Deterioration and spalling of high strength concrete under fire

Prepared by
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for the Health & Safety Executive

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Deterioration and spalling of high strength concrete under fire

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</table>
SUMMARY

When concrete is exposed to fire, the build-up of internal water pressure under steep temperature gradients generates high local stresses, which may cause spalling, potentially explosively. The performance of high strength concrete, particularly in the high humidity of the offshore environment where there is the potential for hydrocarbon fires, has not been researched. The objectives of the present study were therefore to investigate the factors influencing deterioration and explosive spalling of high strength concrete beams and to examine measures to prevent brittle and violent failure.

Six factors suspected of influencing the behaviour of concrete at high temperature were investigated:

a. Relative humidity (RH) of the curing regime prior to testing
b. Rate of heating
c. Level of loading prior to heating
d. Water cement ratio
e. Type of aggregate (limestone, lightweight aggregate (LWA) and modified normal i.e. limestone partly replaced by LWA)
f. Polypropylene fibre content.

A fractional factorial method of experimentation was adopted whereby five of the factors were varied systematically across three levels each to identify trends and quantify the significance of their influence.

Three main series of 27 tests each were undertaken. In the first two series, plain and reinforced concrete beams were tested and the first five factors were varied in both cases. In the third series, the curing regime was constant at 100% RH to give the most onerous conditions for precipitating spalling at high temperature, and the latter five factors were varied for the inclusion of fibres to be assessed. An additional series of tests replicated the initial series for plain concrete beams but used a different combination of curing regimes.

The high temperature work was carried out in a purpose built rig capable of applying loads to beams in flexure within a furnace and at the same time measuring load, deflections and expansions.

Deterioration (as represented by the dilation of the beams) was exhibited by all beams after heat cycling to 700°C, caused by the differential rate of thermal expansion of the constituent materials. Those with reinforcement therefore responded differently from the plain concrete. For example, a significant factor in one series could be equally significant or could be insignificant to the response of the beams in the other series. Similarly a linear trend in one case may be non-linear in the other. However, neither the plain nor reinforced concrete beams were immune from explosive spalling given an appropriate combination of factors.

Those beams that deteriorated early during heating were less prone to explosive spalling because the micro-cracks relieve the built-in strain energies. The high thermal expansion of the polypropylene fibres, particularly relative to LWA, meant that none of the fibre concrete beams failed explosively.

The research has demonstrated that impermeable concrete exposed to transient high temperature is susceptible to explosive spalling and a trade off between durability and permeability should be considered. The tests have also shown that the addition of fibres, such as polypropylene, can be effective in reducing the likelihood of explosive spalling.

A general observation was that limestone concrete, like gravel concrete used in previous tests (1), had a higher propensity for explosive spalling than the lightweight aggregate mix. It is therefore recommended that limestone concrete should be avoided for structures that may be exposed to fire.

However, the converse cannot be stated so firmly as LWA tests by others under a fuel fire produced continuous explosive spalling.
1. BACKGROUND TO RESEARCH

During exposure to fire temperature the effect of heat and mass transfer in concrete becomes important. Under steep temperature gradient (1,2,3,4) the build-up of water pressure develops high local stresses, which might cause concrete spalling. In structures located in high humidity exposure such as in the UK environment or offshore where a high risk of fire may exist a dangerous type of failure, explosive spalling, could take place during the fire. As a consequence of this failure, severe damage may occur which could lead to partial collapse of the structure and increases the probability of serious loss of life.

Although a large number of tests at elevated temperature have been carried out in the past (3 to 14), there has been a limited number of experiments on high strength concrete at elevated temperatures. Scant reference is available on explosive spalling of high strength concrete during fire. Various factors influencing explosive spalling have not been systematically investigated despite the concern, which has been expressed by a number of authorities. In addition methods of avoiding explosive spalling have not been examined widely enough and there is still a great deal of work to be carried out in this field. Some European work has recently been reported on high strength concrete at elevated temperature, but this has not been published yet.

This project was therefore intended to investigate more fully the deterioration and explosive spalling of high strength concrete at elevated temperature and examine means of alleviating brittle and violent failure. Various factors, which were considered to influence spalling on high strength concrete at elevated transient temperatures, have been included in the tests. These were selected to act concurrently on beams during testing and the behaviour of the beams was examined.

The major approach of the investigation has been experimental which includes studying the deterioration of high strength concrete due to the effect of five different material and environmental factors each at three levels, by a fractional factorial method of experimentation. This method involves the selection of a fraction of the full factorial in such a manner that allows the individual and some of the interaction factors to be determined.

In our case the experiment required the testing of 27 beams. The procedure then involves the averaging the results of all the 27 tests. Each factor is then averaged over each of nine results at each of the three levels. The variance at each factor level from the overall average gives an indication of the effect that a change of level of the factor being analysed has on the overall average. The error intrinsic in any test is also estimated and this is compared with the variances of each factor.

A factor is said to be significant if its variance has a probability of less than 10% of being due to an error effect and in such a case is termed as “significant to more than 90%.”
2. INTRODUCTION

This is the third and final report covering the project entitled Deterioration and Spalling of High Strength Concrete during Fire. The project was partly funded by HSE under Participation Agreement No D3614. Description of the project together with the results is given in this report.

The first report covered the work done until February 1998 including the preliminaries and design and details of the experimental work. The second report covered the work performed up to December 1998. The final report covers all the salient work carried out throughout the contract.

The aim of this project was to investigate the deterioration and spalling of different types of concrete during fire and to find methods of alleviating this phenomenon. Previous experience with explosive spalling indicated that the latter was not a deterministic phenomenon and hence a probabilistic method of experimentation was adopted using a fractional factorial approach. Five factors suspected of influencing the behaviour of concrete at high temperature were investigated, each factor being tested at 3 different levels, so that non-linear effects could be studied. The factors were curing of concrete prior to testing, rate of heating, loading prior to heating, water cement ratio and type of aggregate of the concrete. A parallel series of reinforced concrete beams was tested under identical conditions. Polypropylene fibres were also used for a series of tests on concrete beams maintained at 100% R.H. to study any improvements in the behaviour of concrete at high temperatures. This high humidity curing on fibre concrete is a more stringent condition than other forms of curing at high temperature.

During initial testing of the first series of the plain concrete, a beam with a water/cement ratio of 0.5 and cured at 65% relative humidity exploded. Because of this, it was decided to change the R.H. of the higher level of the curing factor from a nominal 100% to 65% and to maintain the lowest level at 0%, for this first series of plain concrete. There were some anomalies in these initial results. These tests were therefore repeated at a nominal curing R.H. of 100% (85%), 65% and 45%, after completing the reinforced concrete series of tests using concrete with the same aggregates, water cement ratio and curing at the same R.H. as the plain concrete beams. The fibre concrete beams were all tested with the concrete cured at 100% RH prior to testing. Cold tests were also carried out on control cubes at 28 days and at time of testing, together with capillary rise test to assess the surface permeability of the concrete. This report describes the experimentation method, experimental data obtained, the processed results and their analyses.
3. EXPERIMENTAL INVESTIGATION

3.1 INTRODUCTION

The objective of the experimental programme was to examine the influence of six main factors, namely curing of concrete prior to testing, heating rate, loading prior to heating, water/cement ratio, types of aggregates and different polypropylene fibre content, on spalling and deterioration of high strength concrete during fire. The use of polypropylene fibres was shown in previous testing to alleviate explosive spalling. The coarse aggregates for the samples were limestone for normal concrete, 45% Lytag replacement of limestone for the modified normal and Lytag for lightweight concrete.

The high temperature tests have being carried out in a purpose built testing rig on 27 (x3) plain, fibre and reinforced concrete beams of similar overall dimensions with a further plain concrete test series of 27 beams as explained in the introduction. Nine additional control beams were cast for each test series and these were tested to failure in the cold state. Three additional beams with embedded thermocouples have been tested to obtain thermal response data for the 3 different rates of heating and the three different types of aggregates.

The design of the experimental programme has been based on the fractional factorial method of analysis. All the factors have been investigated at 3 levels. A description of these factors and levels is given in Table 2. Three levels have been selected so that the non-linear variations in individual and interacting factors can be determined.

3.2 EXPERIMENTAL SETUP

The purpose built electrical furnace is capable of heating, loading beams in bending simultaneously while temperatures, deflections and expansion or dilation of the beams are being monitored. Figure 1 shows a schematic diagram of the experimental set up. The 850mm long beam is placed on a roller C, and a rocker support D, 680mm apart within the furnace enclosure. The load is applied at two points approximately 227mm apart, equidistant from each other and the supports. The deflections are measured at mid point, third points and adjacent to the supports and axial deformation is measured by the sum of dilations at either end. The displacement transducers P are supported outside the furnace and are in contact with silica rods of 10mm diameter passing through apertures within the end walls and floor of the furnace. The other ends are ground to 2mm making point contact with the beam specimen inside the furnace.

