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An Experimental Study

Hertz, Kristian

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INSTITUTE OF BUILDING DESIGN

Report no. **164**

KRISTIAN HERTZ

MICROWAVE HEATING FOR FIRE MATERIAL TESTING OF CONCRETE -AN EXPERIMENTAL STUDY

Den polytekniske Læreanstalt, Danmarks tekniske Højskole
Technical University of Denmark. DK-2800 Lyngby 1983

CONTENTS

Hans Christian Ørsted

PREFACE

The founder of the Technical University of Denmark Hans Christian Ørsted who discovered the electro magnetism belonged to the generation of natural philosophers at the time of romantism.

Though his attitude towards the natural philosophy, which today is called physics, was very religious, he was very much aware of the value of experimentation.

His inclination for practical research led to many discoverings, and became a tradition at the university.

This report deals with the practical use of rapid oscillating electromagnetic waves in fire material testing of concrete, and therefore it should be seen as a small contribution in compliance with the traditions of the university.

Copenhagen, August 1983
Kristian Hertz
M.Sc. Ph.D. Struct.Eng.

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I would also like to thank members of the CIB working group W 14 for useful discussions during the period of work.

Finally I want to express my gratitude to the Danish Council for Scientific and Technical Research (Statens teknisk videnskabelige Forskningsråd), which has supported the work financially.

SUMMARY

The report deals with the first attempt to utilize microwave power for heating rapidly concrete specimens at high temperature levels without introducing large temperature differences and thermal stresses which would conceal the measurement of the properties of the concrete.

Having succeeded in heating the specimens the heating method was improved and used to determine the specific capacity of heat and the residual compressive strength of a rapidly heated concrete.

This was compared to the residual compressive strength of the same concrete heated slowly, and the differences caused by the rate of heating was examined, showing that errors of until 20 pct. can be expected, in case a calculational design for fire resistance of load bearing structures is based on material properties of slow-heated specimens in stead of rapid-heated specimens.

SYMBOLS

c_p	specific capacity of heat
f_{cc}	compressive strength of concrete
f_{cc20}	compressive strength of concrete at 20°C
T	temperature
t	time

INTRODUCTION

In the Theoretical Study Hertz [5] it was concluded from calculations based on the literature that it seemed possible to eliminate temperature differences in concrete specimens almost completely during fire tests using microwave power combined with an adjusting of the surface heat loss for instance by using an insulating material.

The idea was published supported by theoretical investigations only, because it was found to be essential to put forward the theory at an early stage, should the authors research stop for economical reasons, but also to obtain comments that may arise.

Meanwhile, it has been possible to proceed within certain limitations, and the theoretically stated theory has been shown to be valid in practice.

This opens quite new possibilities in fire material testing of concrete.

Concrete specimens of sufficient dimensions can now be heated quickly with almost uniform temperature distributions at any time of the heating, and the problems arising from the thermal stresses are consequently completely avoided.

PRELIMINARY INVESTIGATIONS

Before the theoretically stated heating method could be put into practice, certain preliminary investigations were necessary in order to decide how the temperature distributions in the microwave exposed concrete specimens should be measured and to choose a suitable insulation material for preventing the heat loss from a heated specimen to the cold oven cavity.

Cubes of various sorts of mineral wool were exposed in a 600 W microwave oven of 2.45 GHz, and the temperature increments were measured.

The wool which was the most susceptible to microwave power was a stone wool of 112 kg/m^3. The second most susceptible was a stone wool of 60 kg/m^3 followed by a glass wool of 74 kg/m^3.

Finally a ceramic fibre wool of 111 kg/m^3 was found to be not at all influenced by the microwave power.

Consequently the ceramic fibre wool was chosen as insulation material for the future testings.

For temperature measuring three possibilities were compared.

A continuous temperature recording is a technical possibility.

In order to do this a wire can be carried through the wall of the microwave oven using a pipe filled with an electrically damping material like ferrite.

Still the microwave field would influence the measuring if ordinary thermocouples are used.

This effect has been successfully avoided for copper-constantan thermocouples by Bhattacharyya and Pei [2].

They twisted the two cords of the thermocouple closely together and canceled the field induced in the one cord by that in the other.

As far as known, this was the first time that a continuous temperature recording has been made in a microwave field.

Though, the technical difficulties in using the method seems out of proportion to the value of a continuous temperature recording in the concrete specimens of this project.

The thermal insulation of the specimens and the large heat capacity of the concrete has the effect of stabilizing the temperature during a measurement operation after a heating period, and hence the measurements could just as well be made through the opened door of the oven when the microwave field is not applied.

Later on the drop in temperature during a 60 seconds measurement has been found to be about 5°C at a temperature level of 600°C for a cylinder of height 20 cm and diameter 10 cm provided with a 5 cm ceramic fibre wool insulation.

Measuring the temperature through the door after heating or at intervals of an interrupted heating the thermocouples could either be inserted into holes of the specimen at each measurement or cast into the concrete and connected at each measument.

If the thermocouples should be cast into the concrete, they must not be heated by the microwave field, and various means of protection have been examined.

Several NiCr-Ni thermocouples with quartz-silk insulation were tested, among which some had closely twisted cords. But in all of them strong currents were induced when exposed to the microwave field.

