EXPLOSIVE SPALLING OF CONCRETE EXPOSED TO HIGH TEMPERATURES

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ABSTRACT

A series of tests to investigate explosive spalling of concrete exposed to high temperature is described. The variables studied include curing condition, age and maturity, rate of heating and temperature gradient, and specimen size. The test results are analysed by means of a simplified model.

INTRODUCTION

Concrete exposed to high temperature is liable to fail violently under certain conditions. This paper describes a series of tests conducted at Imperial College, London, which investigated explosive spalling under the following parameters:

a) Curing condition,
b) Age and maturity,
c) Rate of heating and temperature gradient,
d) Size of specimen.

An hypothesis for explosive spalling is presented, based on experimental evidence from tests carried out on gravel aggregate concrete specimens. A simplified model is proposed for the mechanism producing the failure. The stress at failure is estimated from this model.

VARIABLES INVESTIGATED

a) Curing condition: The specimens tested were either moist cured or water cured. The water cured specimens were removed from the moulds 24 hours after casting and were kept submerged under water for 6 days. The moist cured specimens were also removed from the moulds 24 hours after casting but were kept covered under moist hessian wrapped with polythene sheets for 6 days. At the end of the sixth day, all the specimens were stored in the laboratory at 20°C and 50% relative humidity until they were required for testing.

The water cured specimens showed a gain in weight (60 to 90 gms) on the seventh day over the corresponding weights immediately after demoulding. With the moist cured specimens the change in weight varied from -15 to +20 gms.

b) Age and maturity: The specimens were tested after 7 days curing as mentioned above and some after a further 7 days' interval. In many other cases the interval was reduced to 2 or 3 days to establish the limiting critical ages that explosive spalling occurred under various rates of heating and different curing conditions. Some tests were carried out before the end of the curing period, as prior testing indicated that the less mature specimens were more liable to explode.

c) Rates of heating and temperature gradient along the length of the specimen: The test specimens were subjected to three different rates of heating and temperature gradients along the length and are shown in Figures 1 and 2 respectively. The maximum rate of heating designated as H-H had both the end elements and side elements on high (see description of furnace), the medium rate of heating designated as H-L had the side elements on high with the end elements set on low and the low rate of heating designated as H-O had the side elements on high with the end elements off.

d) Specimen size: In general, the test specimens consisted of 840 mm long plain concrete beams with a cross section of 75 mm x 50 mm. The smaller specimens had the same cross section but were only 100 mm long.

MIX RATIO

A nominal 1:2:4 mix ratio (by weight) with a water/cement ratio of 0.64 was used throughout the test series. The cement content was 446.4 kgm/m^3 of concrete. The coarse aggregate consisted of $\frac{3}{8}$ in (10 mm) to $^3/_{16}$ in (5 mm) Thames Valley aggregate. The fine aggregate was composed of 55% coarse sand 3/16 in to No.25 gauge sieve (5mm to 600 microns) and 45% fine sand No.25 to No.52 gauge sieve (600 to 150 microns). The cement was ordinary Portland Blue Circle cement. The mix ratio for a batch of concrete 0.028 cubic meter volume consisting of 6 test beams and their control specimens is given in Table I.

CASTING

Since a detailed description of this operation appears elsewhere (1), only a very brief account will be given here. In each batch a total of six test specimens were cast in partitioned timber moulds together with nine 100 mm cube control specimens cast in steel moulds. The moulds were filled in three equal layers and were compacted by means of a vibrating table.

DESCRIPTION OF FURNACE

The furnace (2) which has a 925 mm x 200 mm x 275 mm heating chamber was electrically heated by elements placed horizontally on the two 925 mm x 275 mm sides. To increase the heating rate further elements were added to the two 200 mm x 275 mm end faces. The elements on either side, i.e. the longer faces referred to as side elements consisted of three pairs of heating elements. Each of these consisted of 9 meters of 20 S.W.G. (0.914 mm) Brightray resistance wire wound around 850 mm x 15 mm diameter fused quartz rods and was encased in grooved ceramic castings mounted along the vertical longer sides of the furnace. Each pair of elements on one side was electrically coupled to the corresponding pair of elements on the other side by means of a four stage rotary switch. This switch could either connect the two pairs in parallel for maximum heating or in series for minimum heating or short circuit one or both the pairs for medium or no heating respectively. These settings were marked as High, Low, Medium and Off on the switches. For the tests described the side elements were maintained at the high positions. The end elements (i.e. those at the smaller faces of the furnace) consisted of two standard one kilowatt electric fire units at each face. The elements on each of the faces were connected in parallel and could be coupled to the other in parallel for maximum heating (H-H) or in series for medium heating (H-L) or turned off for minimum heating (H-O).