Three sets of electrical elements J, one above and two at either side of the beam specimen apply heat to the furnace. The heating rate is controlled electrically by varying the power supplied to the elements. The power ratings have been fixed for the tests at 90%, 60% and 30% to impart high, medium and low rates of heating. The furnace can be set to a specified maximum required temperature, and in the tests described, has been set to 700°C. However if the beam fails before reaching 700°C, the furnace is turned off. Once the set temperature is reached the furnace maintains this heat to a tolerance of + or - 1.5 % or less. The distribution of heat in the furnace is not uniform and creates a higher temperature at the centre than at the ends of the furnace, which is reflected in the beam specimens imposing a certain amount of internal lateral restraint during heating.

The system of applying load remotely from the furnace and concurrently taking load and displacement readings is also shown in Figure 1 and a description of the loading and unloading sequence follows.
The loading on the beam is applied by means of a saddle supported on a rocker B and a roller A 227mm apart placed centrally above and in contact with the top of the beam within the furnace. The saddle contains 2 apertures in line with the centre of the rocker and 2 apertures in line with the centre of the roller to allow 4 threaded rods or hangers J to hang astride the beam specimen and the loading system below. The loading system comprises a motorised screw jack Q, R, F fixed below the furnace and a load cell G attached to the piston below via a ball race. The bottom end of the load cell is attached to a cross-beam H also via another ball race to allow free rotation of the load cell. The cross-beam sits astride two steel beams I each with a pair of apertures at 227mm centres allowing the bottom threaded end of the hangers through. Four nuts below the steel beams, threaded into the 4 hangers, support the steel beams, which in their turn support the load cell. When the electrical motor is turned on, the piston pushes down on the load cell against the remainder of the loading system below the furnace and applies tension to the hangers between the concrete beam in the furnace and the steel beams below, thus loading the concrete beam. When the motor is switched to reverse, the tension in the hangers is reduced thus lowering the applied load. The hangers and all the steel within the furnace is temperature resistant Nimonic or titanium steel.

The screw jack is used for loading the control beams to failure to establish their flexural strength and also for applying the required load to the reinforced concrete prior to heating the beams. During heating, the applied load on the reinforced concrete beams alters as the beam deforms with temperature change and no attempt was made to keep this load constant. For the plain and fibre concrete beams the value of the loads applied is very small and dead weights were suspended to the hangers for the tests, which required loads applied during heating.

An Orion data logger connected to an IBM PC was used to automatically log the data and store them in a file on the hard disk of the computer for subsequent processing.

The rig is a unique facility, as detailed beam deformations can be determined. If strain gauges are embedded within the beam, strains can also be established and all these data can be used to validate thermal and structural computer programs. Unfortunately temperature resistant strain gauges were not allowed for in the research budget and strains are therefore not available. Previous experience with electrical strain gauges (ERS) embedded in concrete gave unsatisfactory results. With recent developments, high temperature ERS have greatly improved and trials carried out in some of our beams show promise. The set up has permitted the behaviour of plain, reinforced and fibre concrete simply supported beams to be investigated under different transient temperature conditions. Since our testing has shown that internal restraints to beams influence explosive spalling, further development of the rig will allow external restraints to be included as a factor in future factorial based testing.

3.3 SPECIMEN DETAILS

The plain concrete and fibre reinforced concrete specimens for temperature testing were beams each having the dimensions of 850 mm in length and 50 x 75mm in cross section. The reinforced concrete specimens had a cross section of 60 X 85mm to allow sufficient cover to the reinforcing stirrups. These same moulds were used for the plain concrete beams, which were cured in the same manner as the reinforced concrete beams.

The specimens were cast in steel moulds 4 beams at a time for each mix. One of the beams was used to find the ultimate load capacity of the beams at room temperature at the time of testing, in conjunction with control cubes and other samples. Fifteen cubes and 4 small cylindrical discs were cast for testing room temperature permeability and strength properties at time of testing for each mix.
3.4 MIXES

The materials used in the testing are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Materials</th>
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<tbody>
<tr>
<td><strong>Cement:</strong></td>
</tr>
<tr>
<td><strong>Fine aggregates:</strong></td>
</tr>
<tr>
<td><strong>Coarse aggregates – Limestone:</strong></td>
</tr>
<tr>
<td><strong>Coarse aggregates – Light weight (Lytag):</strong></td>
</tr>
<tr>
<td><strong>Microsilica:</strong></td>
</tr>
<tr>
<td><strong>Superplasticiser:</strong></td>
</tr>
</tbody>
</table>

*BS812:Pt2:1995

The limestone concrete was selected from the mixes used by the Building Research Establishment, who were carrying out parallel tests in compression, on concrete varying in strength from 40 to 100 N/mm². The modified normal concrete was based on a practical mix used offshore by Mobil Oil on the Mobil Oil Hibernia Platform. A number of trial mixes were carried out to determine the mix proportions of the lightweight and modified concrete trying as much as possible to match the strength of the limestone mixes at BRE. It was not possible to match the higher strength and have practical workable mixes for these latter concrete types, even though superplasticisers had to be used and so W/C was chosen as one of the factors instead of strength. The principal criterion for the concrete workability was that it should be easily placed into the forms without excessive vibration.

Final mix proportions are given in Appendix 1. It will be observed that in order to achieve compatibility in strength for the lightweight concrete with the BRE mixes and at the same time have a modified mix, which has only been used practically on an actual platform, certain inconsistencies occurred. The mixes using 0.35 W/C had a higher mortar fraction than either of the mixes using 0.25 or 0.5 W/C.

3.5 CASTING & CURING PROCEDURE

The concrete was cast in a horizontal pan and paddle mixer and compacted within steel moulds on a vibrating table. Sufficient concrete was produced for each mix to allow for tests on concrete in the wet state. For the reinforced concrete beams, the steel cage had horizontal steel plates, each with a threaded hole, welded to the bottom reinforcing bars. The steel plates and cage were then firmly bolted on to the steel mould to ensure 5mm cover to the stirrups without the necessity of placing spacers along the length of the beam, with a different property to the parent concrete. When the concrete hardened, the bolts were removed and the resulting cavities at the ends were filled with a mortar of the same proportions and consistency as that of the parent concrete.

The moulds filled with concrete were covered with polythene sheets allowing the concrete to harden for 24 hours before de-moulding and placing in water at 20°C. The standard control cubes were kept in water for a further 27 days before testing. The remainder of the concrete was cured in water for 7 additional days before removing the samples for their specified curing regime until required for testing. For the nominal 100 % RH, the samples were covered with burlap, which was maintained wet. The measured RH prior to testing was
> 85%. Some samples were stored in the curing room, which was maintained at 65% RH and 20°C, while others were stored in the laboratory at 45% RH and 20°C. For the initial plain concrete series the beams were oven-dried for the low curing rate.

Three additional beams had instrumentation installed within the moulds before casting. These included one beam containing each of the three types of aggregates used. The beams had 27 thermocouples placed at the central and support cross-sections and along the length of the beam as shown in Figure 2. In addition to the 27 thermocouples embedded in the limestone concrete beam, 16 thermocouples were also placed on the surface surrounding the beam within the furnace during the test. These beams established the concrete temperature regimes at the three furnace rates of heating.

### 3.6 TEST PROCEDURE

The following procedure has been observed for all the heat tests.

- Place the specimen in the furnace
- Place the loading equipment in place
- Close the furnace lid
- Set the maximum temperature to 700 degree C
- Set the safety cut off temperature to 800 degree C
- Set the power according to the required heating rate
- Start the data logger and apply the load, if required.
- Start the furnace
- Maintain the furnace temperature at 700 degree C for 15 minutes
- Switch the furnace off
- Continue to log the data during the cooling period with the lid shut

During the heating period the data is logged at one-minute intervals. During the cooling off period the data was logged at ten-minute intervals for the first series of tests. When the specimen exploded or failed prematurely, the test was stopped immediately.
4. FRACTIONAL FACTORIAL METHOD

Fractional factorial experimentation is a well-established method based on statistical analysis (16, 17, 18, 19, 20, 21). A defined fraction of the full factorial has been selected to assess the influence of each of the factors and the important interacting factors on the overall average effect. One of the advantages of this experimental method is the enormous amount of saving in time and cost compared to performing the full factorial experiments which would require \(3^5 = 243\) tests for five factors at 3 levels. Although three factor and higher interactions are aliased for a 1/9 fraction used in these tests, and cannot be determined, some of the 2 factor interactions and all the single factor effects can be safely assessed. The assessment of interaction of factors is a useful advantage. Unlike classical one factor at a time testing, which assumes certainties in testing conditions, factorial experimentation allows the error inherent in any test due to instrumentation, material uncertainties, or even human errors to be estimated. The resulting variations due to a change in level of any factor investigated can then be compared to the error factor to assess the significance of the change.

4.1 PROCESSING OF RESULTS

The results from the four series of tests are processed independently. First the results of all the 27 tests within a series are averaged. Then, considering each of the five variable factors in turn the nine results at each of the three levels are averaged. These average results can be plotted to assess the effect of a change in level of a particular factor. This process can be repeated for the important interacting factors and their average results plotted. These plots are only indicative of the effect and before one can determine whether such variations are significant and indicate a real change, an analysis of variance (ANOVA) has to be carried out.

The variance of the results at each factor level from the overall average is first established. This gives an indication of the effect that a change of level of the factor being analysed has on the overall average. The next stage is to assess the error factor, which is intrinsic to any testing. The variance of the error factor is then established and this is compared with the variances of each factor. If the variance of the factors have a probability of less than 10% of belonging to the error, a change in factor level is significant to more than 90%. Traditionally 90% is considered just significant, 95% as significant and 99% as highly significant. The significance of the factors for each series of tests can be compared directly at this stage.

