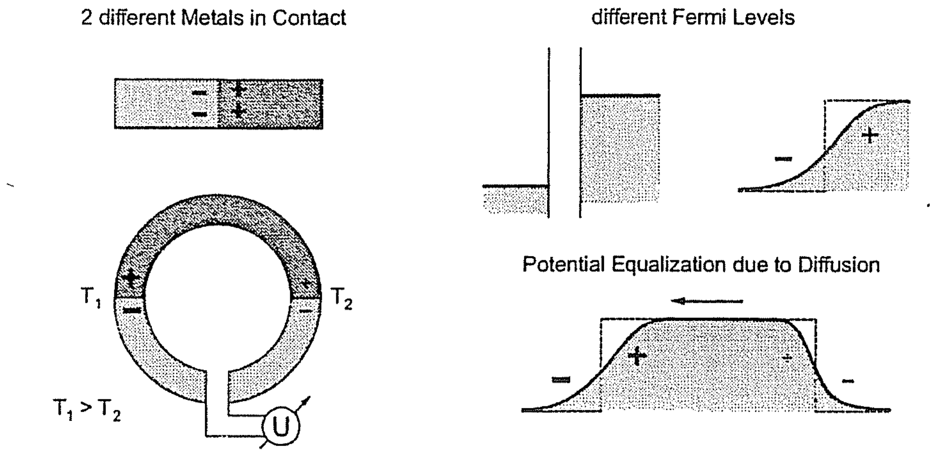

Figure 6: Physical principle of thermocouples – Seebeck-Effect

Bringing two different metals in contact causes a contact voltage that is originated by the two different Fermi levels of the metals. From the metal with the higher occupied electron states to that with the lower occupation occurs a diffusion in order to equalize the potentials. The difference of the potentials depends on the temperature. When considering a ring of the two metals in which one contact is kept at a constant temperature, the temperature at the other contact will cause a voltage proportional to the temperature difference that can be measured between the two contacts (Figure 6).

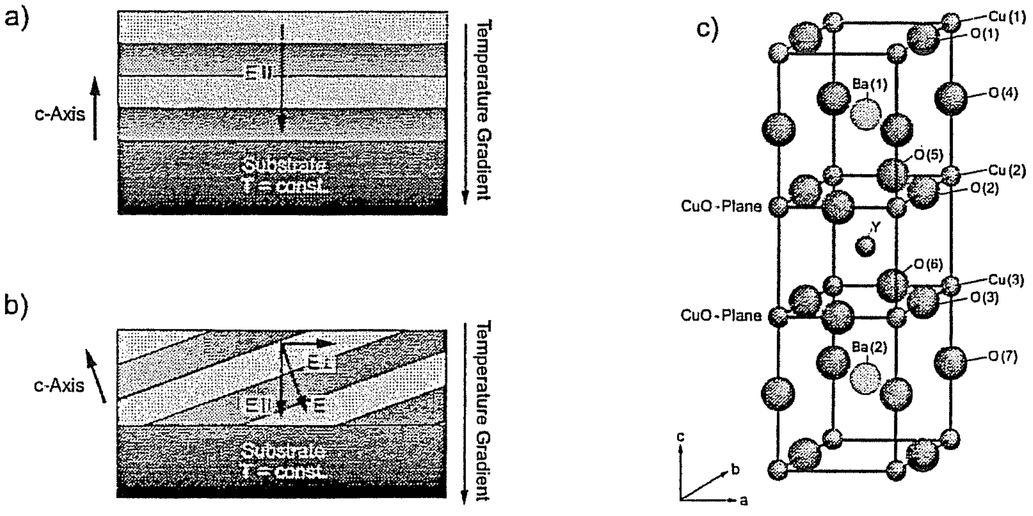

Figure 7: Transversal Seebeck-Effect and Crystal Structure of $YBa_2Cu_3O_7$

Considering many layers of two different metals on a substrate that is kept at constant temperature a voltage is caused by heating the surface of the multilayer (Figure 7 a, 8 a).

This voltage is the sum of all the contact voltages at the layer boundaries. As it is difficult to pick up the voltage between the surface and the substrate the angle of the layers can be tilted so that the electric field caused by the temperature gradient can be divided in a parallel and a transversal part (Figure 7 b).

The voltage caused by this transversal field can be picked up at the sides of the sensor which is a called an atomiclayer thermopile. The multilayer is given by the anisotropy of the high temperature superconductor $YBa_2Cu_3O_7$ whose crystal structure is shown in Figure 7 c. Layers of good conducting copper-oxide are alternating with the Ytterbium and Barium layers that are rather bad conductive [8].

This type of sensor has rise times of a few nanoseconds when used in unencapsulated form as it is in power measurement of lasers for which the sensor was developed [7]. For application in concrete the very sensitive sensor should be encapsulated. This is done by casting it within the same epoxid-bonding-agent as used for the carbon-resistors. For the calibration of the signal many assumptions for the heat transfer to the sensor must be taken into account. These assumptions lead to a sensitivity of 0.01 V/K.