A series of thermocouples was tested with a protection consisting of an aluminium foil cover.

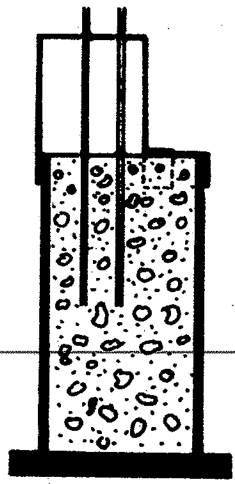
Even if only one milimeter of the cords pointed out from the aluminium cover, the thermocouples were strongly heated in the oven.

Only if the two ends of the cords were protected by an aluminium top, the thermocouples were unaffected by the microwave field.

A number of cylindrical specimens have been tested with two straight aluminium foil protected thermocouples cast into each, and this method of leaving thermocouples in the specimen while heating was shown to be possible, and will no doubt have many applications for the future work with microwave testing of concrete specimens.

However, to avoid any doubt about the sealing of the aluminium top a very simple procedure has been chosen for the first testing series.

Fixed in a guide shoe two rods of 5 mm in diameter were cast into the concrete cylinder, one at the centre and one at a distance of the half radius from this, penetrating from one end of the cylinder along the centre-line to a depth equal to the half cylin-



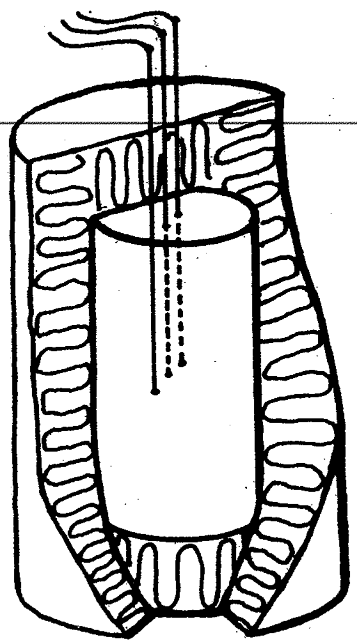
Mould with rods in a guide shoe.

der height.

After curing of the concrete the rods were removed leaving long narrow cylindrical holes in the specimen.

When the insulated concrete cylinder has been heated for a certain period of time in the microwave oven, the door was opened, and a metal sheathed NiCr-Ni thermocouple of diameter 1.5 mm was inserted into each hole and one between the surface of the concrete specimen and the layer of ceramic fibre wool insulation.

In this way three points of the temperature profile from the centre-line and outwards could be determined.



Insulated cylindrical specimen with holes for temperature measurement.

THE FIRST MICROWAVE TEST HEATINGS

So far the idea of using microwave energy for elimination of temperature differences in concrete specimens during material fire tests had only been investigated theoretically.

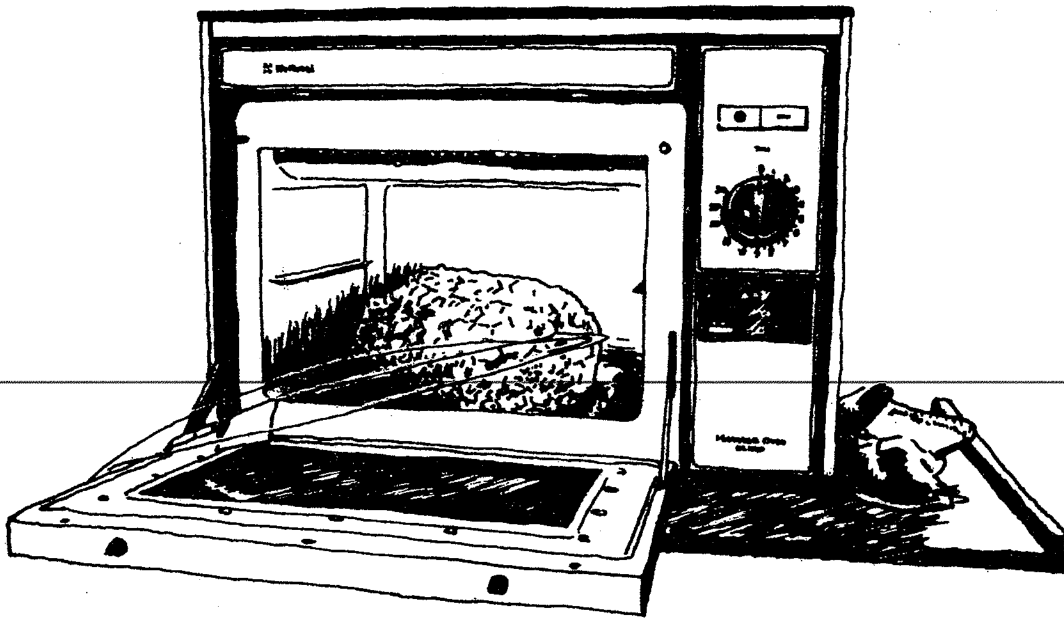
In Hertz [5] it was concluded from calculations based on the existing literature that it seemed possible to eliminate the temperature differences almost completely by using microwave power for heating combined with an adjusting of the surface heat loss for instance by using an insulating wool.