It should be borne in mind that individual test results are not as close to the truth as average effects since these are normally distributed. Also in averaging each factor individual results are used more than once, thus increasing the utilisation and efficiency of the results. These are additional advantages over one factor at a time testing.

4.2 FACTORS INVESTIGATED

The six factors, described in Table 2 are grouped into two sets of five factors each. The first set contains the first 5 factors (see also Table 3). In the second set, factor A (Curing) is kept at a constant nominal 100% RH (85%) as this is expected to give the most critical condition for explosive spalling and sixth factor (polypropylene fibre) is introduced (see also Table 4). Since one ninth of the full factorial experiment has been designed for each set, only 27 tests for each series are required. With the additional 27 tests for the reinforced concrete beams, a total of 81 furnace tests and 27 further plain concrete tests shown in Table 6 have been completed.
Table 2  
Factors and Levels  

<table>
<thead>
<tr>
<th>Factor for concrete /RC</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Curing</td>
<td>0</td>
<td>Nominally 100% RH (65%)+</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Nominally 65% RH (45%)+</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Nominally 45% RH (0%)+</td>
</tr>
<tr>
<td>B. Heating Rate (A)*</td>
<td>0</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>High</td>
</tr>
<tr>
<td>C. Loading (B)*</td>
<td>0</td>
<td>0% of Load capacity at 20°C</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>10% of Load capacity at 20°C</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>20% of Load capacity at 20°C</td>
</tr>
<tr>
<td>D. Water/cement Ratio (C)*</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.50</td>
</tr>
<tr>
<td>E. Aggregate (D)*</td>
<td>0</td>
<td>Light Weight (Lytag, L)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Modified (Mixed N &amp; L, 45% Lytag replacement of Limestone by volume)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Normal Weight (Limestone, N)</td>
</tr>
<tr>
<td>Fibre Contents E*</td>
<td>0 F1*</td>
<td>1 Kg/m³ of polypropylene (Fibrin) fibres</td>
</tr>
<tr>
<td></td>
<td>1 F2*</td>
<td>2 Kg/m³ fibres</td>
</tr>
<tr>
<td></td>
<td>2 F3*</td>
<td>3 Kg/m³ fibres</td>
</tr>
</tbody>
</table>

*Factors for the fibre concrete. RH in brackets have been used for first plain concrete test series
+The RH in brackets refers to the plain concrete beams cured at the lower RH prior to testing

4.3 FACTOR LEVELS & VALUES OF 1/9TH FRACTIONAL FACTORIAL

The principal fraction of the 1/9 fractional factorial experiment for the plain and reinforced concrete test series with the test/beam number in the left hand (LH) column and the levels of each factor in the other columns is shown in Table 3. The principal fraction for the fibre concrete is shown in Table 4. These fractions ensure that all individual factors and interaction factors AB, BC and AC can be determined with sufficient confidence. Interactions of D and E may be aliased and cannot be determined with the same confidence. Hence the factors which are known by experience or intuition to influence the results more strongly are selected as A, B and C.

It should be observed that A, B and C form a complete factorial and D and E exhibit a balanced pattern. This ensures that A, B and C at a given level are given a similar treatment
when combined with levels of D and E. Similarly C, D and E form a complete factorial and in their turn are given similar treatment when combined with A and B. This balanced treatment ensures that none of the factors have any biased effect on the overall average.

Other than the principal fraction, which can be derived by Modulo division, there are of course 8 other fractions, also derived by the same mathematical process, which could have been used. These other fractions would change the order of preference of factors.

4.4 HIGH TEMPERATURE BEAM TESTING SCHEDULES

Table 5 gives the beam testing schedules for the plain, reinforced and fibre concrete test series.
A code reference was given for each beam specimen describing the mix and manner of testing and these are given in Tables 5. The notation used is given below.

**NOTATIONS USED IN Table 5:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Lightweight aggregate concrete (Lytag) – level 0</td>
<td>0</td>
</tr>
<tr>
<td>M</td>
<td>Modified normal weight concrete – level 1</td>
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<tr>
<td>N</td>
<td>Normal weight concrete – level 2</td>
<td>2</td>
</tr>
<tr>
<td>0.25,0.35,0.50</td>
<td>Water/Cement Ratio – levels 0, 1, 2 respectively</td>
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</tr>
<tr>
<td>00,10,20</td>
<td>Percentage of applied load to Load capacity of beam at 20°C – levels 0, 1, 2 respectively</td>
<td></td>
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<tr>
<td>HL</td>
<td>Low rate of heating – level 0</td>
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<td>Medium rate of heating – level 1</td>
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<td>HH</td>
<td>High rate of heating – level 2</td>
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</tr>
<tr>
<td>C1*</td>
<td>Moist curing 85% to 100% RH - level 0</td>
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</tr>
<tr>
<td>C2</td>
<td>Curing room at 65% RH – level 1</td>
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<tr>
<td>C3</td>
<td>Air curing ambient temp 45% RH – level 2</td>
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</tr>
<tr>
<td>F1</td>
<td>1 kg of polypropylene fibre per m$^3$ of concrete - level 0</td>
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</tr>
<tr>
<td>F2</td>
<td>2 kg of polypropylene fibre per m$^3$ of concrete – level 1</td>
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</tr>
<tr>
<td>F3</td>
<td>3 kg of polypropylene fibre per m$^3$ of concrete – level 2</td>
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</tr>
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</table>

*Note that for the initial plain concrete set of beams, the curing was nominally at 65%, 45% and 0% RH respectively

+The load capacity for the reinforced concrete was taken at the yield strength of the beams
### Table 3
The principal 1/9 fractional factorial Table for plain and reinforced concrete beams

<table>
<thead>
<tr>
<th>Test/Beam No.</th>
<th>A(Curing)</th>
<th>B (Heat)</th>
<th>C (Load)</th>
<th>D (W/C)</th>
<th>E (Aggregate)</th>
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### Table 4
The principal 1/9 fractional factorial Table for the fibre concrete beams

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<tr>
<th>Test/Beam No.</th>
<th>A (Heat)</th>
<th>B (Load)</th>
<th>C (W/C)</th>
<th>D (Aggregate)</th>
<th>E (fibres)</th>
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<td>Specimen No. (add R for RC)</td>
<td>Specimen Code Plain concrete</td>
<td>Specimen No.</td>
<td>Specimen Code Fibre concrete</td>
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<td>L/0.35/20/HL/F3</td>
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<td>M/0.50/20/HH/F3</td>
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5. RESULTS

5.1 GENERAL OBSERVATIONS

Table 6 gives a description of the state after testing, of the plain concrete beams subjected to a curing relative humidity (RH) prior to testing of 65, 45 and 0% respectively. For fractional factorial testing the selection of beams for testing is random and the second column of Table 6 showing test number also refers to the fractional factorial number. The Test Reference in column 1 below is similar to the Specimen Code in Table 5 above. Table 6 has been rearranged from Table 3 to give testing in the order of the type of concrete i.e. limestone concrete, modified normal concrete and lightweight aggregate (Lytag) concrete (levels 2, 1 & 0 in Table 3).

Table 6
Observations for plain concrete (tested after curing at 65, 45 & 0% RH)