As for the other sensors also in the case of the thermopile it is important to take into account the connection points and wires. Normally the sensors are connected in a way that the gold-contacts lie above the active surface (Figure 8 c).

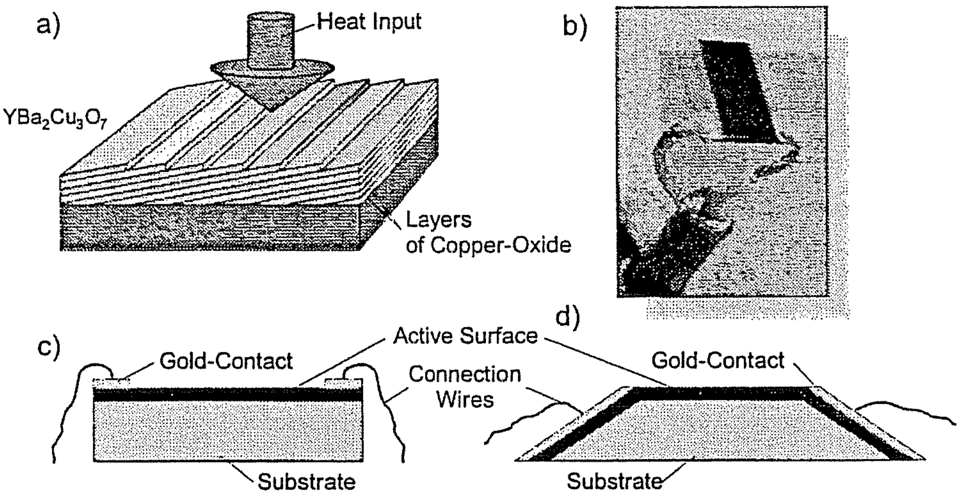

Figure 8: Thermopile in principle and after contacting, principle of contacting

Together with the manufacturer we developed a sensor setup with sloped contact-planes on both sides of the sensor so first the active surface is striked by the incoming pressure wave, before destruction of the contacts can occur (Figure 8 d). The contacting was made by a conducting silver bond (Figure 8 b).

## 5 Experimental Results

A typical pressure profile measured by carbon-resistors in the high pressure region is presented in Figure 9. As expected the peak pressure is reducing very fast. The pressure of 18 000 MPa in a depth of 2 cm decreases to a value of 2 000 MPa in a depth of 7 cm. In the lower region of the slab the signals are overlaid by noise but amplitudes down to 5 MPa can still be resolved. The sensors AB7 and AB8 were positioned in the same horizontal plane as sensor AB3 but with the radius r = 10 cm resp. r = 20 cm apart from the vertical middle axis of the slab, so that the decrease also in horizontal direction could be seen.

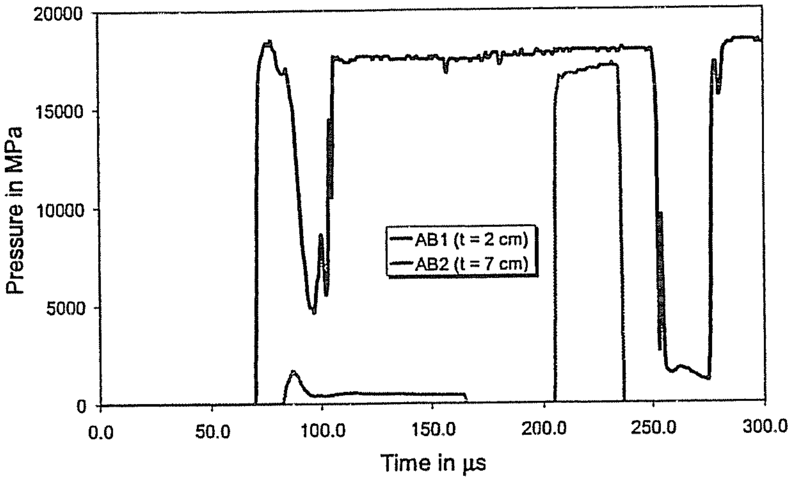

Figure 9: Pressure profiles in the upper region of slab III

The stress measurement is rather difficult due to the higher sensitivity of the sensors. The best results can be gathered in the load direction. In Figure 10 two stress curves from slab II are shown. The rise time for the stress-signals is very short and the peaks are sharper than the pressure peaks.

