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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
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THERMAL END EFFECTS ASSOCIATED WITH A STEEL CORED CYLINDRICAL CONCRETE SPECIMEN

by

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Summary

The temperature distributions at the ends of a steel cored concrete cylinder enclosed in an electric furnace are discussed and methods of obtaining a uniform temperature at the steel-concrete interface are suggested.

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Introduction

A programme of work has been started to determine the effect of high temperatures on the bond strength between concrete and steel. A specimen of reinforced concrete is heated with the object of recording the temperature of the steel-concrete interface at the time of bond failure. It is therefore important that the temperature distribution over the length of the interface should be as uniform as possible. In this note the temperature distributions at the ends of the specimen are considered and methods of obtaining a uniform interface temperature are suggested.

Conditions of test

The specimens are concrete cylinders $4\frac{1}{4}$ in. in diameter and 9 in. in height, with a $\frac{3}{8}$ in. diameter silver steel reinforcing rod which projects from the lower end of the concrete so that a load can be applied between the steel and the concrete. The specimen is heated in a cylindrical electrical furnace.

Method of calculation

Accurate calculation of the transient temperature distribution within the specimen would be extremely laborious and would not be justified as the temperatures at the ends of the specimen are known only approximately. Since the temperature rise of the furnace is slow, the problem is considered to be approximately steady state and temperature predictions are made by comparison of the various thermal resistances to flow of heat within the specimen. The radial thermal resistance of the concrete annulus, the axial thermal resistance of the rod and the cooling resistance from the end of the rod are calculated in Appendices 1, 2 and 3 and are illustrated in Figure 1.

Each end of the specimen is considered separately and methods of obtaining a uniform interface temperature are discussed.

Upper surface

The resistance to heat flow representing cooling from the end of the rod (2,100 units, see Figure 1) is large compared with all the other thermal resistances in the region of the upper surface and the cooling from the end of the rod may therefore be neglected. The thermal resistance associated with the cooling from the top surface of the concrete, on the other hand, is low and will influence the temperature of the top region. Since the total axial thermal resistance of the metal rod is not negligibly small compared with the thermal resistances through which heat is flowing to the metal, the end effects to be expected in the temperature distribution throughout the concrete will also produce non-uniformity in the metal temperature. Reducing the end effect associated with the concrete would be the most direct method of ensuring a more uniform metal-concrete interface temperature. In order to calculate the temperature distribution at the end the specimen is considered to be of solid concrete.

It may then be compared with a finite cylinder with temperature θ_o at the curved surface, cooling to the atmosphere at each end. The specimen is not cooling at the lower end but it may be considered as one half of a cylinder cooling at both ends. For a finite cylinder twice the length of the specimen the temperature on the axis one radius length from the end is $0{\cdot}94\ \theta_o$ (see Appendix 4). As the furnace extends beyond the specimen in the practical case the temperature on the axis one radius length from this end will be very nearly θ_o. The end effects can therefore be expected to extend only over a length of just over 2 in. in the specimen under consideration. From this information the following alternative recommendations can be made to ensure a uniform metal-concrete interface temperature in the required specimen.

1) The specimen should be capped by a 2 in. to $2\frac{1}{2}$ in. high concrete cylinder, or

2) The specimen should be capped by a 1 in. high concrete cylinder together with a thickness of another material having an axial thermal resistance at least as great as that of 1 in. to $1\frac{1}{2}$ in. of concrete (e.g. $\frac{1}{2}$ in. asbestos wood).

The bottom of the specimen

The thermal conditions at the bottom of the specimen differ from those at the upper surface in that the steel rod projects from the end and, since the concrete is supported by an insulating material, convective cooling is absent. It will be necessary to heat the steel supporting block so that its temperature rises at approximately the same rate as that of the steel core. In this way it forms a guard ring. The correct rate of heating may be achieved by interposing an asbestos collar of suitable thickness between the furnace wall and the steel supporting block.

Conclusions

The recommendations given in this note can be summarised as follows.

The top of the specimen should be capped by either:-

1) A 2 in. to $2\frac{1}{2}$ in. high concrete cylinder, or

2) A 1 in. high concrete cylinder together with a thickness of another material giving the same order of thermal resistance as 1 in. to $1\frac{1}{2}$ in. of concrete.