<table>
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<tr>
<th>Test Reference</th>
<th>Test No.</th>
<th>Rate of heating</th>
<th>Curing</th>
<th>Remarks</th>
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<td><strong>Limestone concrete</strong></td>
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<td>N/0.5/HH/10/C2</td>
<td>16</td>
<td>H</td>
<td>Air</td>
<td>Explosive spalling after 26 minutes – Furnace temperature approx. 480°C (Av. Conc. Temp 260°C)</td>
</tr>
<tr>
<td>N/0.25/HH/10/C1</td>
<td>8</td>
<td>H</td>
<td>Moist</td>
<td>Severe cracking at top middle loading zone. Cracks at all surface. Permanent 5.5mm deflection at centre</td>
</tr>
<tr>
<td>N/0.35/HH/20/C1</td>
<td>27</td>
<td>H</td>
<td>Dry</td>
<td>Minor cracking but beam broke during cooling.</td>
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<tr>
<td>N/0.5/HM/10/3</td>
<td>23</td>
<td>M</td>
<td>Moist</td>
<td>Cracking only at the top surface of beam</td>
</tr>
<tr>
<td>N/0.35/HM/20/2</td>
<td>15</td>
<td>M</td>
<td>Air</td>
<td>Severe cracking at the top</td>
</tr>
<tr>
<td>N/0.5/HL/10/C1</td>
<td>19</td>
<td>L</td>
<td>Dry</td>
<td>Minor cracking – beam broken during cooling</td>
</tr>
<tr>
<td>N/0.25/HL/10/C2</td>
<td>11</td>
<td>L</td>
<td>Air</td>
<td>Cracking only on the bottom surface of beam</td>
</tr>
<tr>
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<td>L</td>
<td>Moist</td>
<td>Minor cracking</td>
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<td><strong>Modified concrete</strong></td>
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</tr>
<tr>
<td>M/0.35/HH/0/C1</td>
<td>7</td>
<td>H</td>
<td>Moist</td>
<td>Severe cracking mainly on top surface</td>
</tr>
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<td>H</td>
<td>Dry</td>
<td>Minor cracking</td>
</tr>
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<td>H</td>
<td>Air</td>
<td>Minor cracking – failed during cooling</td>
</tr>
<tr>
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<td>M</td>
<td>Dry</td>
<td>Minor cracking</td>
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<td>Minor cracking</td>
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<td>M</td>
<td>Moist</td>
<td>Minor cracking – failed during cooling</td>
</tr>
<tr>
<td>M/0.35/HL/0/C2</td>
<td>10</td>
<td>L</td>
<td>Air</td>
<td>Minor cracking</td>
</tr>
<tr>
<td>M/0.5/HL/10/C1</td>
<td>2</td>
<td>L</td>
<td>Moist</td>
<td>Minor cracking</td>
</tr>
<tr>
<td>M/0.25/HL/20/C3</td>
<td>21</td>
<td>L</td>
<td>Dry</td>
<td>Minor cracking – failed during cooling</td>
</tr>
<tr>
<td><strong>Lightweight aggregate concrete</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L/0.25/HH/0/C3</td>
<td>25</td>
<td>H</td>
<td>Dry</td>
<td>Minor cracking – top surface</td>
</tr>
<tr>
<td>L/0.35/HH/10/C2</td>
<td>17</td>
<td>H</td>
<td>Air</td>
<td>Minor cracking</td>
</tr>
<tr>
<td>L/0.5/HH/10/0/C1</td>
<td>9</td>
<td>H</td>
<td>Moist</td>
<td>Severe cracking</td>
</tr>
<tr>
<td>L/0.25/HM/0/C2</td>
<td>13</td>
<td>M</td>
<td>Air</td>
<td>No visible cracking</td>
</tr>
<tr>
<td>L/0.35/HM/10/C1</td>
<td>5</td>
<td>M</td>
<td>Moist</td>
<td>No visible cracking</td>
</tr>
<tr>
<td>L/0.5/HM/20/C3</td>
<td>24</td>
<td>M</td>
<td>Dry</td>
<td>Minor cracking</td>
</tr>
<tr>
<td>L/0.25/HL/0/C1</td>
<td>1</td>
<td>L</td>
<td>Moist</td>
<td>No visible cracking</td>
</tr>
<tr>
<td>L/0.35/HL/10/C3</td>
<td>20</td>
<td>L</td>
<td>Dry</td>
<td>No visible cracking</td>
</tr>
<tr>
<td>L/0.5/HL/20/C2</td>
<td>12</td>
<td>L</td>
<td>Air</td>
<td>Minor cracking</td>
</tr>
</tbody>
</table>

* Beam 16 spalled explosively and a heating element failed during testing beam v3

Table 7 shows a summary of the observations for all the plain and reinforced beams subjected to a regime of curing prior to testing of RH of 85, 65 and 45% respectively. The fibre concrete beams, cured at a nominal 100% RH, are also shown for comparison. Again the Table has been laid out to show the types of aggregate concrete together to facilitate comparison of the
beam condition of all the beams tested including the plain concrete beams tested prior to curing at the lower RH shown in Table 6.

Table 7
Observations for all beams tested after curing at 85, 65 & 45% RH (the beams that failed violently are shown in bold italic print)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Rate of heating</th>
<th>Plain Concrete (RH of beams C1 = 85%, C2 = 65% &amp; C3 = 45%)</th>
<th>Reinforced Concrete (RH = 85%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Limestone concrete</td>
<td>Fibre Concrete</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>H</td>
<td>Explosion C2, W/C=0.5</td>
<td>Failed on cooling (FOC)</td>
</tr>
<tr>
<td>8+</td>
<td>H</td>
<td>Explosion C1, W/C=0.25</td>
<td>FOC</td>
</tr>
<tr>
<td>27*</td>
<td>H</td>
<td>Failed on cooling (FOC)</td>
<td>FOC</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>Cracks at sides (CAS)</td>
<td>CAS Beam hogs (BH)</td>
</tr>
<tr>
<td>23+</td>
<td>M</td>
<td>FOC</td>
<td>Severe cracking (SC)</td>
</tr>
<tr>
<td>15*</td>
<td>M</td>
<td>FOC</td>
<td>FOC</td>
</tr>
<tr>
<td>11+</td>
<td>L</td>
<td>FOC</td>
<td>CAS</td>
</tr>
<tr>
<td>3*</td>
<td>L</td>
<td>FOC</td>
<td>MC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23+</td>
<td>M</td>
<td>Cracks at sides (CAS)</td>
<td>CAS Beam hogs (BH)</td>
</tr>
<tr>
<td>15*</td>
<td>M</td>
<td>FOC</td>
<td>Severe cracking (SC)</td>
</tr>
<tr>
<td>11+</td>
<td>L</td>
<td>FOC</td>
<td>CAS</td>
</tr>
<tr>
<td>3*</td>
<td>L</td>
<td>FOC</td>
<td>MC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>H</td>
<td>Explosion C1, W/C=0.35</td>
<td>FOC</td>
</tr>
<tr>
<td>26+</td>
<td>H</td>
<td>FOC</td>
<td>CAS</td>
</tr>
<tr>
<td>18*</td>
<td>H</td>
<td>FOC</td>
<td>CAS Beam sags (BS)</td>
</tr>
<tr>
<td>22</td>
<td>M</td>
<td>Explosion C3, W/C=0.35</td>
<td>FOH</td>
</tr>
<tr>
<td>14+</td>
<td>M</td>
<td>FOC</td>
<td>CAS (BH)</td>
</tr>
<tr>
<td>6*</td>
<td>M</td>
<td>FOC</td>
<td>CAS (BS)</td>
</tr>
<tr>
<td>10</td>
<td>L</td>
<td>CAS</td>
<td>CAS (BS)</td>
</tr>
<tr>
<td>2*</td>
<td>L</td>
<td>FOC</td>
<td>CAS (BS)</td>
</tr>
<tr>
<td>21*</td>
<td>L</td>
<td>FOC</td>
<td>CAS (BS)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>H</td>
<td>Explosion C3, W/C=0.25</td>
<td>CAS (BH)</td>
</tr>
<tr>
<td>17+</td>
<td>H</td>
<td>FOC</td>
<td>Failed on heating (FOH)</td>
</tr>
<tr>
<td>9*</td>
<td>H</td>
<td>FOH</td>
<td>Explosion C1, W/C=0.25</td>
</tr>
<tr>
<td>13</td>
<td>M</td>
<td>CAS</td>
<td>CAS (BH)</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>FOC</td>
<td>CAS (BS)</td>
</tr>
<tr>
<td>24*</td>
<td>M</td>
<td>FOC</td>
<td>CAS (BS)</td>
</tr>
<tr>
<td>1</td>
<td>L</td>
<td>CAS</td>
<td>CAS (BH)</td>
</tr>
<tr>
<td>20+</td>
<td>L</td>
<td>FOC</td>
<td>CAS (BS)</td>
</tr>
<tr>
<td>12*</td>
<td>L</td>
<td>FOC</td>
<td>CAS (BS)</td>
</tr>
</tbody>
</table>

*Beams were loaded to 20% of cold strength prior to heating
+Beams were loaded to 10% of cold strength prior to heating
Glossary: FOC = Failed on cooling; FOH = Failed on heating; CAS = Cracks along sides, SC = Severe cracking at top and bottom, MC = Minor cracking at top and bottom
(BS) = beam sags at end of test, (BH) = Beam hogs at end of test.
Table 8 shows Table 7 rearranged for the plain and reinforced concrete beams, in the order of rate of heating since this was observed to be the most predominant factor in causing violent failure in subsequent analysis.
Table 8
Observations for plain and RC beams rearranged in heating rate order (the beams that failed violently are shown in bold italic print)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Plain Concrete (Wo-Wt) kg!</th>
<th>Remarks</th>
<th>Reinforced Concrete (Wo-Wt) kg!</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low heating rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>CAS</td>
<td>CAS (BH)</td>
<td>CAS (BH)</td>
<td></td>
</tr>
<tr>
<td>2+</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>3*</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BH)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>CAS</td>
<td>CAS</td>
<td>CAS (BH)</td>
<td></td>
</tr>
<tr>
<td>11+</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>12*</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>CAS</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>20+</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>21*</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>Medium heating rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CAS</td>
<td>CAS</td>
<td>CAS (BH)</td>
<td></td>
</tr>
<tr>
<td>5+</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>6*</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
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<tr>
<td>13</td>
<td>CAS</td>
<td>CAS</td>
<td>CAS (BH)</td>
<td></td>
</tr>
<tr>
<td>14+</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BH)</td>
<td></td>
</tr>
<tr>
<td>15*</td>
<td>FOC</td>
<td>5.82</td>
<td>Explosion C2, W/C=0.35</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>5.51</td>
<td>Explosion C3, W/C=0.35</td>
<td>CAS</td>
<td></td>
</tr>
<tr>
<td>23+</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BH)</td>
<td></td>
</tr>
<tr>
<td>24*</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>High heating rate</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7.64</td>
<td>Explosion C1, W/C=0.35</td>
<td>6.37</td>
<td>Explosion C1, W/C=0.35</td>
</tr>
<tr>
<td>8+</td>
<td>8.14</td>
<td>Explosion C1, W/C=0.25</td>
<td>6.12</td>
<td>Explosion C1, W/C=0.25</td>
</tr>
<tr>
<td>9*</td>
<td>FOH</td>
<td>3.49</td>
<td>Explosion C1, W/C=0.5</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>7.36</td>
<td>Explosion C2, W/C=0.5</td>
<td>5.20</td>
<td>Explosion C2, W/C=0.5</td>
</tr>
<tr>
<td>17+</td>
<td>FOC</td>
<td>4.14</td>
<td>Explosion C2, W/C=0.35</td>
<td></td>
</tr>
<tr>
<td>18*</td>
<td>FOC</td>
<td>CAS</td>
<td>CAS (BS)</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>6.4</td>
<td>Explosion C3, W/C=0.25</td>
<td>4.53</td>
<td>Explosion C3, W/C=0.35</td>
</tr>
<tr>
<td>26+</td>
<td>FOC</td>
<td>CAS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27*</td>
<td>FOC</td>
<td>4.53</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

! Wo–Wt = Weight before test less weight after test of intact pieces of concrete
Note C1 was curing at 85%, C2 at 65% & C3 at 45% RH.