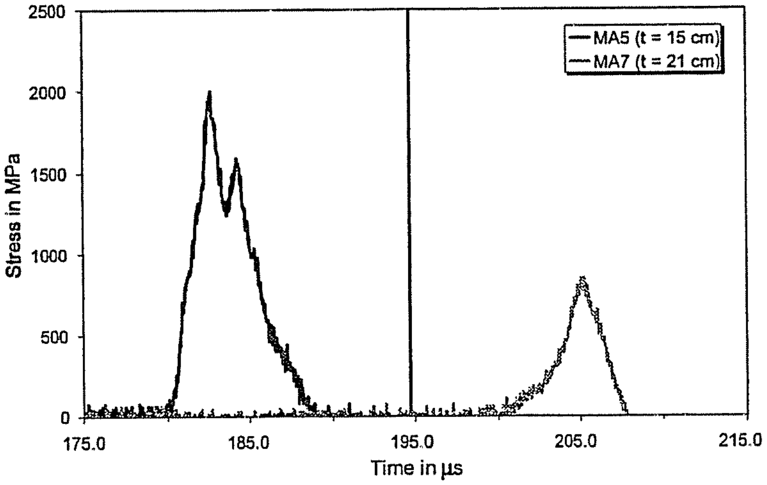

Figure 10: Stress measurement with manganin gauges in slab II

The strain measurement leads to results with the highest strain of 12 % (DMS1) is measured in the upper part of the slab, which decreases to 3 % in a depth of 12 cm (DMS3). In this level a gauge was also embedded perpendicular to the load direction (DMS4). This gauge also registered a negative strain of about 5 % what leads to the assumption that in this region the incoming wave is more and more spreading in the horizontal direction and is no longer propagating as a plane wave in this part of the slab.

In addition to a measured temperature curve the pressure registered in a position that lies symmetric to the position of the thermopile in slab III is also shown in Figure 11. The coincidence of the signals can be seen and a temperature rise of 17 K for a pressure of 25 MPa has been measured.

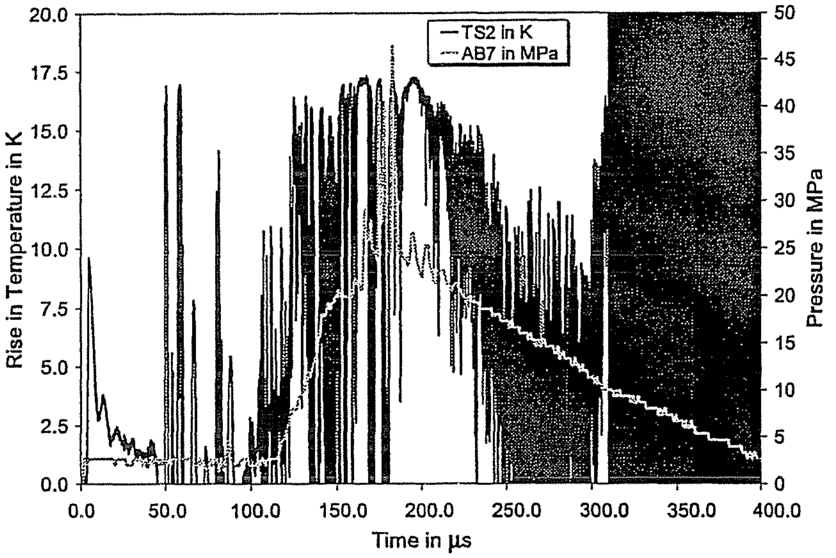

Figure 11: Temperature with pressure curve of a symmetric position in slab III

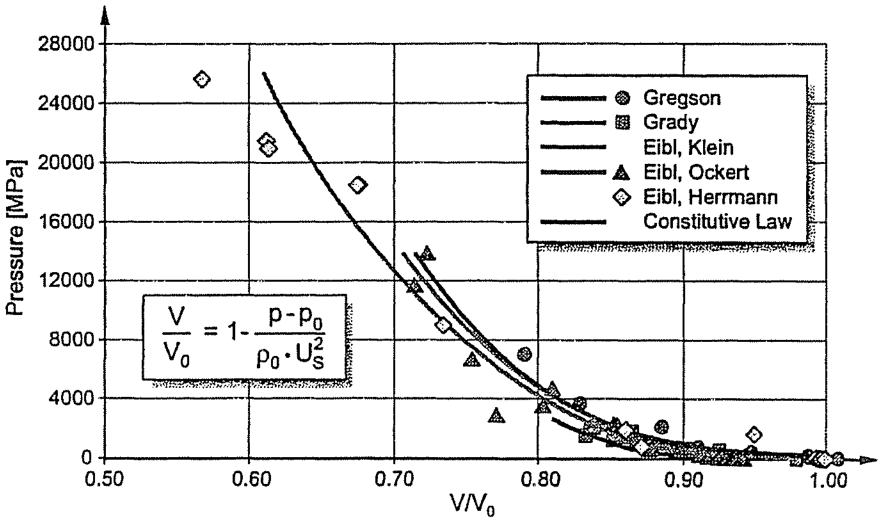

Figure 12: Hugoniot-Curve with new points from recent test series [4], [5], [9]

For the same explosive used for the charge the wave-velocity can be determined by derivation of a polynomial-fit of third degree of the propagation-time-history for all the tests. The result is a function for the wave-velocity in dependence of the depth of wave-propagation. Using the resulting wave velocities, points of the Hugoniot can be gained by calculating for each point with a known pressure the relation $V/V_0$. The new Hugoniot points gained in this series are presented together with known points in Figure 12.