At the bottom of the specimen the thickness of an insulating material interposed between the furnace wall and the metal parts linked to the steel reinforced rod should be adjusted so that at the time of bond failure the projecting portion of the rod and the portion above it within the specimen will be at approximately the same temperature.

Acknowledgement

Acknowledgement is due to Dr. P. H. Thomas for advice regarding Appendix 4.

Reference

Carslaw & Jaeger. "Conduction of Heat in Solids". Oxford, 1947. Page 190 V.

Appendix 1

The radial thermal resistance of an annulus of the concrete

The thermal resistance between the outer and inner faces of an annulus 1 cm. in height is given by

$$R = \frac{1}{2\pi K}\left[\log_e \frac{r_2}{r_1}\right]$$

where K = thermal conductivity, taken as

$0{\cdot}0022$ cal cm^{-1} sec^{-1} $^{o}C^{-1}$

r = radius, limits being taken as

$$r_1 = \frac{0{\cdot}375}{2} \times 2{\cdot}54 \text{ cm.}$$

$$r_2 = \frac{4{\cdot}25}{2} \times 2{\cdot}54 \text{ cm.}$$

Evaluating this expression gives

R = 176 c.g.s. units/per cm height.

Appendix 2

The axial thermal resistance of a steel rod

The axial thermal resistance per cm length of rod is given by

$$R = \frac{1}{AK}$$

where A is the cross sectional area of the rod (of diameter 0·375 x 2·54 cm.) and K is the thermal conductivity, taken as 0·11 cal cm^{-1} sec^{-1} $^{o}C^{-1}$.

Evaluating this expression gives

$$R = 12{\cdot}7 \text{ c.g.s. units/cm length.}$$

Appendix 3

The equivalent resistance representing cooling from the end of the rod

The thermal resistance representing cooling from the end of the rod will be given by

$$R = \frac{R_c/\text{unit area}}{A}$$

where A is the area of the end of the rod (of diameter $0{\cdot}375 \times 2{\cdot}54$ cm) and R_c is the resistance representing cooling from unit area (1 cm^2).

R_c is itself a function of temperature and including the effects of both radiation and convection it may be taken to have a value of 1,500 c.g.s. units where the surface temperature is 300°C.

Using these values in the expression for R gives

$$R = 2{,}100 \text{ c.g.s. units.}$$

Appendix 4

The axial temperature distribution in a solid cylinder

For the finite cylinder $o \leqslant r < a$, $o < z < l$, with $r = a$ kept at θ_o and radiation into medium at zero at the other surfaces, the temperature v is given by [1]

$$v = 2\sum_{n=1}^{\infty} \frac{I_o(\alpha_n r)\{\alpha_n \cos\alpha_n z + h\sin\alpha_n z\}}{I_o(\alpha_n a)\{(\alpha_n^2 + h^2)l + 2h\}} \int_o^l \theta_o\{\alpha_n \cos\alpha_n z' + h\sin\alpha_n z'\} dz'$$

where α_n are the positive roots of

$$\tan \alpha l = \frac{2\alpha h}{\alpha^2 - h^2}$$

and a = radius of cylinder
l = length of cylinder
$h = \frac{H}{K}$
H = cooling coefficient
K = thermal conductivity.

For r = o this reduces to

$$v = 4\theta_o \sum_{n=1}^{\infty} \frac{\gamma}{\beta_n} \frac{\{\beta_n \cos\beta_n z/l + \gamma\sin\beta_n z/l\}}{I_o(\beta_n a/l)\{\beta^2 + \gamma^2 + 2\gamma\}}$$

where $\beta_n = \alpha_n l$
$\gamma = hl$

H may be taken as $0{\cdot}67 \times 10^{-3}$ cal cm^{-2} sec^{-1} $^{o}C^{-1}$ for a surface temperature of 300°C.

