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MICROWAVE HEATING FOR FIRE MATERIAL TESTING OF CONCRETE - A THEORETICAL STUDY

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CONTENTS

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PREFACE

At the request of Hermann von Helmholtz, Heinrich Hertz made research on the properties of dielectrics. In this connection he found very rapid electric oscillations extremely interesting and during the work he showed the possibility of transmitting power by electromagnetic waves.

So far this discovery has been of greater importance than the results concerning the dielectrics.

Today we call the very rapid electric oscillations microwaves and the term is used for waves with a wavelength of the same magnitude as the length of the circuit applied, which is normally less than about 1 m and frequences more than about 300 MHz.

As the use of microwaves would be advantageous in testing the properties of concrete at high temperatures a preliminary study has been made on the subject.

Copenhagen, March 1981
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SUMMARY

A new idea is proposed about the use of microwave energy for elimination of temperature differences in concrete specimens during material fire tests.

A theoretical study is made on the subject and it is concluded that it seems possible to eliminate thermal gradients and stresses almost completely, when providing the specimens with a thermal insulation.

ACKNOWLEDGEMENTS

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Especially I would like to express my sincere gratitude to senior lecturer T.Jakobsen for reading the manuscript and for many inspiring discussions.

SYMBOLS

A	area
a	energy
D	dielectric displacement
D_o	amplitude of dielectric displacement
d	thickness
E	power
f	frequency
k	thermal conductivity
P	polarization
Q	power per unit volume
R	radius of specimen
r	radius
T	temperature
t	time
$\tan\delta$	loss - tangent
V	electric potential
x	distance from surface
α	constant of damping
δ	phase-displacement-angle
ϵ'	dielectric constant
ϵ''	loss-factor
ϵ_o	vacuum permittivity
ϵ_r	relative permittivity
$\epsilon'_r - j\epsilon''_r$	complex relative permittivity
ε	electric field
ε_o	amplitude of electric field
ω	angular freqency

INTRODUCTION

In estimating the fire resistance of a construction, one of two procedures has to be used: Test of entire structural members and their joints, or determination of their fire resistance by calculation based on knowledge of the material properties.

If the first procedure is used each structural member and joint has to be tested under, strictly speaking, as many conditions as there are applications for. Not only the temperature - time function but also the moisture distribution, the insulation, the radiation and convection conditions as well as the load and supporting conditions could be altered.

Naturally some sort of standard conditions would be used to reduce the number of testings, but still new testings may be demanded for each new design and size of the structural members and joints applied.

To reduce testing costs and the time necessary for designing the structure, it would be desirable to use the second procedure, especially if such a calculation could be an integrated part of the common analysis of the construction.

Therefore, it is of extreme importance to ensure a calculational approach, especially in connection with the new building fire codes, which are being developed these years in many countries and international organizations.

Concerning concrete constructions it is today possible to calculate the temperature distribution with a reasonable accuracy from the properties of the construction, the room and the fire load.

Also the internal stresses arising from differences in temperature and restrained thermal movements can be estimated, although further research on this subject would be desirable.

The resistance of the construction to the superimposed external and internal forces is then to be calculated, and this requires knowledge of the material properties of the concrete exposed to a temperature development like the actual one.

In order to find, for instance, the compressive strength you have to use a specimen of a certain size. But when such a specimen is heated in an oven about 10°C per minute, which is a realistic heating rate for the critical points of a fire-exposed construction, large temperature gradients and large internal stresses will arise and alter the testing result or perhaps break the specimen into pieces.

To ensure homogeneity in the calculations, it would be convenient to use the same test specimen as used in the normal temperature range. In Denmark this is a cylinder with height 30 cm and diameter 15 cm, and in this cylinder the heating rate mentioned above will produce internal temperature differences of nearly 400°C and stress differences of more than 30 MPa, when the surface temperature reaches 600°C.

Some will find this dilemma so discouraging that they are liable to give up the pure fire testing of materials, but the author finds that other methodes of heating ought to be tried. Such a heating possibility, which seems to eliminate the problem totally, is dielectric heating with microwave power combined with a thermal insulation.