## 6 Conclusions

In order to get more material data for standard concrete of a compressive strength of 40°MPa new points of the Hugoniot-Curve were gained by the presented test series of concrete slabs under shock loading caused by contact charges. The technique using carbon-resistors has been improved. Successful stress and strain measurement in the load direction has been performed. For these measurements special encapsulations have been developed. A new attempt for measuring the rise in temperature during an adiabatic compression was made and a first curve was presented. This technique seems to be worth to be developed further in order to get a fast temperature sensor for the application of temperature measurement in opaque materials where optical methods cannot be used.

## References

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## Abstract

On detonations or hypervelocity impacts concrete structures are loaded with shockwaves. These shockwaves cause a steep increase in pressure within the wavefront which propagates at high velocity. For a numerical simulation of such process a constitutive material law $F = f(\varepsilon, \dot{\varepsilon}, T)$ is needed which adequately describes concrete under these conditions. As basis for such a constitutive law tests on concrete under explosive loads were performed and different material parameters were investigated.

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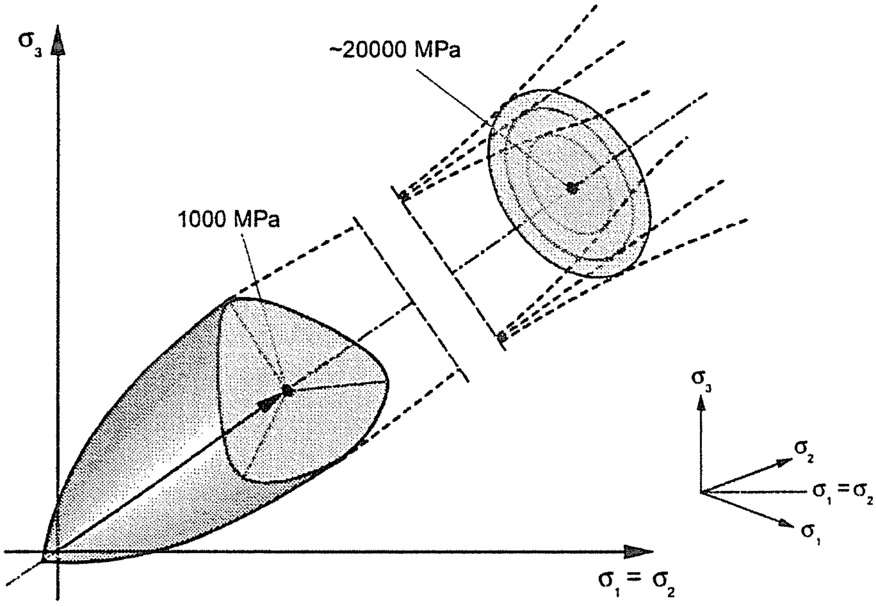

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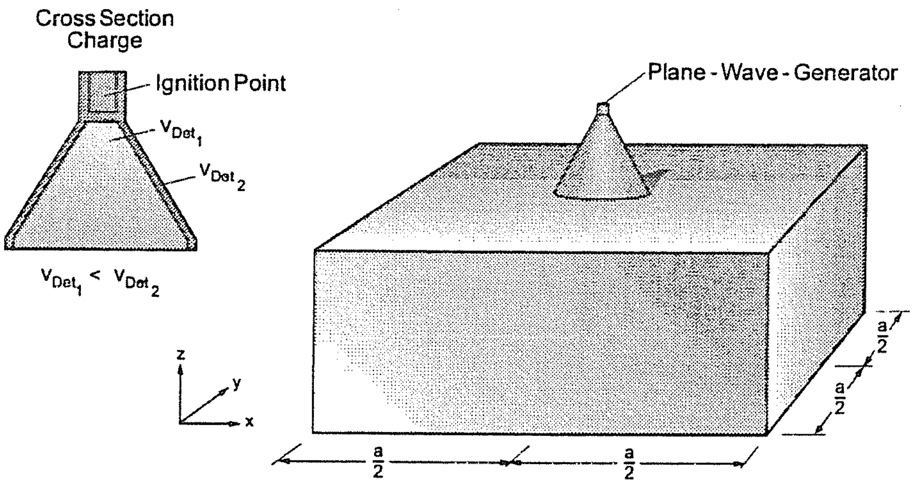

Figure 2: Test setup with plane-wave-generator

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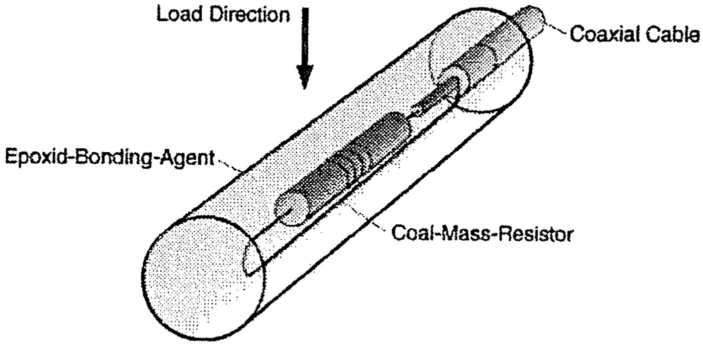