Thermal conductivity of concrete = ·0022 cal cm^{-1} sec^{-1} $^{o}C^{-1}$ = K

Length of specimen = 23 cm = $l/2$
Radius of specimen = 5·4 cm = a

For $z = a/2$ $\quad v = {\cdot}81\,\theta_o$
$z = a$ $\quad v = {\cdot}94\,\theta_o$

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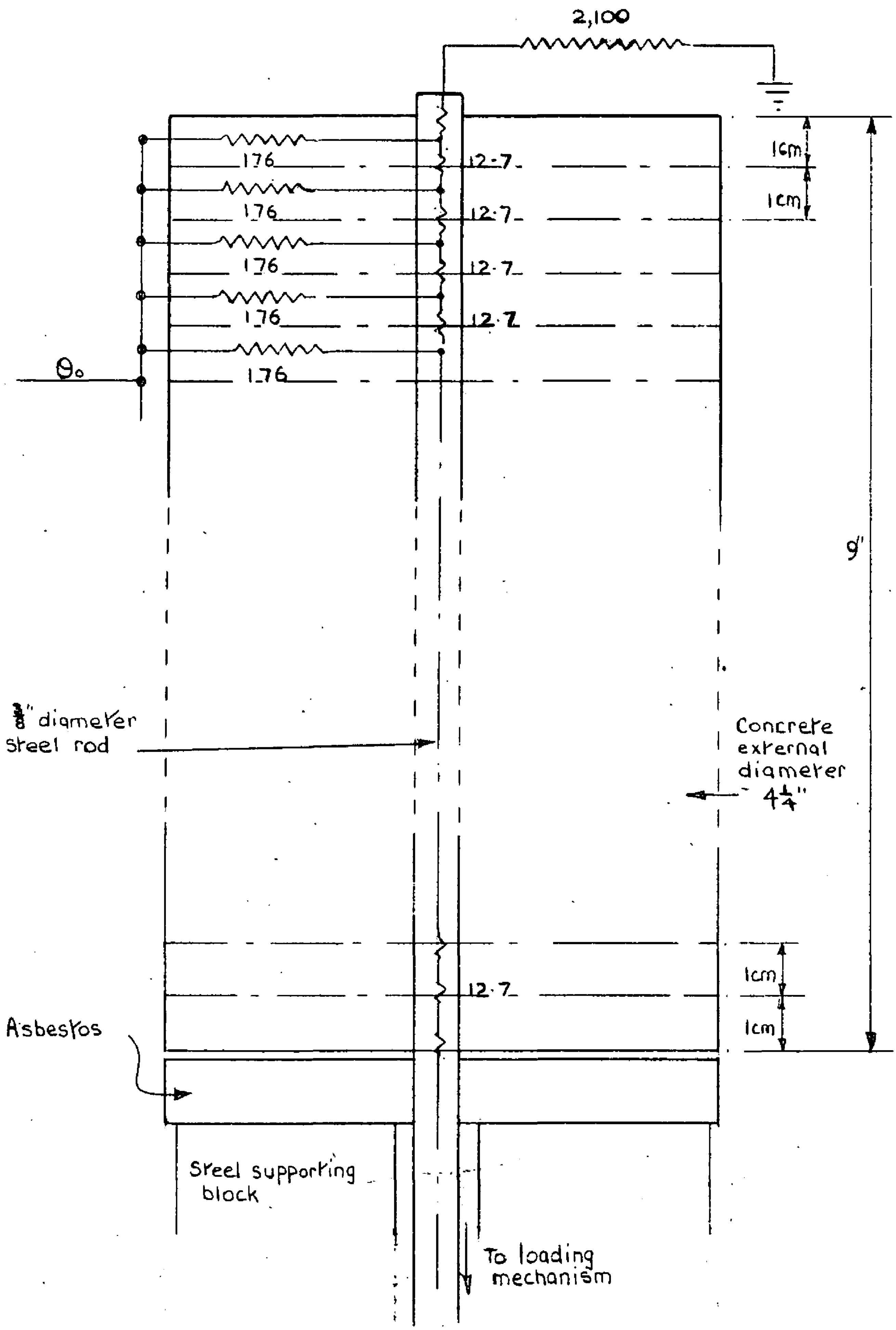

FIG. 1. THERMAL TRANSFER RESISTANCES WITHIN SPECIMEN