TEST PROCEDURE

The specimen was placed inside the furnace on the previously set up weighing assembly (1). The thermocouple leads from the specimen were connected to a multi-channel millivolt recorder. Finally, the furnace top was covered with four layers of 37.5 mm thick light-weight cerafelt coverings which acted as the furnace lid.

As the specimen was being heated at the desired rate, the following measurements were continuously monitored:

i) Furnace temperature,
ii) Temperature at various points within the specimen,
iii) Change in weight of the specimen.

The test was terminated either when the specimen exploded or after the furnace temperature had reached 450°C and held at this temperature for two hours. In all, 26 large specimens and 8 of the smaller size were tested. Of the former, 10 were moist cured and the rest were water cured. Five of the smaller ones were water cured and three were moist cured. Each of the larger specimens had 9 internal thermocouples as shown in figure 3. The figure also shows the location of 5 thermocouples embedded in the smaller specimens.

TEST RESULTS

None of the smaller specimens showed any tendency to explode, regardless of the vicinity of the specimens to the highest hot spots within the furnace. However many of the larger specimens exploded violently at various heating rates, curing conditions and concrete age as shown in Table II.

DISCUSSION

Figure 4 shows a typical temperature-time curve of a concrete specimen which did not explode. It will be noted that two stages of evaporation can be recognised; the first at about 100°C and the second at around 180°C. Those specimens which exploded, did so during the second evaporation period. The mechanism which produced these violent failures can only partly be explained by "Moisture Clog" phenomenon (3). In this instance this theory would entail the movement of most of the moisture towards the colder centre portion of the specimen creating a saturated core surrounded by a dry layer. With further heating the temperature gradient becomes more severe, resulting in a high heat flow and desorption at the interface of the two layers. The colder core cannot readsorb this vapour and consequently it must find its way out through the increasingly hotter dry layer, gradually expanding and meeting increasing resistance, creating in our case a rapid pressure build up.

Two other factors also contribute in creating conditions inducing explosive spalling. One is the additional stresses arising from temperature gradients in the specimen, the other is due to the existence of adsorbed water within the concrete, which is difficult to dislodge. It is postulated that this is water in the smaller pores possibly within the gel structures, which in this series of tests evaporated in the second stage. It is interesting to note that in another series of tests (4) specimens which had been allowed to air cure for over a period of a year only exhibited the second stage of evaporation. The first stage was missing as the easily evaporable water which in the explosive series of tests was released at around 100°C, was here lost during curing.

The reasons why water cured specimens were more susceptible to explosive spalling are twofold:
a) more water was available for evaporation, and b) the formation of the products of hydration. The cement paste microstructure for these specimens was denser at the surface with a large number of gel pores forming. Heating accelerates the formation of this boundary layer as indicated by X-ray crystallography tests which detected a harder surface layer on the water cured and heated specimens. The water cured specimens which were over 28 days old did not explode since the surface cracks were allowed to form while they were air drying for over 21 days before testing. Similar arguments can be advanced about the young moist cured concrete, except that less water was available for evaporation than in the water cured specimens. It was also probable that the surface was not as impermeable, particularly with the more mature specimens, because of the formation of surface cracks.

Thus, explosive spalling in our case was the result of a combination of effects, i.e. formation of "Moisture Clog", build-up of pressure in the smaller pores and presence of thermal stresses. Although the build-up of pressure was quite high, the concrete could contain it until the outer layer cracked. This initial crack developed when the sum of the stresses produced by the above effects reached the limiting tensile strength of concrete. Figure 5 shows probable locations of such cracks, and line of actions of principal tensile stresses. The sudden release of energy then caused the violent failure.

It will be remembered that the smaller specimens were not susceptible to explosive spalling as were the larger specimens. This does not appear to be in agreement with work carried out elsewhere (5). We believe the reason for this was that the temperature gradient

was less severe for our smaller specimens than that for the larger specimens. One other factor which emphasises the importance of the thermal stress distribution is that when the longitudinal temperature distribution was uniform (Series H-L), the limit for explosive spalling was not as critical (see Table II) as the case when the distribution was non linear (Series H-O) even though the rate of heating was slower.