Table 9 shows the highest expansions for the 3 series of tests after heating to 700°C at different rates of heating and maintained at this temperature for a period. For the beams that exploded, the expansions were taken just before failure and the expansions are shown in italic bold print in the Table. The mean expansion at the three rates of heating for the three types of concrete beams are also given as is the overall mean expansion for each of the three types of concrete beams in bold print. Those beams that exploded were not included in the averaging.
### Table 9

Highest expansions in mm for all beams tested (Values in bold italic taken prior to explosive spalling)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Rate of heating</th>
<th>Plain Concrete (RH of beams C1 = 85%, C2 = 65% &amp; C3 = 45 %)</th>
<th>Reinforced Concrete</th>
<th>Fibre Concrete (RH = 85%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RH of beams C1 = 85%, C2 = 65% &amp; C3 = 45 %)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>H</td>
<td>1.59</td>
<td>2.12</td>
<td>9.32</td>
</tr>
<tr>
<td>8+</td>
<td>H</td>
<td>1.49</td>
<td>2.38</td>
<td>7.43</td>
</tr>
<tr>
<td>27*</td>
<td>H</td>
<td>9.62</td>
<td>1.78</td>
<td>9.30</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>9.62</td>
<td>-</td>
<td>8.68</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>9.75</td>
<td>8.69</td>
<td>9.16</td>
</tr>
<tr>
<td>23+</td>
<td>M</td>
<td>10.10</td>
<td>8.23</td>
<td>10.68</td>
</tr>
<tr>
<td>15*</td>
<td>M</td>
<td>9.29</td>
<td>2.37</td>
<td>7.81</td>
</tr>
<tr>
<td>Mean</td>
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<td>9.71</td>
<td>8.46</td>
<td>9.31</td>
</tr>
<tr>
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<td>L</td>
<td>9.87</td>
<td>8.25</td>
<td>9.35</td>
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<tr>
<td>11+</td>
<td>L</td>
<td>9.2</td>
<td>5.84</td>
<td>8.45</td>
</tr>
<tr>
<td>3*</td>
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<td>8.39</td>
<td>8.95</td>
<td>7.37</td>
</tr>
<tr>
<td>Mean</td>
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<td>9.15</td>
<td>7.68</td>
<td>8.39</td>
</tr>
<tr>
<td>O/A Mean</td>
<td></td>
<td>9.46</td>
<td>7.99</td>
<td>8.76</td>
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<tr>
<td>Modified concrete</td>
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<td></td>
</tr>
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<td>7</td>
<td>H</td>
<td>1.37</td>
<td>1.96</td>
<td>7.44</td>
</tr>
<tr>
<td>26+</td>
<td>H</td>
<td>10.31</td>
<td>7.7</td>
<td>9.76</td>
</tr>
<tr>
<td>18*</td>
<td>H</td>
<td>9.30</td>
<td>8.27</td>
<td>6.68</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>9.81</td>
<td>7.99</td>
<td>7.96</td>
</tr>
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<td>M</td>
<td>2.03</td>
<td>7.52</td>
<td>11.12</td>
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<td>7.91</td>
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<td>10.22</td>
<td>7.06</td>
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<td>8.28</td>
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<td>L</td>
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<td>8.83</td>
<td>5.93</td>
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<td>7.93</td>
<td>8.42</td>
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<tr>
<td>Lightweight aggregate concrete</td>
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<td></td>
<td></td>
</tr>
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<td>25</td>
<td>H</td>
<td>1.99</td>
<td>7.95</td>
<td>9.62</td>
</tr>
<tr>
<td>17+</td>
<td>H</td>
<td>9.64</td>
<td>1.67</td>
<td>10.22</td>
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<td>9*</td>
<td>H</td>
<td>6.99</td>
<td>1.79</td>
<td>8.63</td>
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<tr>
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<td>9.49</td>
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<td>6.80</td>
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<td>9.66</td>
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<td>5+</td>
<td>M</td>
<td>9.16</td>
<td>7.64</td>
<td>9.46</td>
</tr>
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<td>M</td>
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<td>L</td>
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<td>8.59</td>
<td>9.98</td>
</tr>
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<td>12*</td>
<td>L</td>
<td>7.40</td>
<td>7.83</td>
<td>8.32</td>
</tr>
<tr>
<td>Mean</td>
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<td>5.94</td>
<td>8.32</td>
<td>9.20</td>
</tr>
<tr>
<td>O/A Mean</td>
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<td>7.00</td>
<td>7.84</td>
<td>9.32</td>
</tr>
</tbody>
</table>

### 5.2 PROPERTIES OF CONCRETE

The properties of concrete at ambient temperature of the beams tested at elevated temperature are given in appendix 1. Tables A1.1 to A1.3 gives the nine mix proportions and the 28-day concrete strength of the normal, modified normal and the lightweight aggregate concrete used in the tests. The control cube strength of the concrete and the compressive and flexural strength at day of testing are shown on Tables A1.4 & A1.5. Figure A1.1 shows the capillary
5.3 PROCESSED RESULTS

Typical lateral displacement thermal cycles of the plain, reinforced and fibre lightweight concrete are given in Figure 3. Figure 4 shows typical deflection thermal cycles of beams that deteriorated during the heating cycle.

Figure 5 gives typical lateral displacement thermal cycles of the plain and reinforced limestone concrete and Figure 6 shows typical deflection thermal cycles of beams that deteriorated during the heating cycle.

Figures 7 and 8 give typical lateral displacement and deflection relationships with furnace temperature of the plain and reinforced limestone concrete beams prior to explosion.

Typical processed results of heating and cooling cycles showing furnace temperature, time from start of heating together with lateral displacements and deflections of the beams are presented in appendix 2. The heat cycles are accompanied by plots of temperature against deformations with attendant sketches of transducer locations in relation to the beam.

Appendix 3 shows typical temperature distribution contours for the limestone concrete at discreet time periods after beginning of heating for all three rates of heating averaged along the longitudinal axis of the specimen.

Appendix 4 shows a typical fractional factorial analysis for the plain concrete series of tests, where the beams were cured at 65%, 45% & 0% RH prior to heating. Although there is a great deal of statistical and arithmetical work in deriving the Tables, the procedure is programmed on Microsoft excel so that any other result selected can be very easily analysed.
6. DISCUSSION

6.1 THERMAL CYCLES

The thermal cycles shown in Figures 3, 5 & 7 (and Figures A2.2 & A2.3 in appendix 2) comprise three separate parts. During heating the lateral displacements increase quasi-linearly initially. These lateral displacements or beam expansions include an element of thermal coefficient of expansion together with an element of shrinkage as the concrete loses its moisture. At a certain temperature these expansions become non-linear and the expansion rate starts increasing perceptibly. This increase is due to concrete deterioration. As the testing temperature is reached and maintained at this high temperature further expansion occurs indicating increased deterioration. This increased expansion at peak temperature is more pronounced at the fast rate rather than at the low rate of heating as the concrete temperature lags much more behind that of the furnace temperature. During cooling a curve similar to heating emerges, displaced in the positive direction or by the amount of the accumulated overall crack widths of the beam.

As expected the mean expansion of the plain limestone concrete beams was higher than that of the modified normal and the latter expanded more than the lightweight concrete beams as observed in Table 9. This was not the case for the reinforced concrete beams, which exhibited similar and smaller mean expansions at 700°C for the limestone and modified concrete indicating that the steel reinforcement even at this high temperature is restraining cracking. However the mean dilations of the plain lightweight (LWA) concrete beams was lower than that of the LWA reinforced concrete and still lower than that of the LWA fibre concrete beams. This indicates that both the steel and particularly the fibres, which have higher thermal coefficients than the LWA concrete, introduce incompatibilities in movement between the LWA concrete and the fibres at these elevated temperatures. This was observed by the residual extensive micro cracking on the surface of the lightweight aggregate fibre concrete beams after heat cycling.