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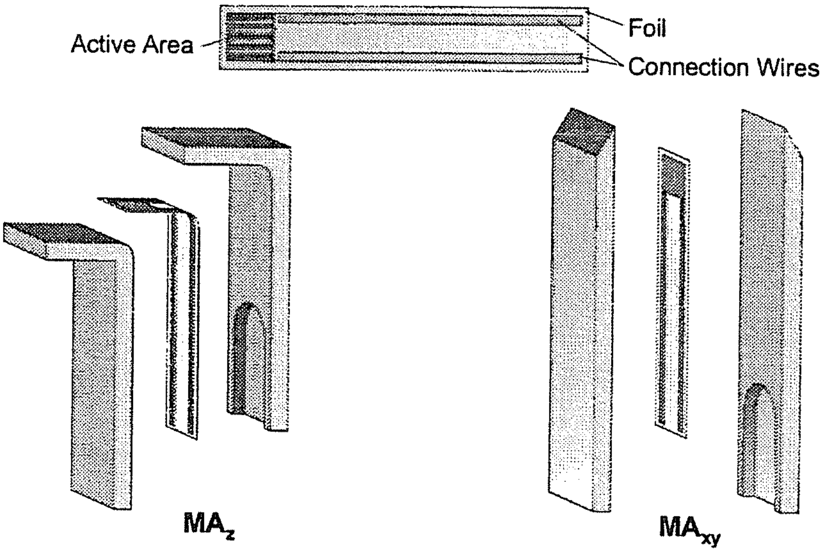
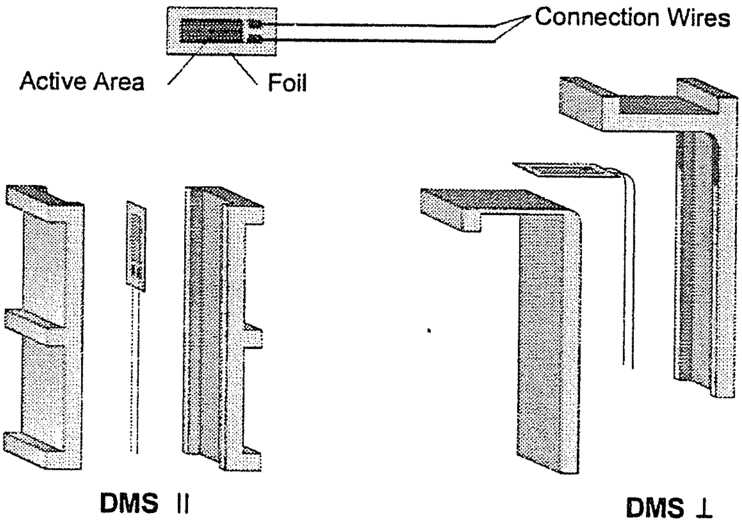


Figure 4: Encapsulation for manganin gauges



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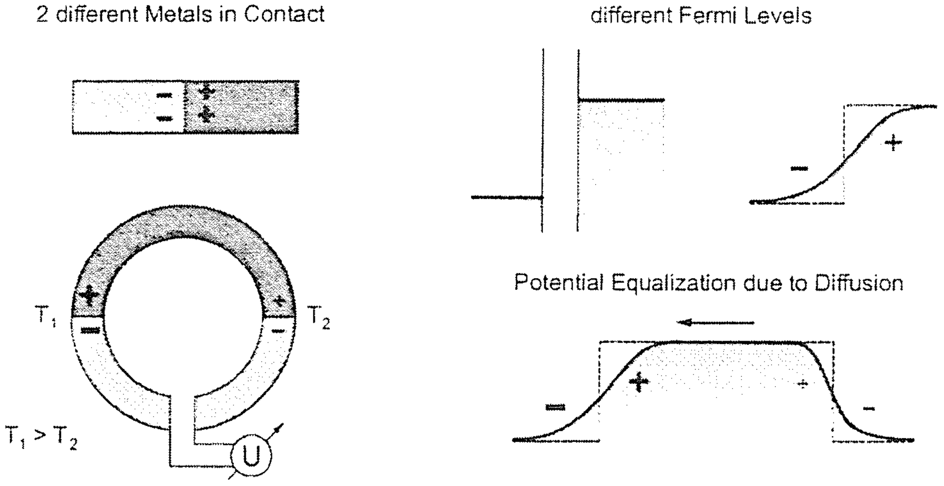