OSBERVATIONS

Water curing can produce a crack free concrete with a hard impermeable layer on the outside which can inhibit shrinkage. It has been suggested (6) that shrinkage which is an undesirable property in concrete can be reduced by injecting chemicals at the surface to prevent evaporation of water. As can be seen from the above research if concrete is subjected to heat, the sealing of the surface may produce more harm than good.

The results presented in this paper are applicable to the type of materials, mix proportions curing conditions and heating rates investigated. However, it is known (7) that concrete with other mix ratios and materials subjected to different rates of heating and at different ages are susceptible to explosive spalling if the build up of vapour pressure cannot be relieved.

ACKNOWLEDGEMENT

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APPENDIX

It is difficult to calculate the exact magnitudes of stresses developed in the specimen due to steam pressure as water evaporates because of many uncertainties involved. However these difficulties may be overcome if a simplified model is assumed to represent the entire volume of the voids of the specimen.

The specimen before test consisted of aggregates, partially hydrated cement gel and free water (here referring to all uncombined water except that absorbed by the aggregates) and some air voids left during casting as well as voids left by moisture lost during storage. For the sake of simplicity, the mass of partially hydrated cement paste has been assumed to consist of (i) a mass of fully hydrated cement gel and (ii) a mass of completely unhydrated cement particles. The mass of fully hydrated cement gel was determined by estimating the weight of cement that could be fully hydrated by the amount of water available to chemically combine with the entire cement paste at the time of test.

Previous work by Sullivan (2) indicated that by the end of 28 days, 20% of the effective water of moist cured concrete used in these tests combines chemically with the cement. The degree of hydration at any other age was factored by the ratio of strength at the age at test to the 28 day strength. This total mass of fully hydrated cement paste is taken as the equivalent gel mass for the age considered.

The volume occupied by the aggregates, the equivalent gel mass and the unhydrated cement particles were evaluated from the mass of materials actually used. The sum of these three volumes established the volume occupied by solids. The remaining volume of the specimen consisted of free water plus air voids before the test and free water plus steam during the test.

In the simplified model, a hollow sphere was assumed to represent the entire void present in the specimen excluding the voids within the aggregates which were surrounded by the solid aggregate material and further surrounded by the impermeable cement gel. The equivalent gel mass which formed the shell of this hollow sphere was assumed to contain water and steam present inside the specimen at any time during test, any air entrapped within the voids being neglected as most of this would have been forced out with the initial stage of evaporation. The second stage of evaporation at the higher temperature increases the internal pressure and hoop tension develops in the shell of the sphere. The calculated hoop stresses were considered as those which developed in the cement paste structure during heating.

The calculated stress values are plotted against age in figure 6. From this figure it can be seen that explosive failure always occurred to the left of the straight line joining the minima for all three rates of heating at the same curing condition. It would therefore be unsafe to have this type of concrete subjected to the temperature rates and curing conditions as indicated in the diagram. It will be noted that the calculated stress would be comparable to the actual stress arising from the build up of vapour pressure only. The thermal stresses due to the non-linear temperature distribution are not included and would have to be superimposed.

LIST OF REFERENCES

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2. P.J.E. Sullivan and M.L. Poucher, The Properties of Concrete at Elevated Temperatures. Concrete Structures and Technology Research Report No. 68/3 Imperial College of Science and Techology.

3. G.W. Shorter and T.Z. Harmathy, Proceedings, Institute of Civil Engrs., England Vol. 20, 1961.

4. A.A. Akhtaruzzaman, The effect of Transient and Stationary Temperatures on Concrete. Ph.D., University of London to be submitted.

5. von C. Meyer-Ottens, Abplatzungsversuche. Paper presented in a Symposium on Fire Resistance of Prestressed Concrete, held in Braunschweig, Germany, June 1965.

6. Free discussion at the I.A.B.S.E. conference on Shrinkage and creep of concrete bridges at Madrid, September 1970.

7. Private communication, Fire Research Station, Borehamwood, England.

Table I. Weights of unmixed constituents per batch of concrete (0.028 cubic meter)

Aggregate size	Weights
3/8 in to 3/16 in (10 mm to 5 mm)	50.0 kgms
3/16 in to No.25 (5 mm to 600 micron)	13.5 kgms
No.25 to No.100 (600 micron to 150 micron)	11.5 kgms
Cement	12.5 kgms
Water	8.0 kgms
Total	95.5 kgms.