The deflections go through quite a different cycle to that for expansions (see Figures 4, 6 & 8 and Figures A2.5, A2.6 & A2.7) in Appendix 2. As the furnace temperature is higher from top to bottom, the beams particularly the unloaded ones begin to hog. With further heating the concrete temperature becomes more uniform and the hogging starts to decrease until the creep deflections due to the applied loading and/or self weight start to predominate and the cracked beam starts sagging. When the furnace is turned off the lid is open slightly. The higher temperature on the upper surface of the beams flows towards the cooler lower surface and to the outside reversing the hogging trend and the beam continues to sag.

A number of phenomena can be recognised during the deflection thermal cycling. When the scale of the deflections is increased, it will be observed that the hogging during heating seems to reduce at furnace temperatures of 200°C to 300°C and at around 400°C. These furnace temperatures approximate to an average concrete temperature of 100°C to 150°C and 200°C respectively. This coincides with temperatures when the loss of evaporable moisture and gel pore water start to evaporate and these curves are very similar to those produced when the loss in weight of concrete beams is weighed during transient heating (1). A dip is observed in the deflections at around 600°C (550°C concrete temperature) during heating and again at 550°C during cooling. These reflect the calcium hydroxide in the cement matrix dehydrating during heating and re-hydrating during cooling and contribute to additional movements and further deterioration.
6.2 EXPLOSIVE SPALLING FOR PLAIN AND REINFORCED CONCRETE

The beams never reached the peak temperature of 700°C when they failed violently. Explosive spalling normally occurred after 27 to 50 minutes at a furnace temperature varying from around 400°C to 600°C, the explosions being more violent at the higher temperature. This latter temperature is associated with moisture/vapour dissipating within the gel pores. It can be observed in Table 9 and in the appendix that the expansion prior to explosion was always less than those which did not explode indicating that they were either more intact at this temperature or the expansion was restrained. Either of these effects would have increased the built-in internal strain energy leading to the violent failure, when a small flaw developed in the concrete during this period.

When the beams were cured at a relative humidity of 45% only three (3) of the 108 beams tested exploded. However when the relative humidity was above 65% all types of concrete were susceptible to explosive spalling (10 of the 13 that exploded) with the limestone concrete (6 out of 10) being more affected than the other two concrete types (Table 7). One of the beams which was cured at 65% that exploded was one of a set belonging to the series which were cured at the lower relative humidity (Table 6).

The other predominant factor for explosive spalling was the rate of heating as indicated in Table 8. Ten (10) from 54 beams exploded at a high rate of heating, only 3 from 81 beams exploded at a medium rate of heating but none of the beams exploded at the low rate of heating.

The water cement ratio (W/C) of the beams that exploded was not a major factor in explosive failure as the surface absorption of each type of concrete was not vastly dissimilar. Table A 1.4 in appendix 1 shows that the capillary rise values of some of the 0.35 W/C for the air cured concrete, were marginally higher than the other two types of concrete.

For plain concrete only one (1) of the 6 beams that exploded was loaded. The beam that exploded did so at a higher temperature than the others and was loaded with 10% of the initial failure load. This explosion was very violent as evidenced from the high loss in material after the explosion (Table 9). The weight of material loss can be taken as the violence of the explosion. Initial loading before heating could prematurely crack the concrete, which relieves high strain energy built-in within the concrete prior to explosive failure. Cracking may not have taken place for the loaded concrete beam, which exploded.

For reinforced concrete only 2 of the 7 beams that exploded were unloaded. The reinforcing steel prevented initial cracking and could have also added an additional restraint increasing the internal strain energy prior to failure. It may be recalled that the steel reinforcing bars had steel plates welded at their ends, for supporting the cage during casting.

None of the 27 fibre concrete beams failed explosively.

6.3 DETERIORATION OF BEAMS AFTER THERMAL CYCLING

All the beams deteriorated when subjected to these high temperatures as indicated in Tables 6, 7 and 8. The beams initially hogged before sagging on cooling. A number of concrete and fibre beams especially those that were preloaded before heating, failed by breaking during cooling and two fibre beams failed during heating. Those that did not fail suffered minor to severe cracking and some exhibited large deflections. A number of the fibre concrete beams remained intact after failure, even though they exhibited extensive micro cracking on the surface.
The reinforced concrete beams also remained intact after cooling with the preloaded beams sagging or returning to the original flat position, and the unloaded beams hogging. All these beams exhibited flexural cracking along the sides. Cracks also developed near the ends where the steel plates were located.

The highest expansion at 700°C in Table 9 represents contributions from the thermal coefficient of expansion, shrinkage effects and part accumulated cracks within the beams due to incompatibilities in movement of the aggregate and the matrix together with micro-cracking within the cement paste. _Hence these expansion values can be taken as criteria for assessing deterioration of the different types of concrete._

Comparing the deterioration for each type of concrete at the three rates of heating (Table 9), the following can be observed:

- For all the plain concrete beams the high rate of heating appears to create more damage than the lower rates, particularly to the LWA concrete.
- For the reinforced concrete beams the trend appears to be reversed possibly due to the increased period within the furnace increasing the steel temperature. But the reversal is not conclusive as all the reinforced limestone concrete beams at high rate of heating exploded.
- There is no clear trend for the effect of heating on the damaging effect on fibre concrete.
- For the plain concrete beams cured at the lower relative humidity, only one beam exploded and it was possible to take the expansions at peak temperature at the same instant of time for the relevant heating rate. These expansions were converted into strains by dividing them by the average concrete temperature and length of the beams, as explained in Section 4.3.

6.4 DAMAGE ASSESSMENT

6.4.1 Explosive spalling

The criterion for assessing the factors influencing explosive spalling was based on the weight of intact concrete remaining after failure. Although only 6 plain concrete and 7 reinforced concrete beams exploded, analyses of variance exposed interesting differences in the factors influencing explosive spalling as indicated in Table 10 and in Figure 9.

Figure 9 showing all the factors for the plain concrete beams plotted against levels indicate that heating rate and loading influenced explosive spalling. A low heating rate produced the lowest number (actually 0) increasing exponentially with heating rate. Unloaded beams resulted in the highest number of explosive spalling, this effect decreasing non-linearly with loading, no explosions occurring at the highest load. The Table of significance indicates that a change of factor level for heating is significant to >95% and for loading this is significant to >>90%. Although the other factors seem to vary with level, the analysis of variance (ANOVA) indicates no significance i.e. below 90%. _It will be recalled that a change in factor level which influences the overall average to a level of greater than 90%, has a probability lower than 10% of being due to the error of the experiment._
Table 10
ANOVA Significance for explosive spalling for the plain and RC beams

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Plain concrete</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Curing)</td>
<td>-</td>
<td>&gt;90</td>
</tr>
<tr>
<td>B (Heating)</td>
<td>&gt;95</td>
<td>&gt;&gt;99</td>
</tr>
<tr>
<td>C (Loading)</td>
<td>&lt;95</td>
<td>-</td>
</tr>
<tr>
<td>D (W/c)</td>
<td>-</td>
<td>&gt;95</td>
</tr>
<tr>
<td>E (Aggregate)</td>
<td>-</td>
<td>&gt;&gt;95</td>
</tr>
</tbody>
</table>

Figure 9 showing all the significant factors for the reinforced concrete beams plotted against levels indicate that curing, heating rate, W/C and aggregates influenced explosive spalling. Curing at 45% RH (level 2) gave the lowest probability of violent failure increasing non-linearly and levelling off at a point above 65%. The significance in the change of level in RH was > 90%. Again no explosions are indicated at the low heating rate increasing exponentially with rate, the significance for this factor being >>99%. The water cement ratio gave an interesting non-linear effect with 0.35 W/C as a maximum.

The significance in the change of level in W/C was > 95%. The limestone concrete was the most susceptible to explosive spalling with a minimum occurring between the lightweight aggregate and the modified normal concrete, the significance for this factor being >>95%.

One factor to note was that the mixes with a W/C of 0.35 were more susceptible to explosive spalling. Noting the comments on the mortar fraction of these mixes, a more compact concrete with a smaller gel pore structure and also a lower internal permeability. Thus during heating, the vapour pressure in the pores increases, which increases the stresses arising within the gel structure of the concrete. Hence the internal strain energy leading to a greater propensity for explosion than the more permeable mixes.

6.4.2 Deterioration

The criterion for assessing the factors influencing deterioration in the experiment where explosive spalling did not take place, was based on the maximum dilation of all the beams in the fractional factorial experiment with fictitious extrapolated expansion values given to the beams that exploded for the plain concrete. For the RC beams actual expansion values were taken for the beams prior to explosion. Some of the factors influencing deterioration as they change from one level to another are shown in Figure 10 and the significance of their effect shown in Table 11.

Table 11
ANOVA Significance for deterioration for the plain, reinforced and fibre concrete beams

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Plain concrete</th>
<th>RC</th>
<th>Fibre concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Curing)</td>
<td>-</td>
<td>&gt;90</td>
<td>Not applicable</td>
</tr>
<tr>
<td>B (Heating)</td>
<td>&lt;95</td>
<td>&gt;&gt;99</td>
<td>&lt;90</td>
</tr>
<tr>
<td>C (Loading)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D (W/c)</td>
<td>-</td>
<td>&gt;95</td>
<td>&gt;&gt;95</td>
</tr>
<tr>
<td>E (Aggregate)</td>
<td>&gt;&gt;95</td>
<td>&gt;95</td>
<td>&lt;90</td>
</tr>
<tr>
<td>F (Fibre)</td>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 10 showing some of the significant factors for the plain concrete beams plotted against levels indicate that heating rate and aggregate type influenced deterioration. A low heating rate produced the lowest deterioration, increasing quasi linearly with heating rate. The LWA concrete (level 0) beams were the least deteriorated followed by the modified normal and the limestone concrete. The significance of these two factors was <95% and >>95% respectively.