One problem in following up the idea by practical investigations was to eliminate the damages from a possible steam explosion (explosive spalling).

Heating up a concrete specimen rapidly, large pore pressures will develop pressing to the surfaces the free and chemically bound water, which has been released by the heating.

The risk of explosion depends mainly on the heating rate, the moisture content and the permeability of the concrete for a specimen of fixed geometry, and for ordinary concrete pore pressures of a magnitude of about 20 atmospheres (2 MPa) may occur.

25 atm. are found for closed pores from measurements by Petrov-Denisov et. al. [9], 20 atm. pore pressure are calculated by Basant and Thonguthai [1] for a heating rate of 80°C per minute, and Thelandersson et. al. [8] found about 12 atm. for a rather thin section of 5 cm heated by 24°C per minute.



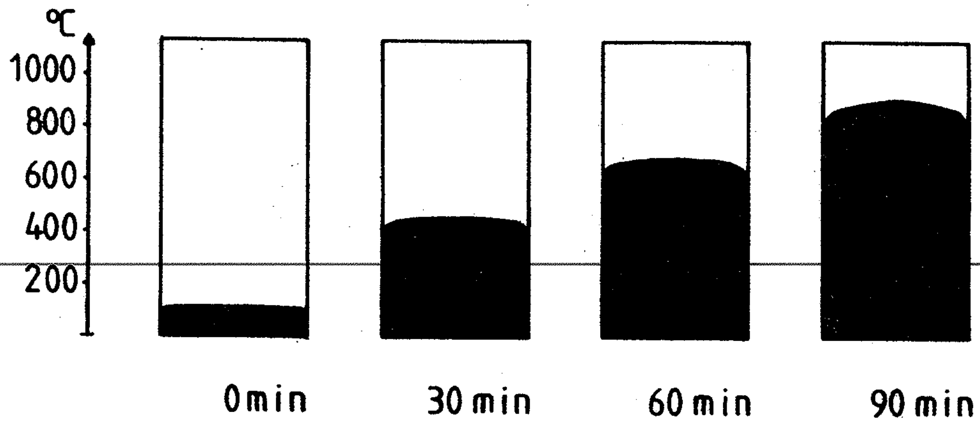
The first microwave test heating.

To diminish the risk of steam explosion, the specimens are placed in a heating cabinet at 105°C for at least a 25 hour period before the microwave heating, and to avoid destruction of the oven and harm to the personnel, the insulated specimen was at the first heatings provided with a strong nylon netting, that makes no hindrance for the microwave field.

The very first heating took place at March 24, 1982.

A concrete cylinder of diameter 10 cm and height 20 cm was provided with circular sheaths of aluminiu foil at the two ends and insulated by 2.5 cm ceramic fibre wool in a nylon netting.

The specimen was placed in a 2.45 GHz microwave oven at 600 W. and the aluminium sheaths were intended to make the cylinder exposed as if it was a part of



Measured temperature distributions
at 30 minutes intervals.

a cylinder of infinite height.

At intervals of 15 minutes the door was opened and the temperature distribution was measured.

The cylinder was heated by approximately 10°C per minute with an almost uniform temperature distribution.

After 90 minutes exposure the temperature of the specimen was 900°C and the test had to be stopped because the radiation from the surface of the ceramic fibre wool insulation could ignite the plastic ceiling of the cold oven cavity.

At this time the concrete was illuminating with a bright white colour.

At the second heating test the power of the oven was adjusted to be 1200 W, and the concrete cylinder insulated by 5 cm ceramic fibre wool was heated $20^{o}C$ per minute with an almost uniform temperature distribution to a maximum temperature level of $800^{o}C$.

If the heat loss from the hot specimen to the cold oven cavity is considered to be small related to the power absorbed by the specimen, this leads to a specific capacity of heat for the concrete of