Table II. Upper limiting ages at which explosive failure occurred.

Heating Rate	Curing Condition	Upper Age Limit	Furnace Temperature
H-H	water cured	28 days	380°C
H-H	moist cured	10 days	421°C
H-L	water cured	10 days	390°C
H-L	moist cured	3 days	378°C
H-0	water cured	18 days	380°C
H-0	moist cured	5 days	378°C

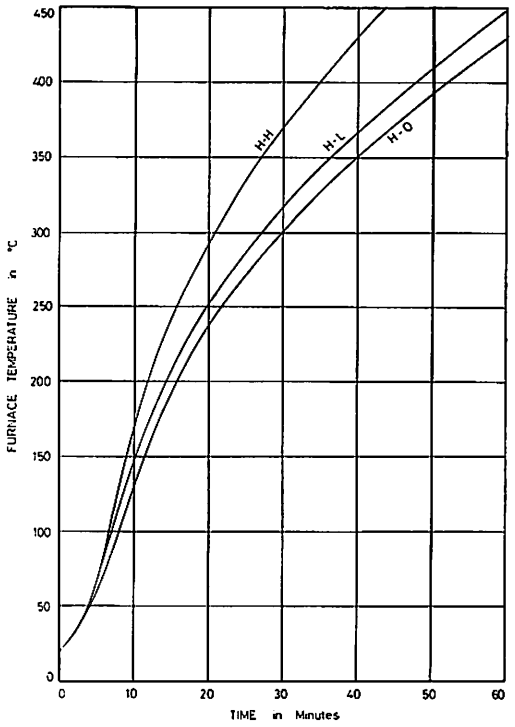
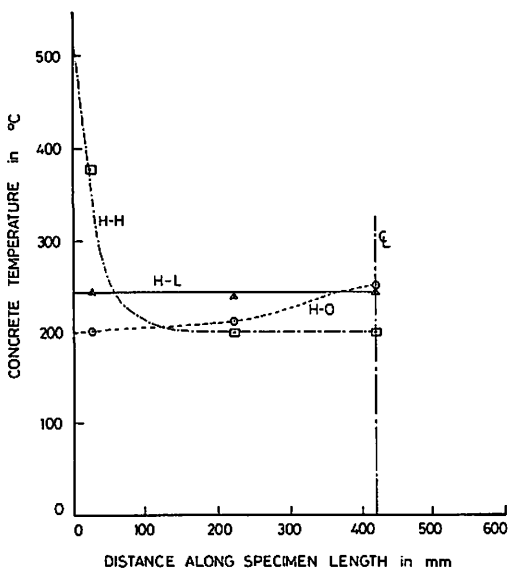


Figure.1. TIME-FURNACE TEMPERATURE PLOT FOR DIFFERENT HEATING RATES



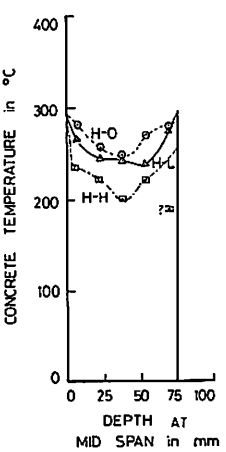


Figure.2. TEMPERATURE DISTRIBUTION WITHIN CONCRETE SPECIMEN (furnace temperature 400°C)