Figure 10 also showing some of the significant factors for the reinforced concrete beams plotted against levels indicate that curing, heating rate, W/C and aggregates also influenced deterioration but in a different way to explosive spalling. Sometimes the effect was completely reversed. Curing at 45% RH (level 2) gave the highest probability (lowest for explosive spalling) of deterioration decreasing non-linearly and levelling off at a point above 65%. The significance in the change of level in RH was > 90%. Deterioration was highest (lowest for explosive spalling) at the low heating rate decreasing non-linearly with increasing rate, the significance for this factor being >>99%. The water cement ratio gave an interesting non-linear effect for deterioration with 0.35 W/C as a minimum (maximum for explosive spalling). The significance in the change of level in W/C was > 95%. The modified normal concrete (level 2) was the most susceptible to deterioration (the least for explosive spalling) showing a maximum along a curve with a decreasing susceptibility towards the lightweight aggregate and the limestone concrete, the significance for this factor being >>95%.

Figure 11 also shows, that for fibre concrete, the only factor which appeared significant to a value of >>95% in influencing deterioration was W/C ratio. The significance of rate of heating and type of aggregates on deterioration of fibre concrete was just below 90%, which statistically is not significant.

The order of damage assessment for the plain concrete beams cured at 65%, 45% and 0% can be seen by inspection of the average of the main effects in the fractional factorial Table in appendix 4. The average estimated irreversible expansions of the limestone, modified and lightweight aggregate concrete are 14.9, 13.7 and 8.8, micro-strain /°C, in the order of damage to the concrete. The other factors appear to have some non-linear effect and the significance of these changes is given in the ANOVA Table. The strains of the significant factors are plotted against level in Figure A4.1 also in appendix 4.

The ANOVA Table is partly reproduced in Table 12 and shows the significance of each factor with a change in level using overall strains as a criterion for deterioration.

<table>
<thead>
<tr>
<th>SIGNIFICANCE %</th>
<th>Plain concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACTOR</td>
<td></td>
</tr>
<tr>
<td>A (Curing)</td>
<td>-</td>
</tr>
<tr>
<td>B (Heating)</td>
<td>&gt;99</td>
</tr>
<tr>
<td>C (Loading)</td>
<td>&gt;90</td>
</tr>
<tr>
<td>D (W/c)</td>
<td>&gt;95</td>
</tr>
<tr>
<td>E (Aggregate)</td>
<td>&gt;&gt;99</td>
</tr>
</tbody>
</table>

Figure A4.1 shows that deterioration increased from LWA to Limestone concrete, the change being significant to >>99%. Deterioration was highest at a W/C of 0.35 decreasing towards the 0.25 and 0.5 W/C ratio being significant to 95%. This was in agreement with the plain concrete tested at the higher RH. Deterioration also increased linearly with loading (significance >>90%) and heating created the higher damage at the low and medium rate of heating and lowest damage at the high heating rate, being significant to 99%.
The time taken for the furnace to reach 700°C for the different rates of heating was longest for the slow rate. For this reason the average concrete temperature for the lower rate of heating, when the furnace first reached 700°C was generally higher. At this instant therefore the concrete in each beam was subjected to a longer heating period. This meant that the temperature of the steel reinforcing bars reached a higher temperature as well. This accounts for the effect on the reinforced concrete beams which became more deteriorated at the lower rate of heating unlike the plain concrete beams, which were marginally more damaged at the faster rate of heating. The effect of steeper temperature gradients due to the higher rate of heating seems to have a more deteriorating effect on the plain concrete than the reinforced concrete.

The intensity of damage for the plain concrete beams in the first series of tests (see Table 6) indicated that the cracks in the limestone concrete were more severe and deeper than for the modified and limestone concrete after the heat cycle. This confirms the damage assessment above. This was also observed in the plain concrete beams cured at the higher RH shown in Table 7 although the LWA and modified concrete exhibited intensive surface crazing. Moreover Tables 6, 8 & 9 indicate that the lightweight aggregate concrete to be the least damaged on the criterion of overall expansion values at 700°C. Reinforced limestone concrete was also more susceptible to explosive spalling, but neither the lightweight nor the modified normal concrete was immune from violent failures, when the right combination of factors prevailed.

Early deterioration produces cracking, which tends to relieve internal strain energy reducing the possibility of explosive spalling and partly explains the reason for the factors which increase deterioration also reduce the chances of explosive spalling. The other factor is lateral restraint, which was imposed by thermal gradients imposed by the furnace heating. Although such restraint could prevent cracks opening out during heating thus reducing deterioration, these restraints increase the built-in stresses within the concrete. This increases the built-in strain energies, which increases the violence in failure, when this strain energy is suddenly released through a small flaw in the concrete.

6.5 THERMAL CONTOURS

The thermal distributions of the limestone concrete beams show similar patterns for all the three rates of heating except that the peak temperatures are reached earlier for the high rate. Local cold spots are apparent, which are associated with cooling as moisture in the pores within the cement matrix start to evaporate. These cold spots change in character during heating and in the beams that do not explode tend to disappear. The furnace heating produced a higher temperature in the central portion than the ends particularly at the higher rate of heating, which produces a certain amount of internal lateral restraint to the beam. This effect together with the pressures within these local cold spots increase stresses within the gel structure, which in their turn increase the built in strain energy. The higher strength concrete with the stronger gel structure, which behaves as a rigid continuum can support higher strain energies before failure. If a part of the microstructure suddenly fails, the sudden release of energy causes explosive spalling. If, on the other hand, while the beam is being heated visible cracks appear due to loading or other imposed stresses, the gel structure is no longer continuous and the cracks dissipate the energy. In this case cracking or normal spalling may occur but it is unlikely that explosive spalling will take place.
7. CONCLUSIONS

7.1 DETERIORATION

Deterioration of the different types of concrete was all influenced by the factors shown in Table 13, but not in the same manner. Comments below and in the Table have only been made on the factors, which have been assessed by an analysis of variance (ANOVA) to be significant.

- A change in curing did not affect deterioration of concrete but there was a large difference in deterioration for the reinforced concrete from around 60% to 85%.
- Deterioration increased linearly slightly with increasing rate of heating for the plain concrete, but decreased non-linearly when the concrete was reinforced.
- Deterioration was at a minimum for reinforced concrete at 0.35. There was a tendency for deterioration to be a maximum for the plain concrete but this was not statistically significant.
- For the aggregate factor, there was a faster increase in deterioration from plain LWA concrete to modified normal (MN) than from MN to limestone whereas for the reinforced concrete, where modified concrete showed a maximum, deterioration decreased towards LWA and limestone reinforced concrete.

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Plain concrete</th>
<th>Plain concrete</th>
<th>RC</th>
<th>Fibre concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Curing)</td>
<td>-</td>
<td>-</td>
<td>60% to 85% RH*</td>
<td>Not applicable</td>
</tr>
<tr>
<td>B (Heating)</td>
<td>Low to high rate</td>
<td>-</td>
<td>High to low rate</td>
<td>-</td>
</tr>
<tr>
<td>C (Loading)</td>
<td>Linear increase</td>
<td>-</td>
<td>Minimum at 0.35</td>
<td>Minimum at 0.35</td>
</tr>
<tr>
<td>D (W/C)</td>
<td>Maximum at 0.35</td>
<td>Maximum at 0.35</td>
<td>Maximum</td>
<td>Modified</td>
</tr>
<tr>
<td>E (Aggregate)</td>
<td>LWA to limestone</td>
<td>LWA to limestone</td>
<td>Maximum</td>
<td>Modified</td>
</tr>
<tr>
<td>F (Fibre)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*a slight increase in deterioration at 45% RH

It should be observed that the plain concrete beams initially tested after curing the mixes at 65%, 45% and 0% RH confirmed the order of deterioration for the aggregate, heating rate and W/C factors in Table 11. The order of the deterioration for the former concrete, which was significant, with increase in loading was not so for the plain concrete cured at the higher curing rates.

For the fibre concrete the only significant factor, which affected deterioration was W/C with a minimum at 0.35, slightly tailing away at 0.25 and at a faster rate towards 0.5. A similar trend was also noticeable for plain concrete but this factor was not statistically significant. For the reinforced concrete, this trend was reversed indicating a minimum deterioration at a W/C of 0.35 with the 0.25 and 0.35 W/C increasing equally in deterioration. This apparent anomaly may be accounted for in the 0.35 mixes having a higher mortar fraction than the other mixes making the 0.35 concrete more compact.