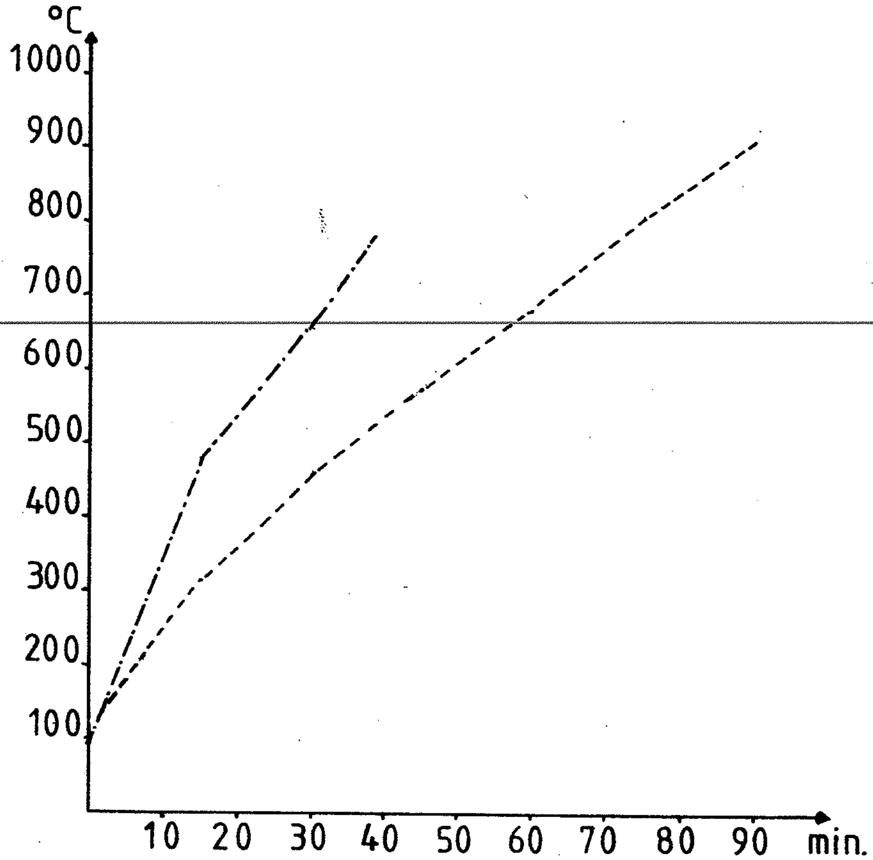
$$c_p = \frac{0.6\ kJ}{s}\ \frac{min}{10^{o}C}\ \frac{60\ s}{min}\ \frac{1}{3.5\ kg} = 1.03\ \frac{kJ}{kg^{o}C}$$

This is in agreement with the values refered in Hertz [6], which show that the value 1.0 $kJ/kg^{o}C$ describes the heat capacity for the concrete almost exactly at all temperatures when used in relation to the density of the dry concrete.

These values have of course been used as basis for the choice of 600 W and 1200 W in order to achieve the heating rates of $10^{o}C$ and $20^{o}C$ per minute.

However, the heat capacity has so far been found by cooling a pre-heated specimen, and some uncertainty has always been present by using the value for heated concrete because all chemical processes should be reversed in the material.

By the microwave heating it is for the first time possible to measure the heat capacity of the heated concrete by knowing the energy output of the magnetrones and measuring the temperature rise of a concrete specimen provided with a large light-weight thermal insulation having a very low heat capacity and being unaffected by the microwave field.



Measured temperature rise in time of the first heatings at 600 W and 1200 W.

DETERMINATION OF EXPOSURE TIME

In order to determine the precise correlation of maximum temperature and exposure time a series of 64 cylindrical concrete specimens with measuring holes has been heated two by two for varying intervals of time, and the resulting temperature distribution was measured.

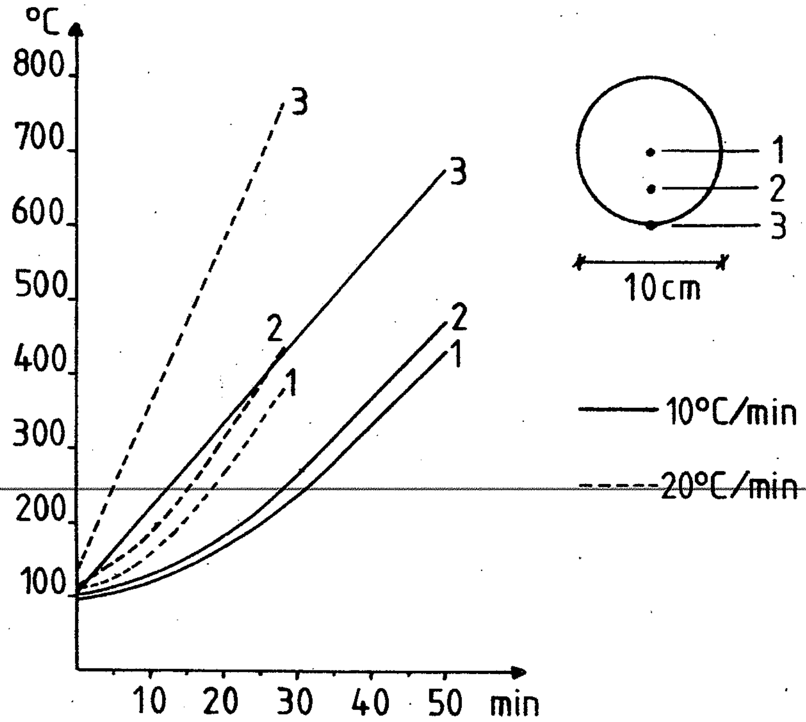
Both specimens were provided with aluminium foil sheaths at the ends and 5 cm ceramic fibre wool insulation. But unlike the very first heatings the explosion security netting was omitted, since no explosion has occured even at a heating rate of 20°C per minute.

Using a power of 1200 W the two specimens were heated precisely 10°C per minute from 300°C and slightly faster from 105°C to 300°C.

The time temperature correlation was found to be as follows when heating from 105°C.

200°C - 8 minutes
300°C - 17 minutes
400°C - 27 minutes
500°C - 37 minutes
600°C - 47 minutes

In each specimen the temperature distribution was virtually found to be uniform, but a small shadow effect was observed due to a minor unevenness of the electric field in the heavyly loaded oven cavity. As a result of this effect the left specimen was heated 10°C too little and the right 10°C too much.