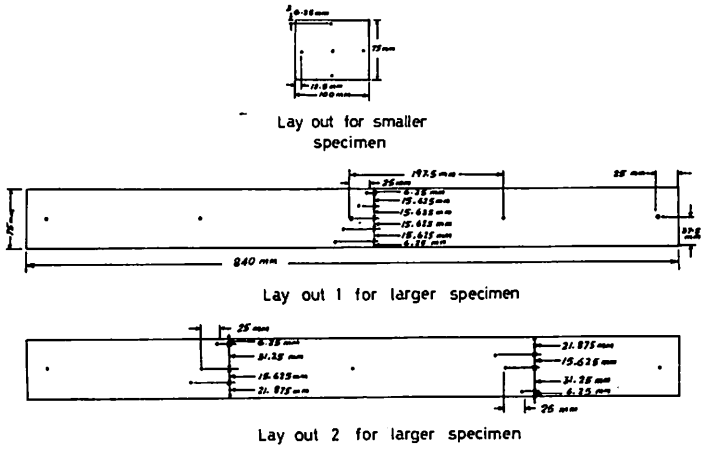


Figure.3. THERMOCOUPLE LAY OUTS

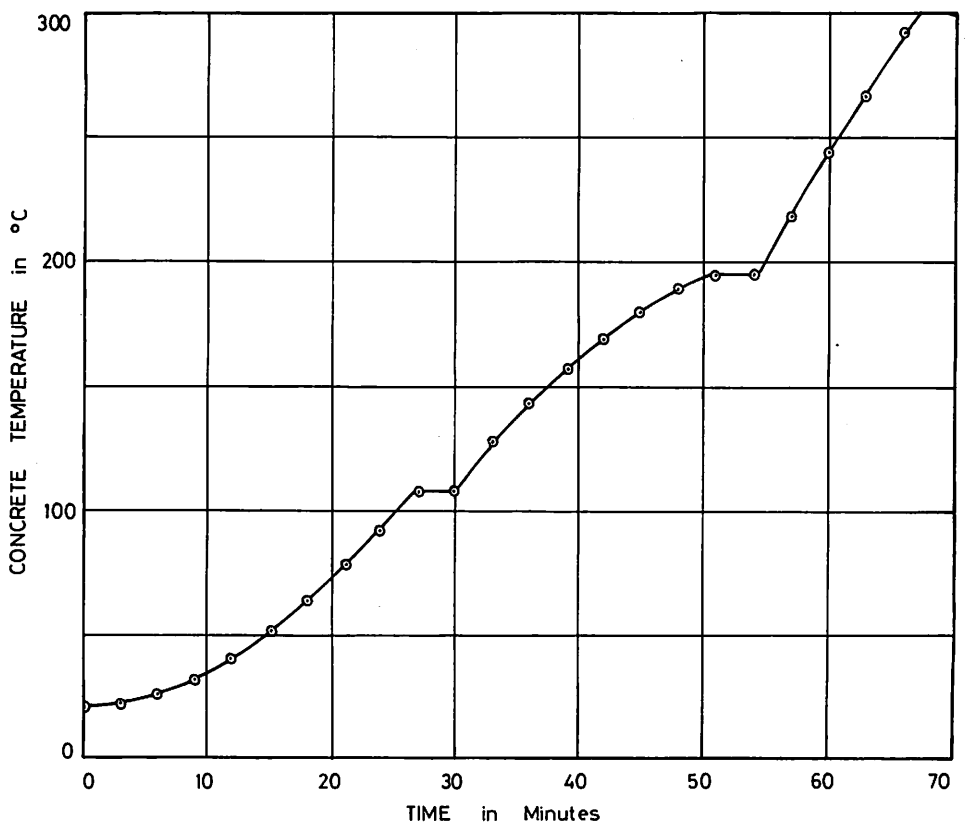


Figure.4. TYPICAL TIME-TEMPERATURE CURVE FOR A SPECIMEN

Figure 5. EXPLODED SPECIMEN REASSEMBLED SHOWING PROBABLE LOCATIONS OF INITIAL CRACKS & THE LINES OF ACTION OF PRINCIPAL TENSILE STRESSES