Figure 6: Physical principle of thermocouples – Seebeck-Effect

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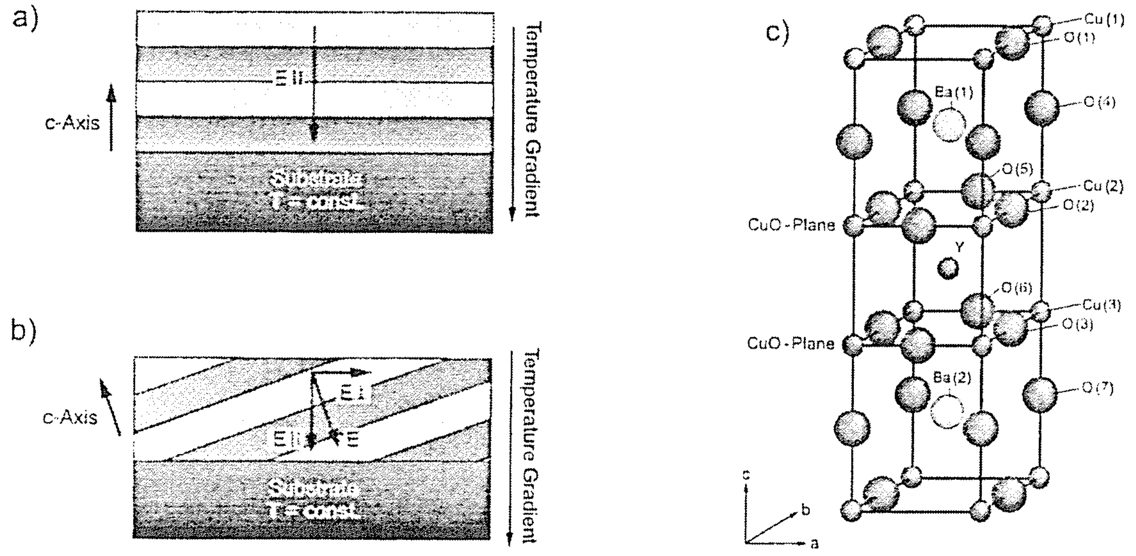

Figure 7: Transversal Seebeck-Effect and Crystal Structure of $YBa_2Cu_3O_7$

Considering many layers of two different metals on a substrate that is kept at constant temperature a voltage is caused by heating the surface of the multilayer (Figure 7 a, 8 a).

This voltage is the sum of all the contact voltages at the layer boundaries. As it is difficult to pick up the voltage between the surface and the substrate the angle of the layers can be tilted so that the electric field caused by the temperature gradient can be divided in a parallel and a transversal part (Figure 7 b).

The voltage caused by this transversal field can be picked up at the sides of the sensor which is a called an atomiclayer thermopile. The multilayer is given by the anisotropy of the high temperature superconductor $YBa_2Cu_3O_7$ whose crystal structure is shown in Figure 7 c. Layers of good conducting copper-oxide are alternating with the Ytterbium and Barium layers that are rather bad conductive [8].

This type of sensor has rise times of a few nanoseconds when used in unencapsulated form as it is in power measurement of lasers for which the sensor was developed [7]. For application in concrete the very sensitive sensor should be encapsulated. This is done by casting it within the same epoxid-bonding-agent as used for the carbon-resistors. For the calibration of the signal many assumptions for the heat transfer to the sensor must be taken into account. These assumptions lead to a sensitivity of 0.01 V/K.

As for the other sensors also in the case of the thermopile it is important to take into account the connection points and wires. Normally the sensors are connected in a way that the gold-contacts lie above the active surface (Figure 8 c).

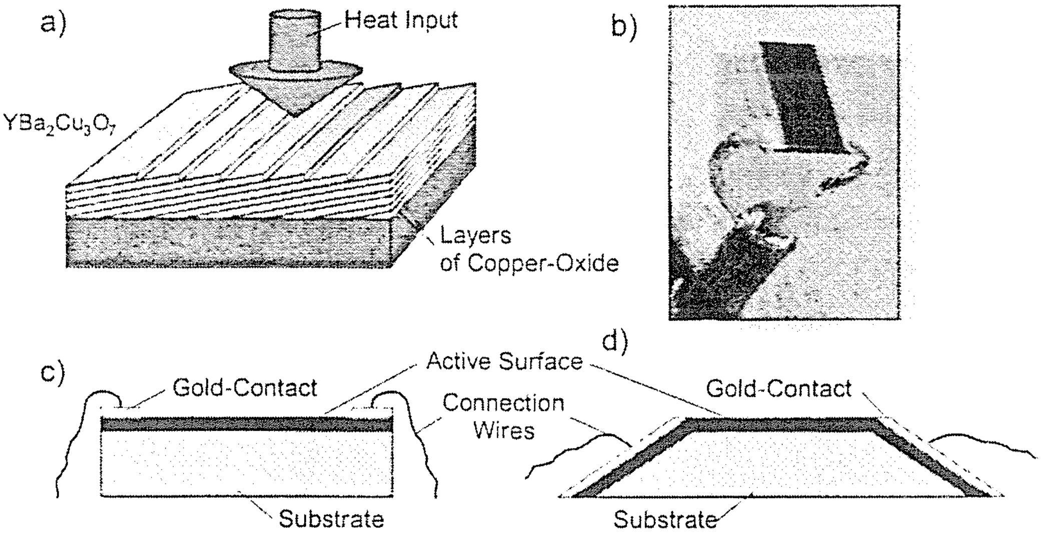

Figure 8: Thermopile in principle and after contacting, principle of contacting

Together with the manufacturer we developed a sensor setup with sloped contact-planes on both sides of the sensor so first the active surface is striked by the incoming pressure wave, before destruction of the contacts can occur (Figure 8 d). The contacting was made by a conducting silver bond (Figure 8 b).