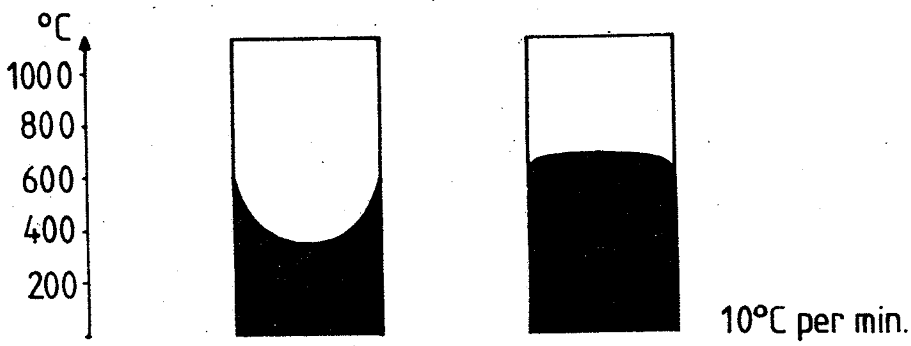
Measured temperature rise in time of specimens heated in a traditional electric oven.

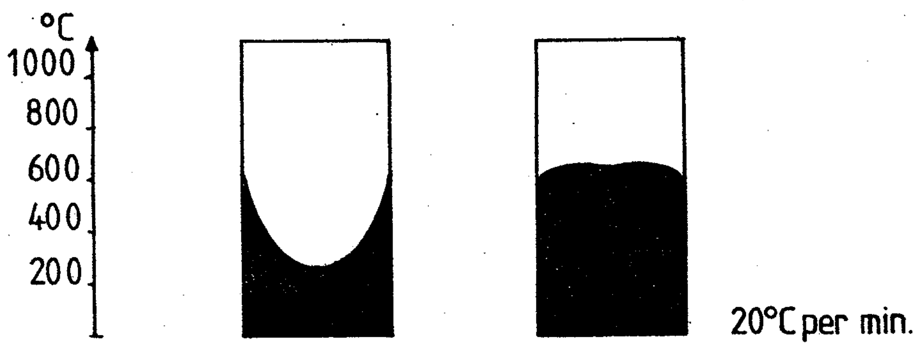
Presenting the results of the compressive strength testings the effect is of course corrected by using reference temperatures of for example 290°C and 310°C in stead of fixed 300°C.

In order to demonstrate the difference in heating by means of microwave power and in the usual way, a small series of specimens with measuring holes has been heated in a small oven by a 3500 W electric heating coil, and the temperature distributions have been recorded.

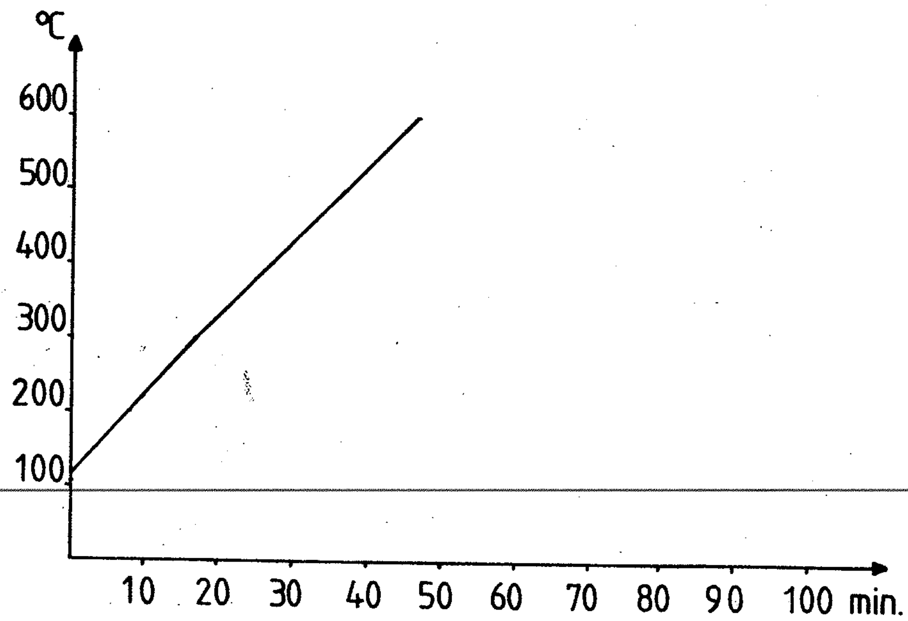
The rate of heating of the specimen surface was controlled to be 10°C and 20°C by means of an automatic PID controlling unit.

At a surface temperature of 600 C the maximum temperature differences were observed to be 240°C at





Measured temperature distributions in concrete cylinders (100 mm) heated 10°C per minute and 20°C per minute normally left and by microwave power right.



Temperature rise in time of the final microwave heating procedure.

$10^{\circ}C$ per minute and $325^{\circ}C$ at $20^{\circ}C$ per minute, i.e. about 10 times as much as the microwave heated specimens.

TESTING OF RESIDUAL COMPRESSIVE STRENGTH

A series of 90 cylindrical concrete specimens has been tested in order to investigate the residual compressive strength of rapid-heated concrete, and first of all the difference of the residual strength for a rapid-heated and a slow-heated concrete.