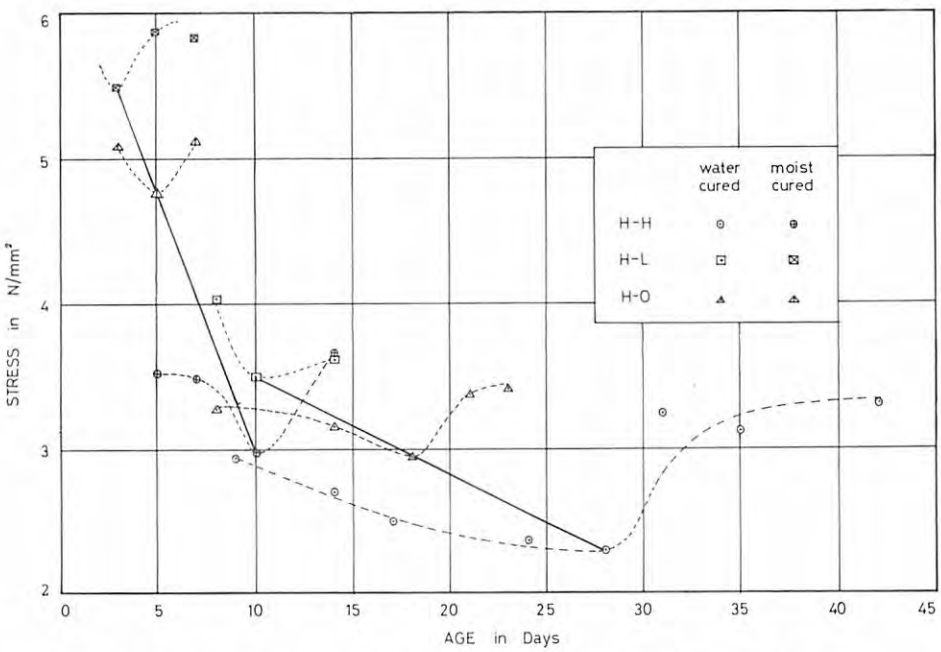


Figure.6. CALCULATED STRESS DUE TO STEAM PRESSURE AT VARIOUS AGES

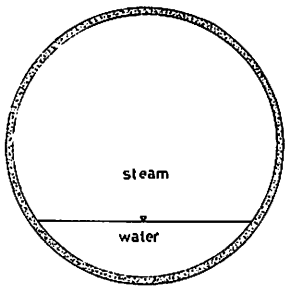


Figure.7a. SIMPLIFIED MODEL

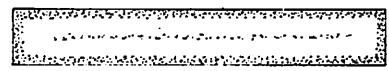


Figure.7b. FORMATION OF DENSE GEL LAYER IN WATER CURED AND MOIST CURED SPECIMENS

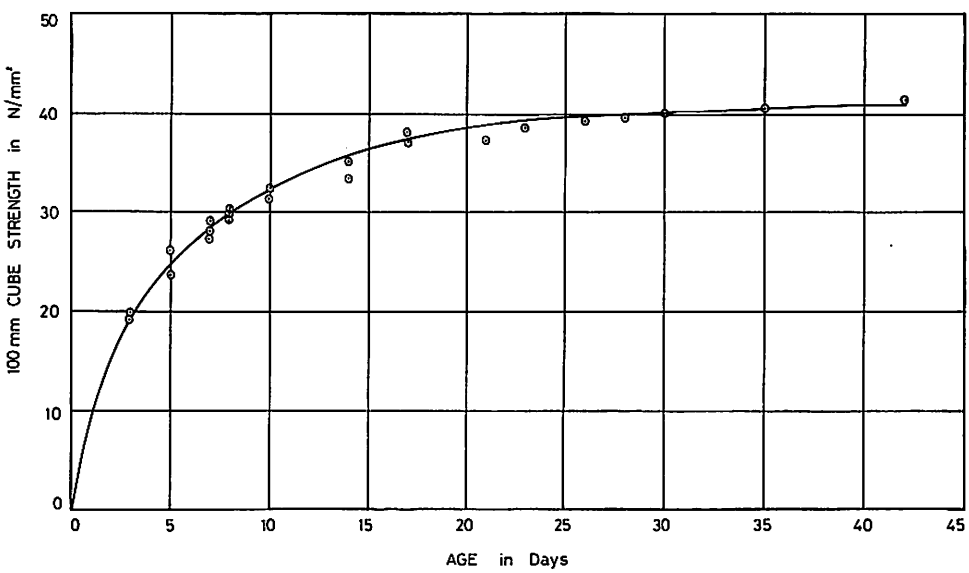


Figure.8. CONCRETE STRENGTH VARIATION WITH AGE

DISCUSSION

Q L. A. TATE, U. K.

What is the reason for the high temperature gradient at the end for the H-H heating regime ?

A P. J. E. SULLIVAN, U. K.

We found that rate of heating was an important parameter in causing explosive spalling. Under heating H-H a high temperature gradient was achieved by having heaters at the ends of the furnaces set on high. This effect not only caused high stress gradients but also induced a high moisture movement towards the centre of the specimen.
It will be observed that under this severe condition violent failures occurred on both the moist and wet cured conditions indicating that the additional stresses were superimposed on the already existing imposed stresses due to the combination of pore pressure effects described in the paper.