ON DIELECTRICITY

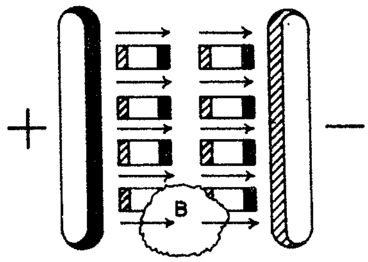
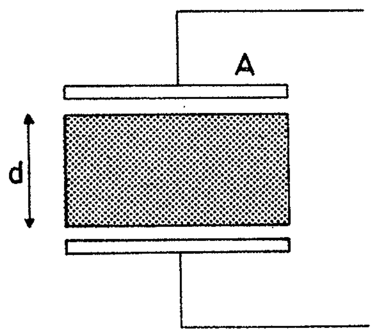


Illustration from Hertz [5]

Some materials such as benzene, paraffin and carbon tetrachloride are electrically neutral. But most materials possesses molecules forming electric dipoles attempting to orientate themselves in the direction of an applied electric field.

When the field oscillates with a sufficient rapidity, that is approximately 1 GHz, the hindrance of the movement due to the material structure will result in a considerable heat development. The microwaves radiate into the material, which heats itself by internal friction.



Conductors with a media.

Considering two plane conductors each with a surface area A and distance d, and between which a dielectric media is positioned in a steady electric field the electric charge on the surface of the medium will be $\mp$ P pr. unit surface.

On the surfaces of the conductors the corresponding charge will be $\pm P$, but also a charge $\pm \epsilon_o \varepsilon$, where ϵ_o is the permittivity in vacuum and ε the field intensity. The total charge on the surfaces is called the electric displacement D.

Vectorially it is

$$\underline{D} = \epsilon_o \underline{\varepsilon} + \underline{P}$$

For materials where $\underline{P}$ is parallel with $\underline{\varepsilon}$ it is often written

$$\underline{D} = \epsilon_r \epsilon_o \underline{\varepsilon}$$

where ϵ_r is called the relative permittivity.

If the field is time-dependent

$$\varepsilon = \varepsilon_o \cos \omega t$$

you will notice that the dielectric displacement will have a phasedisplacement by an angle δ relative to the field (Püschner [10]).

$$D = D_o \cos (\omega t - \delta) = (\epsilon_r' \cos \omega t + \epsilon_r'' \sin \omega t) \varepsilon_o \epsilon_o$$

Therefore two constants depending on the frequency are used. Their relation is

$$\frac{\epsilon_r''}{\epsilon_r'} = \tan \delta$$

With a complex notation you wil get

$$\varepsilon = \varepsilon_o e^{j\omega t}$$

and

$$D = (\epsilon_r' - j\epsilon_r'')\,\varepsilon\,\epsilon_o$$

$\epsilon' = \epsilon_r'\epsilon_o$ is called the dielectric constant and is a measure of the electric field energy that can be stored in the material. $\epsilon'' = \epsilon_r''\epsilon_o$, which is known as the loss factor is a measure of the heat development. $\tan\delta$ is called the loss tangent.

It is often observed that ϵ'' increases and ϵ' decreases when the frequency increases (Tinga and Nelson [11]).

ϵ_r' is normally of values about 1 to 8, but for water it is 80. $\tan\delta$ is from 0.0001 for polystyrene to 0,7 for some sorts of glass (Cable [2]).

CONCRETE AND MICROWAVES

As microwave-heating until now mostly has been utilized in cooking and biological research only little information is available about concrete.

However, distinct values of the dielectric constants are tabulated by von Hippel [7] and supplemented by Tinga and Nelson [11].

From this it will be seen that many solids for example fused quartz will show an increase of ϵ' as well as of $\tan\delta$ when the temperature is increased and that this development takes place at higher temperatures the higher the frequency of the field is.

For concrete some investigations are made by Hasted and Shah [4], especially on the influence of the moisture content.