The concrete used was identical to a concrete which has previously been investigated for a number of mechanical properties, when exposed to a slow heating of 1°C per minute. (Se for example Hertz [4] and [7]).

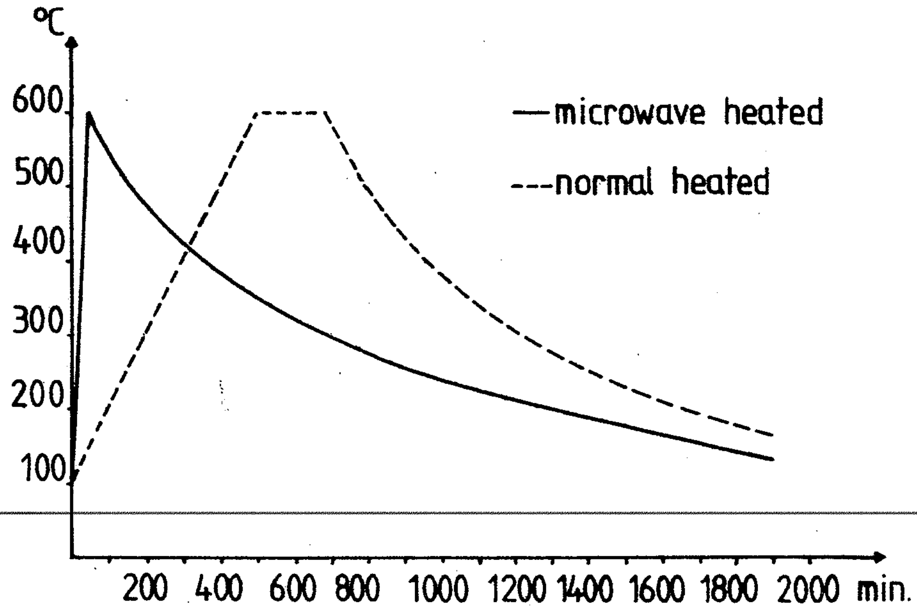
The concrete had a compressive strength of 20 MPa before heating, and it was made with Danish sea gravel aggregate, which is a mixture of quartz, granite and limestone.

The water/cement ratio was as much as 0.87, and thus the concrete was more porous and more susceptible to the influence of high temperatures than most other concretes being used.

This means that the relative decrease of the mechanichal properties of this test concrete conservatively can be used for other concretes in the design process.

The specimens were cylinders of diameter 10 cm and height 20 cm, and they were provided with circular aluminium sheats at the ends and 5 cm ceramic fibre wool insulation.

They were heated two by two 10 C per minute at 1200 W and a microwave frequency of 2.45 GHz in an oven with two magnetrones for the time necessary to achieve the miximum temperature wanted.



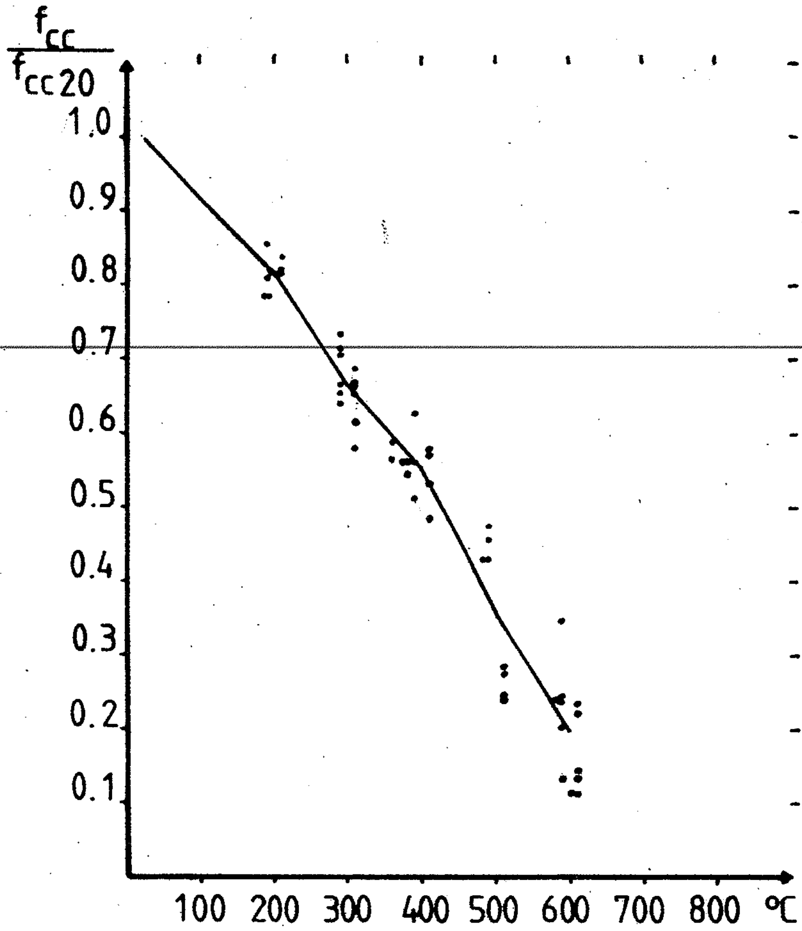
Temperature - time curves for rapid and slow heated specimens.