## 5 Experimental Results

A typical pressure profile measured by carbon-resistors in the high pressure region is presented in Figure 9. As expected the peak pressure is reducing very fast. The pressure of 18 000 MPa in a depth of 2 cm decreases to a value of 2 000 MPa in a depth of 7 cm. In the lower region of the slab the signals are overlaid by noise but amplitudes down to 5 MPa can still be resolved. The sensors AB7 and AB8 were positioned in the same horizontal plane as sensor AB3 but with the radius r = 10 cm resp. r = 20 cm apart from the vertical middle axis of the slab, so that the decrease also in horizontal direction could be seen.

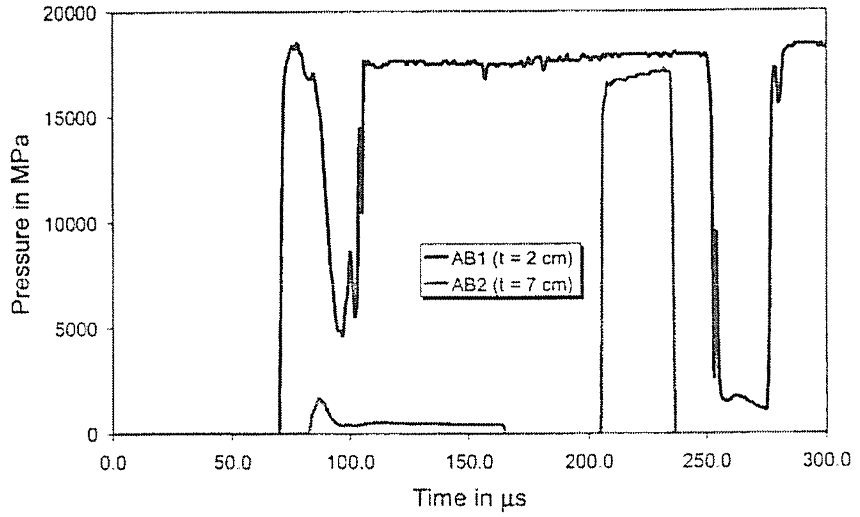

Figure 9: Pressure profiles in the upper region of slab III

The stress measurement is rather difficult due to the higher sensitivity of the sensors. The best results can be gathered in the load direction. In Figure 10 two stress curves from slab II are shown. The rise time for the stress-signals is very short and the peaks are sharper than the pressure peaks.

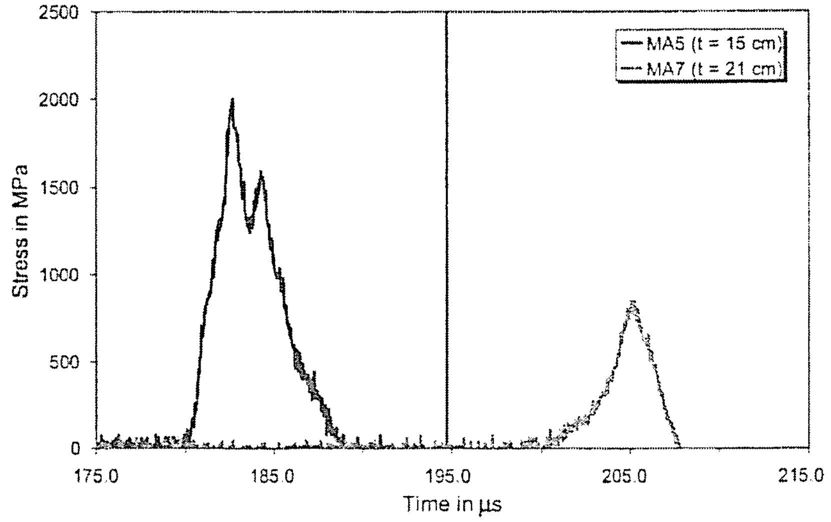

Figure 10: Stress measurement with manganin gauges in slab II

The strain measurement leads to results with the highest strain of 12 % (DMS1) is measured in the upper part of the slab, which decreases to 3 % in a depth of 12 cm (DMS3). In this level a gauge was also embedded perpendicular to the load direction (DMS4). This gauge also registered a negative strain of about 5 % what leads to the assumption that in this region the incoming wave is more and more spreading in the horizontal direction and is no longer propagating as a plane wave in this part of the slab.

In addition to a measured temperature curve the pressure registered in a position that lies symmetric to the position of the thermopile in slab III is also shown in Figure 11. The coincidence of the signals can be seen and a temperature rise of 17 K for a pressure of 25 MPa has been measured.