It is obvious that the concrete is more susceptible for microwave-power when the moisture-content is high, because water absorbs the energy efficiently. But even when drying the concrete it will still possess a value of $\epsilon_r'' \approx 0{,}3$ and as Alexander Watson concludes in Okress [9], vol. 2, p. 111, it will always be able to receive microwave energy.

As you must expect an increase by temperature of the loss factor at the same time the value decreases due to the loss of moisture during a simulated fire test an average value about $\epsilon_r'' \approx 0{,}5$ will be a realistic guess until special investigations are made on the subject.

All three methods of microwave heating generally used can become pertinent for heating of concrete: Direct heating, heating by concentrated radiation and heating in a microwave oven.

DIRECT DIELECTRIC HEATING

The dielectric material, here called the load, is placed between two metallic conductors providing the oscillating field, one of these having an earth connection (Cable [2]).

The conductors may be pistons of a testing machine in order to investigate the effect of static or dynamic loading during heating etc.

The voltage is delivered from a generator of 1 to 30 kW with frequences from 2 to more than 100 MHz (B.E.D.A. [1]).

The power left in a body of cross-section-area A (m^2), thickness d (m), loss factor ϵ'' will according to Cable [2] be

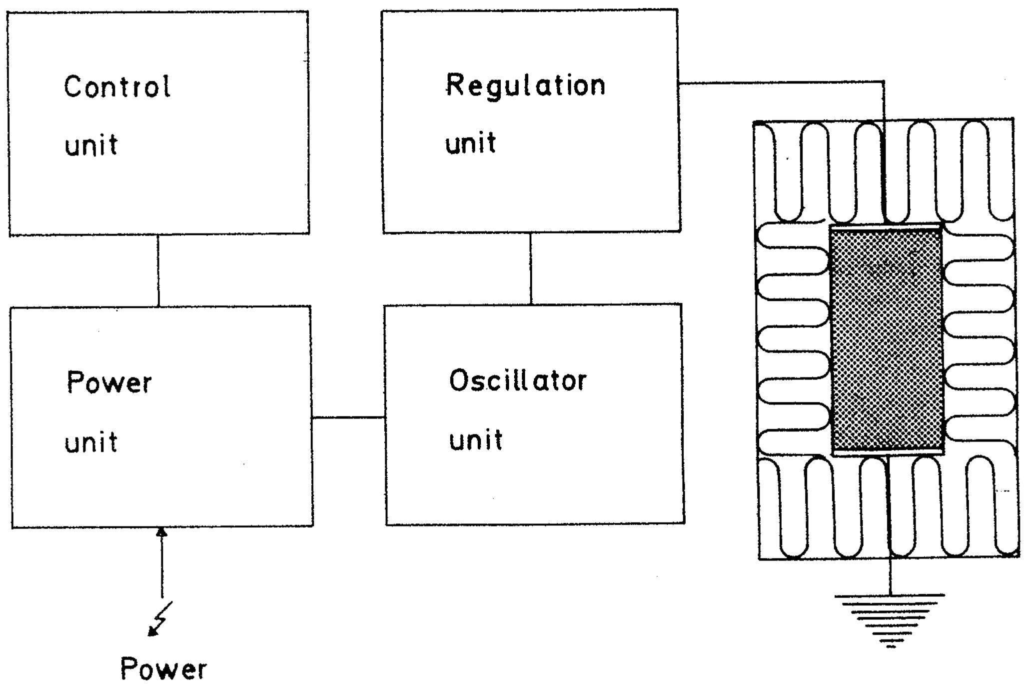
$$E = 55.5 \times 10^{-12} \times V^2 f \epsilon'' \frac{A}{d} (W)$$

with an electric field of frequency f (Hz) and potential difference V (volt).

The frequency used must be allowable for heating purpos according to the decisions of the International Telecommunication and Radio Conferences in Geneva. They are as follows (Okress [9]).

Allowable frequency			Wavelength
13.560 kHz	±	6.78 kHz	22.1 m
27.160 kHz	±	160 kHz	11.0 m
40.680 kHz	±	20 kHz	7.37 m
915 MHz	±	25 MHz	0.328 m
2.450 MHz	±	50 MHz	0.122 m
5.800 MHz	±	75 MHz	0.0517 m
22.125 MHz	±	125 MHz	0.0136 m

In order to diminish the heat loss to the surroundings the specimen may be provided with a thermal insulation



Direct dielectric heating.