At the end of heating the insulated specimens were immediately placed in a box provided with an additional insulation of 15 cm mineral wool to ensure a slow natural cooling sequence.

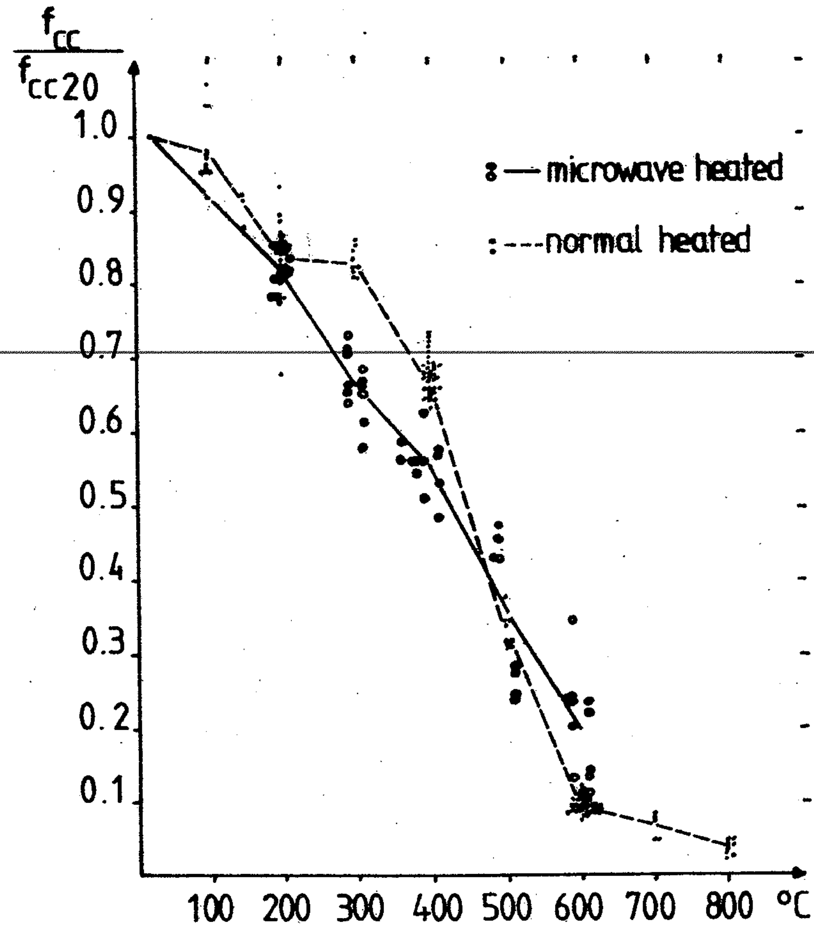
From the cooling box the specimens were placed in a standard climate room of 20°C and 65% relative moisture until one week after the heating, when the compression test took place.

This delay of one week of the compression test ensure that the strength of the concrete has decreased to a minimum (Hertz [3]) and has also been used for the previous investigations at the slow rate of heating.

From the test results it can be seen that the residual compressive strengt of rapid heated concrete



Residual ultimate stress of concrete with Danish sea gravel heated 10°C per minute.



Residual ultimate stress of concrete with Danish sea gravel heated by microwave power 10°C per minute and heated normally 1°C per minute.

decreases almost linearly as the temperature increases.

This straight line curve is quite different from the typical S-shaped curve, which is the result of a slow heating rate.

The residual compressive strength of rapid-heated concrete is about 20 pct. less than the slow-heated at a maximum temperature of 200°C, 10 pct. less at 300°C and about 10 pct. more at 600°C.

It can also be seen that the dispersion of the test results increases in temperature for the rapid-heated concrete end decreases for the slow-heated.

A possible explanation to the observations can be found from the nature of the processes destroying the concrete, while it is heated.

These processes are described in Hertz [3] and summarized briefly in Hertz [4].

While the concrete is heated the free water and from approximately 150°C the water of the hydrated calcium silicates evaporates, and consequently the hydrated cement paste shrinks.

At the same time the aggregate expands and from 300°C microcracks are developed through the matrix because of the stresses between the aggregate and the matrix.

Heating the concrete rapidly the thermal stresses are developed much quicker, and the matrix can not to the same extend reduce the stresses by creeping.

The rapid-heated concrete therefore becomes more brittle, and from 220°C to 400°C a more destructive cracking takes place, and thus the residual strength is less than for the slow-heated concrete.

From approximately 400°C the calcium hydroxide in the matrix will decompose, and while cooling and curing within the seven days after the heat exposure the residual calcium oxide absorps water from the air and expands, and the expansion opens the cracks of the matrix.

Therefore, the residual strength drops about 65 pct. from 400°C to 600°C for slow-heated specimens.

However, the dehydration of the calcium hydroxide as well as the water absorption of the calcium oxide needs time to take place.

By heating at 10°C per minute it seems that the process does not develop fully and the residual strength drops only about 35 pct. from 400°C to 600°C.