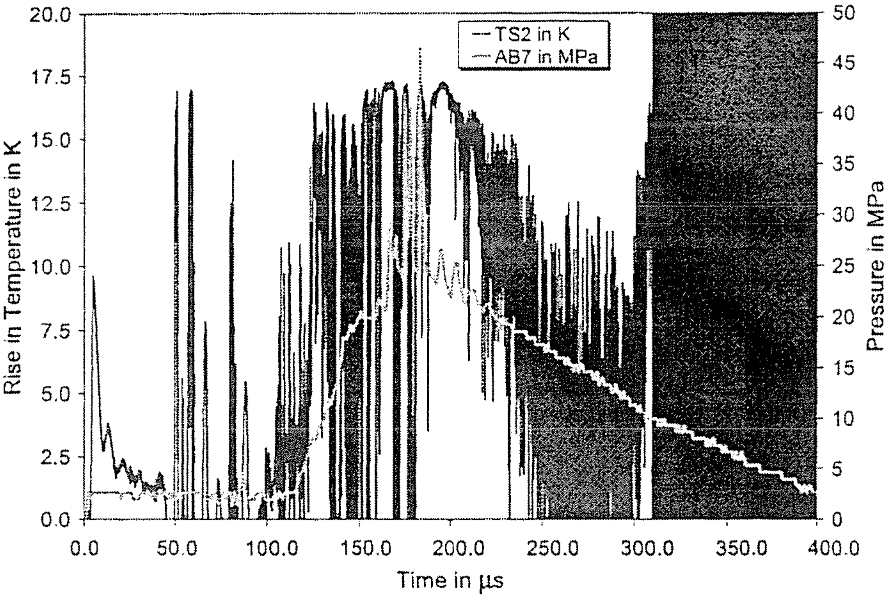

Figure 11: Temperature with pressure curve of a symmetric position in slab III

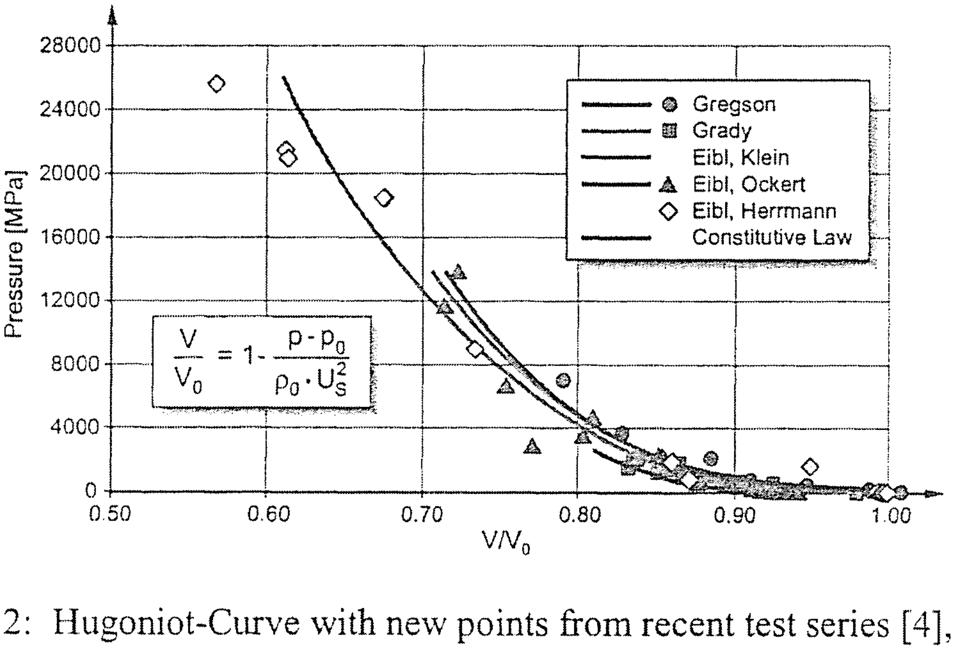

Figure 12: Hugoniot-Curve with new points from recent test series [4], [5], [9]

For the same explosive used for the charge the wave-velocity can be determined by derivation of a polynomial-fit of third degree of the propagation-time-history for all the tests. The result is a function for the wave-velocity in dependence of the depth of wave-propagation. Using the resulting wave velocities, points of the Hugoniot can be gained by calculating for each point with a known pressure the relation $V/V_0$. The new Hugoniot points gained in this series are presented together with known points in Figure 12.

## 6 Conclusions

In order to get more material data for standard concrete of a compressive strength of 40°MPa new points of the Hugoniot-Curve were gained by the presented test series of concrete slabs under shock loading caused by contact charges. The technique using carbon-resistors has been improved. Successful stress and strain measurement in the load direction has been performed. For these measurements special encapsulations have been developed. A new attempt for measuring the rise in temperature during an adiabatic compression was made and a first curve was presented. This technique seems to be worth to be developed further in order to get a fast temperature sensor for the application of temperature measurement in opaque materials where optical methods cannot be used.

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