HEATING BY CONCENTRATED RADIATION

The microwaves are produced by an oscillator tube, a so-called magnetron and guided through a wave guide to a distance of a few centimetres from the concrete surface.

This procedure of course gives rise to a very intense heating and large thermal stresses. The method is therefore only applicable where these stresses are wanted.

Watson (in Okress [9]) uses a source of 2 kW or 5 kW and a frequency of 2.45 GHz for concentrated heating of concrete slabs with thicknesses 15 cm and 23 cm in order to break them.

The same application is reported by Okada, Ohwi and Mori [8], where the equipment was of 30 kW and 915 MHz.

It was necessary to use concentrated power of more than 15 kW producing temperature differences through the depth from the surface of more than 100°C before a specimen of 30 × 30 × 40 cm was crushed.

The method requires approximally 10 times as much power as a mechanical breaking. But you can diminish the problems arising from noise and dust.

Therefore it has been used for hole-cutting-operations on concrete slabs in hospitals etc.

HEATING IN A MICROWAVE OVEN

From one or several magnetrons the microwaves are guided by a waveguide to the cavity. The waveguide is a metal tube of distinct dimensions. For example a rectangular tube of 2 mm aluminium and measure 95 x 55 mm^2.

The walls of the cavity are all made of metal in order to reflect the waves and a metal stirrer can be used to disperse them and ensure a homogeneous power distribution.

The load is positioned in the center of the cavity and all surfaces including the bottom are exposed.

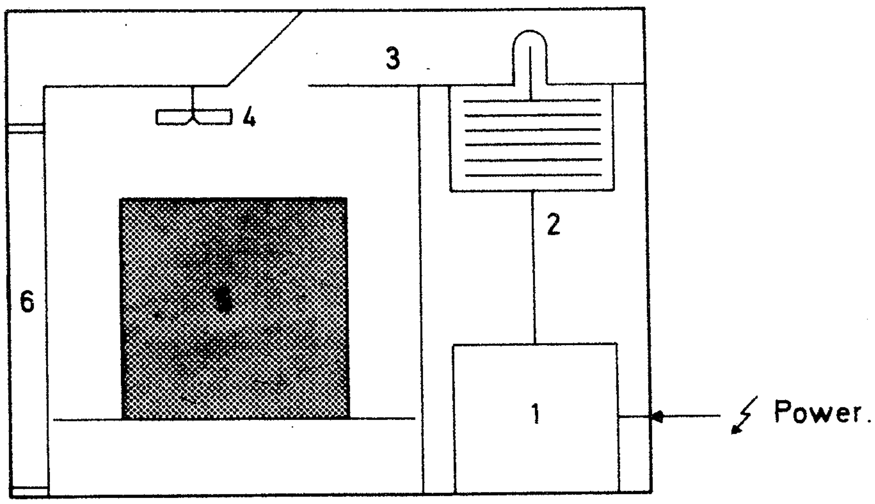
Human beings cannot endure direct exposure of microwaves. Therefore a limit of the intensity of radiation from an oven is set up in Public Law 90-602, The Radiation Control for Health and Safety Act of 1968 (U.S.A., October 6., 1971).

The value is 5 mW/cm^2 measured 5 cm from the outer surface of the oven.

To diminish the risk of radiation, especially the door of the oven has to be carefully designed and maintained.

Watson (Okress [9]) has used a 2 kW oven with the frequency 2.45 GHz to accelerate the curing of concrete cubes. He observed a loss of strength that must be due to the formation of the coarse-crystalline structure that is normally a result of a high-temperature-curing.

A general warning has to be given at this place. When heating concrete by microwaves the evaporation problems must be observed.



Principle for a microwaveoven.

1. Power unit.
2. Magnetron.
3. Waveguide.
4. Stirrer.
5. Load in cavity.
6. Door.

If the load is too small compared to the power of the oven the heating will be too rapid and a vapor explosion can be the result.