The theory of an unfinished process is also supported by the increased dispersion of the test results for the rapid-heated concrete from 400°C.

The fact that the rapid-heated concrete has a smaller residual strength than the slow heated at maximum temperatures from 200°C to 400°C is critical to the structural use of the test results, because large part of the cross-sections of a concrete structure reach maximum temperatures of this level by fire exposure, and the parts achieving higher temperature levels will have a very small strengths, which are often negligible in calculation of the load-bearing capacity of the structure.

This means that the use of test results of ordinary slow-heated specimens may give rise to an error of

20 pct. in estimating the load-bearing capacity of a structure exposed to a fully developed fire course, and perhaps even more in case instability phenomena are decisive for the estimation.

By using microwave heating, the specimens can be heated rapidly and consequently these errors are avoided.

FUTURE POSSIBILITIES FOR MICROWAVE TESTINGS

By this experimental study it is shown that heating by means of microwave power is not only a theoretica possibility, but a very convenient heating method for practical material testings.

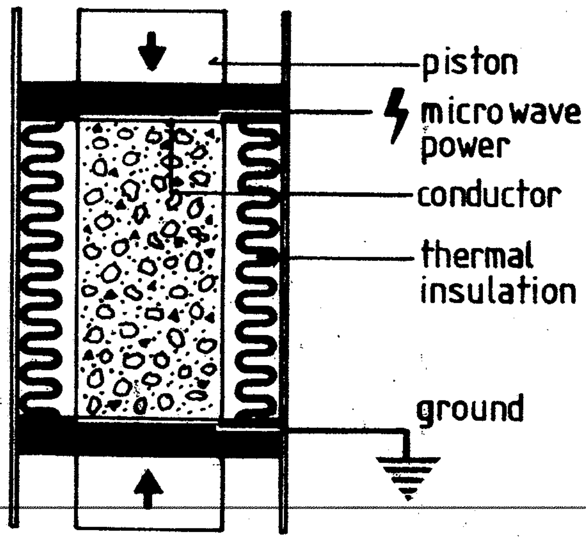
As far known it has for the first time become possible to heat concrete specimens rapidly without introducing destructive temperature differences, and it is shown that the deviation of the residual strength of rapid heated concrete from slow-heated is considerable and should not be neglected in a precise design for fire resistance of concrete struc tures.

It is also shown that it is possible in practice to determine the specific capacity of heat of concrete simply by heating and comparing the temperature increment to the microwave energy introduced in the specimen per unit weight.

In the future only economy seems to raise limitations to the development of new fire test methods based on microwave heating.

An obvious possibility is the simultaneous heating and compression which is essential to the study of the mechanical properties of concrete at transient conditions, i.e. heating and loading at the same time.

This can be achieved by using the pistons of the test machine as conductors leading the microwave power directly into the concrete specimens.



Simultaneous compression and heating using the pistons as conductors.

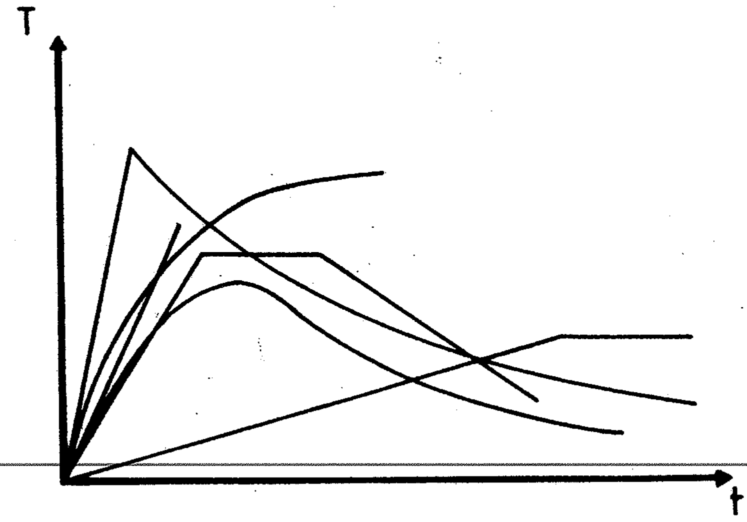
This direct dielectric heating by means of conductors is very simple and was one of the first applications of microwave power.

The specimen ought to be totally enclosed in a metal cabinet which should be insulated in order to diminish the heat loss from the hot specimen.

Naturally the direct dielectric heating is suitable for biaxial testing of concrete at high temperatures as well, and very likely this is the simplest heating method for transient testings even at slow heating rates.

Microwave power is not only a possibility for rapid and slow heatings at constant heating rate.

By means of an ON-OFF controll of the magnetrones the concrete can be heated by almost any heating



Possible heating curves for microwave heated specimens

curve.

For example a PID ON-OFF control unit could be used measuring the temperature of a reference specimen and comparing this measured temperature to the temperature wanted, given by a curve, which is read optically or simulated mechanically or by a computer program.

A more simple procedure would be to calculate the ON-OFF intensity from the curve wanted and the known capacity of heat, and to check the heating by a series of test specimens.

By means of such a procedure almost any fire course could be followed.

Though of course the cooling must not be too fast and explosive spalling should still be avoided.

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