The author has been told that "only a small specimen" of cement paste has exploded like a hand grenade making serious damage to the oven and the laboratory.

This effect is of course equal to the well-known spalling effect, and has nothing to do with the microwaves.

Though it forms a limitation for the heating rate that can be used and thus a limitation for how small the load can be.

The damping of the microwave energy in the concrete is described by the expression

$$a_x = ae^{-2\alpha x}$$

where a and a_x are the energy at the surface and in the depth x from this respectively, and α is a constant of damping that for $\tan\delta \ll 1$ is

$$\alpha = \frac{\pi \epsilon''}{\lambda \epsilon'} = \frac{\pi \epsilon''_r}{\lambda_o \sqrt{\epsilon'_r}}$$

where λ and λ_o are the wavelength in the load and in vacuum and

$$\lambda = \frac{\lambda_o}{\sqrt{\epsilon'_r}}$$

The depth in which the energy is reduced to 1/e (= 0.368) of the origainal is

$$x_{(1/e)} = \frac{1}{2\alpha} = \frac{\lambda_o}{2\pi \tan\delta \sqrt{\epsilon'_r}}$$

(Püschner [10], p. 97 and Copson [3], p. 23).

The depth of penetration increases with the wavelength and decreases with the loss factor of the material.

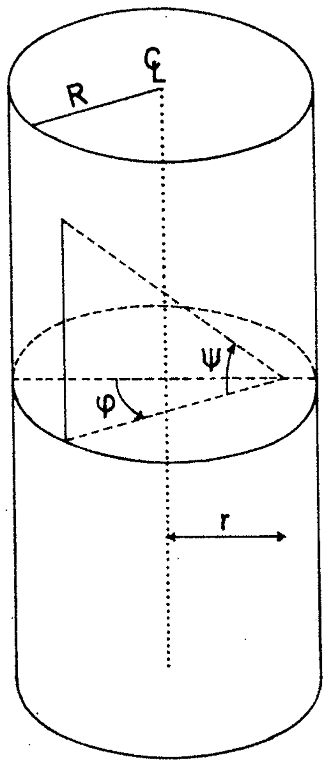
Some materials such as glass and paper have small values of the loss factor and are transparent for microwaves.

For concrete with $\epsilon_r' \approx 5$ and $\epsilon_r'' \approx 0.5$ that is $\tan\delta \approx 0{,}1$ you have

$$\alpha = 2.143\ m^{-1} \qquad \text{and} \qquad x_{(1/e)} = 0.23\ m$$

for waves of frequency 915 MHz.

If the load is a circular concrete cylinder of radius R and provided with discs of aluminium foil at the ends it can be considered as if it was of infinite height.



Concrete cylinder.

A unit volume in the distance r from the center line, will then with angles defined on the drawing receive a power that related to the power in the free uniform field is

$$a_r = \frac{2}{4\pi}\int_0^{\frac{\pi}{2}}\int_0^{\frac{\pi}{2}} \cos\psi \, e^{\left(\frac{-2\alpha(r\cos\varphi + \sqrt{R^2 - r^2\sin^2\varphi})}{\cos\psi}\right)} d\psi d\varphi$$

For a cylinder of R = 0.075 m with a heating rate of 10^{o}C per minute and simultaneously thermal levelling, values of a and the temperature T_r are tabulated below.

r	0.000	0.025	0.050	0.075	m
a_r	0.638	0.649	0.689	0.796	-
T_r	543	550	569	600	C^{o}

In the microwave oven it is only the load that is heated. The oven cavity is cold and the concrete will therefore release heat creating an internal thermal gradient in the material.

A part of a cylinder with the length ℓ and radius R is considered. The part releases power Q(W) and the heat current is considered stationary. All parts of the cross-section deliver an equal amount of heat per unit area while receiving the microwave power.

The cylindrical shell $\ell 2\pi r\,dr$ then gives $Q2r\,dr/R^2$ and is passed by Qr^2/R^2. With the thermal conductivity k and temperature T you have

$$(\ell 2\pi r)\,k\frac{dT}{dr} = -Q\frac{r^2}{R^2}$$

and

$$\frac{dT}{dr} = -\frac{Q}{2\pi\ell k}\,\frac{r}{R^2}$$

The temperature distribution is then

$$T_r = T_c - \frac{Q}{4\pi\ell k}\,\frac{r^2}{R^2}$$

The temperature difference between then center and the surface is

$$\Delta T = T_c - T_R = \frac{Q}{4\pi\ell k}$$

The thermal gradients arising from the heat release is reverse to those arising from the damping of the microwave power and the total thermal distribution is achieved by superposition of the two.

By insulating the cylinder it will therefore be possible to reduce the internal differences to almost none.

Using 10 cm glass-wool with $k_i = 0.15\ W/m^{o}C$ on the cylinder previously mentioned the surface of this will get the temperature $T_1 = 100^{o}C$ and it will release 520 W/m^2 to a cavity of a temperature $30^{o}C$.

The balance of heat for the surface of the insulation gives

$$4.8(100 - 30) + \frac{5.67 \cdot 10^{-8} \; (373^4 - 303^4)}{\frac{1}{0.81} + \frac{0.522}{6}\left(\frac{1}{0.04} - 1\right)} = 520 \text{ W/m}^2$$

and

$$\frac{0.15}{0.35 \ln \frac{0.175}{0.075}}(600 - 100) \approx 520 \text{ W/m}^2$$

In total the cylinder surface gives of $520 \, \pi \, 0.35 \times 0.30 = 172$ W and the maximum temperature difference because of this is

$$\Delta T = \frac{172}{4 \, \pi \, 0.3 \cdot 0.90} = 50^{\circ}C$$

where for the thermal conductivity of concrete is used the value 0.90 W/m$^{\circ}$C.

This temperature distribution is then superimposed to the one from the microwave-damping-effect with $\Delta T = -57^{\circ}C$.

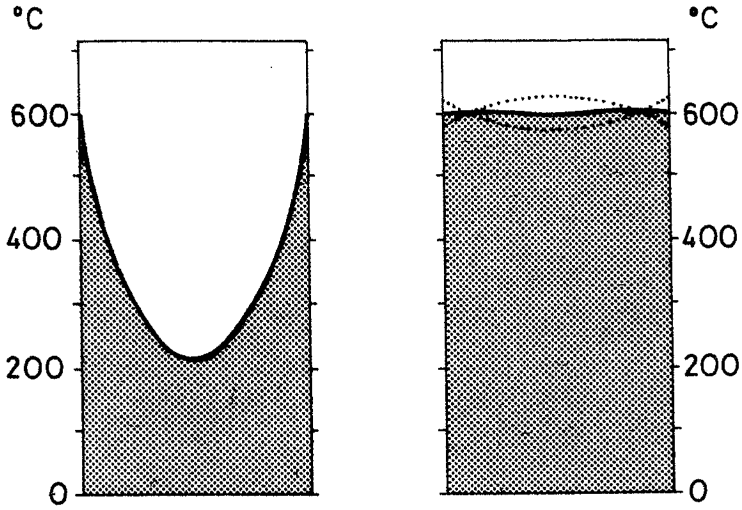
The result is therefore

$$-\Delta T = T_R - T_C = 7^{\circ}C$$

for a cylinder heated 10°C per minute to 600°C in a microwave oven of the frequency 915 MHz. The power necessary will be

$$12.72 \cdot 0.95 \cdot \frac{10}{60} + 0.2 \approx 2.2 \text{ kW}$$

(Weight of cylinder 12.72 kg, specific thermal capacity 0.95 kJ/kg$^{\circ}$C and heat loss approx. 200 W).



Temperature distributions in concrete cylinders (150mm) heated 10°C/min normally left and by microwaves right.

If the insulating material chosen absorbs microwave power it will contribute to the heat necessary for maintaining the temperature desired at the surface of the specimen, and a smaller thickness must be applied.

CONCLUSION

From calculations based on the existing literature it seems possible to eliminate temperature differences in concrete specimens almost completely during fire tests by using microwave power combined with a regulation of the surface heat loss for instance by using an insulating material.

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