7.2 EXPLOSIVE SPALLING

Explosive spalling of the plain and reinforced concrete was also influenced by all the factors shown in Table 14, but again not in the same manner. Comments below and in the Table have only been made on the factors, which have been assessed by an analysis of variance (ANOVA) to be significant.
The following comments apply to the plain and reinforced & fibre concrete beams:

- Curing conditions did not appear to affect explosive spalling in plain concrete beams, but the reinforced concrete beams were more susceptible to explosive spalling between 85% and 65% and reduced considerably at 45%.
- Heating rate increased the chances of explosive spalling from the medium to high rate of heating for both plain and reinforced concrete, no explosions taking place at the low rate.
- Loading decreased the chance of explosive spalling to plain concrete, but did not have any effect on reinforced concrete.
- A W/C ratio of 0.35 appeared to be the most susceptible for reinforced concrete to explode, with the susceptibility decreasing towards a ratio of 0.25 and 0.5. For plain concrete a W/C of 0.35 and 0.25 had a greater possibility of explosion than that with a W/C of 0.5, but this was however, not statistically significant.
- Reinforced limestone concrete had a greater inclination to fail violently. This reduced with modified and then slightly increased with LWA reinforced concrete. The aggregate type did not statistically significantly affect plain concrete, although the modified mixes appear to be the least affected.
- Only one explosion occurred for the plain concrete cured at the lower RH. This occurred on a limestone concrete beam with a W/C of 0.35, cured at 65% heated at the high rate with no load applied.
- No explosions took place on any of the fibre concrete beams even though they were cured at a nominal RH of 100% prior to testing.

### Table 14

<table>
<thead>
<tr>
<th>Factor</th>
<th>Plain concrete</th>
<th>Reinforced Concrete (RC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Curing)</td>
<td>-</td>
<td>60% to 85% RH *</td>
</tr>
<tr>
<td>B (Heating)</td>
<td>Medium to high*</td>
<td>Medium to high*</td>
</tr>
<tr>
<td>C (Loading)</td>
<td>High to low*</td>
<td>-</td>
</tr>
<tr>
<td>D (W/C)</td>
<td>-</td>
<td>Maximum at 0.35</td>
</tr>
<tr>
<td>E (Aggregate)</td>
<td>-</td>
<td>Modified to limestone (slight increase to LWA)</td>
</tr>
</tbody>
</table>

*Note no explosions occurred at the low rate of heating and at high load

Some identical concrete mixes for the plain and reinforced concrete beams failed explosively at the high rate of heating. However, since different factors affected explosive spalling for the plain and reinforced concrete, some of the former with identical mixes to the reinforced concrete beams exploded but not the latter. The reverse also occurred as can be observed in Tables 4 & 5. The factors influencing explosive spalling in Table 11 accounts for the differences occurring in some identical mixes for the two types of concrete not failing violently.

The design of the furnace creates a heating regime, which imposes lateral restraint in addition to local cool spots especially for the high heating rate. The stresses imposed by these effects and by pore pressures are locked in the pore gel structure and can produce quite high strain energies particularly in the higher strength concrete, which can resist failure far longer. When a local defect releases this pent up strain energy a violent failure of the gel structure occurs. This is the mechanism by which the higher strength more compact moist concrete heated at the faster heating rate in conjunction with the various imposed restraints created explosive spalling in our tests.
8. RECOMMENDATIONS

From the conclusions it is recommended that, if high strength concrete is liable to be exposed to transient high temperature, the following should minimise explosive spalling:

- Polypropylene fibres to be added to offshore concrete
- A trade off has to be established between a durable concrete and permeability as impermeable concrete is more susceptible to explosive spalling
- Limestone concrete like gravel concrete used in previous tests by the author (1) should be avoided
- Lightweight aggregate concrete has a great deal to recommend but tests by others under a fuel fire has shown that continuous explosive spalling resulted during heating

Deterioration always occurs during transient heating and again limestone concrete fared worst amongst the aggregates used in the concrete and it is recommended that if basalt aggregates are available, these should be used. Basalt aggregates were not used in the tests, but previous testing by the author, indicated that basalt aggregates performed better than limestone and still better than gravel concrete at transient elevated temperature (5).

The conclusions apply to the rate of heating and the types of aggregates used in the testing and interpolation between the factors is permissible. Although the highest rate of heating was lower than that under a cellulose fire and even lower than that of a fuel fire, the fractional factorial method of experimentation can predict the trend under these situations. The testing indicated that the probability of explosive spalling in reinforced concrete beams increased exponentially with rate of heating and linear extrapolation would therefore be valid.

The remaining factors are conditions, which can occur in practise and the results of deterioration and probability of explosive spalling due to a change of level of the factors investigated, are valid. Interpolation between levels to suit the practical situation being investigated can also be done.

The factors influencing concrete and reinforced concrete affect deterioration in different ways, as explained in the conclusions and care has to be exercised in using data from plain concrete tests for reinforced concrete. It may be recalled that plain and reinforced concrete beams with identical concrete mixes subjected to identical heating rates, were influenced by different degrees of significance. It should be remembered that a higher significance implies a higher probability of the influence of the factor.

A number of factors, which deteriorate concrete at the initial stages of heating, may reduce the chances of explosive spalling. Thus polypropylene fibres, which have much higher expansions than concrete, particularly lightweight aggregate (LWA) concrete, produce a large number of micro-cracks. This suggests that other fibres, which have expansions incompatible with the cement matrix may also alleviate explosive spalling and this will be investigated in future research. Microcracks relieve the built-in strain energies within the concrete alleviating the probability of explosive spalling. However, limestone concrete, which also exhibited higher deterioration than LWA concrete was more prone to explosive spalling.

However it should be stressed that under a combination of adverse factors no type of concrete tested was immune from explosive spalling.

Patrick J E Sullivan
9. REFERENCES


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FIGURES FOR MAIN TEXT
Figure 1
General arrangement of furnace and loading rig (showing instrumentation)

Note: Refer to Figure 1 for the instrumentation and parts to the rig
<table>
<thead>
<tr>
<th>KEY</th>
<th>DESCRIPTION</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Roller</td>
<td>Part of loading saddle</td>
</tr>
<tr>
<td>B</td>
<td>Rocker</td>
<td>&quot;</td>
</tr>
<tr>
<td>C</td>
<td>Roller</td>
<td>Supporting concrete specimens</td>
</tr>
<tr>
<td>D</td>
<td>Rocker</td>
<td>&quot;</td>
</tr>
<tr>
<td>E</td>
<td>Aperture</td>
<td>Monitoring</td>
</tr>
<tr>
<td>F</td>
<td>Screw jack</td>
<td>Load application</td>
</tr>
<tr>
<td>G</td>
<td>Load cell</td>
<td>Load measurement</td>
</tr>
<tr>
<td>H</td>
<td>Cross beam</td>
<td>Load transmission</td>
</tr>
<tr>
<td>I</td>
<td>Beam</td>
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</tr>
<tr>
<td>J</td>
<td>Hangers</td>
<td>&quot;</td>
</tr>
<tr>
<td>K</td>
<td>Deflection bridge</td>
<td>Holding vertical transducers</td>
</tr>
<tr>
<td>L</td>
<td>Column</td>
<td>Supporting horizontal transducer channels</td>
</tr>
<tr>
<td>M</td>
<td>&quot;</td>
<td>Supporting concrete beams on roller C and rocker D</td>
</tr>
<tr>
<td>N</td>
<td>Channel</td>
<td>Supporting horizontal transducers</td>
</tr>
<tr>
<td>P</td>
<td>Transducers</td>
<td>Horizontal and vertical movement measurement</td>
</tr>
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<td>Q</td>
<td>Electric motor</td>
<td>Load application</td>
</tr>
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<td>R</td>
<td>Reduction box</td>
<td>&quot;</td>
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<tr>
<td>S</td>
<td>Channel</td>
<td>Supporting furnace and loading rig</td>
</tr>
<tr>
<td>T</td>
<td>Heating elements</td>
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<tr>
<td>U</td>
<td>Column (wall)</td>
<td>Supporting Channels S</td>
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**Figure 1a Instrumentation and parts to the rig.**

![Sketch of thermocouple positioning within and on beam](image1)

**Figure 2 Positioning of thermocouples used to create temperature distribution graphs**

![Figure 2](image2)
Figure 3 Typical axial expansion / temperature relationship for lightweight plain, reinforced and fibre (FC) concrete beams subjected to identical conditions.
Figure 4 Typical displacement / temperature relationship for lightweight plain, reinforced and fibre beams subjected to identical conditions.
Figure 5 Typical axial expansion / temperature relationship for plain and reinforced limestone concrete beams
Figure 6 Typical displacement / temperature relationship for plain and reinforced limestone concrete beams
Figure 7 Typical axial expansion / temperature relationships for plain and reinforced limestone concrete beams prior to explosive spalling
Figure 8 Typical deflections / temperature relationships for plain and reinforced limestone concrete beams prior to explosive spalling.
Figure 9 Change of factor level with explosive spalling of reinforced concrete (RC) and plain concrete (PC) beams
(Note: probability of explosive spalling is relative to changes in factor level)
Figure 10 Change of factor level with deterioration of reinforced concrete (RC) Plain concrete (PC) and fibre concrete (FC) beams
APPENDIX 1

TRIAL MIX DESIGN DETAILS & PROPERTIES OF CONCRETE USED IN BEAMS TESTED
TRIAL MIX DESIGN DETAILS

Final mix proportions being used for plain and reinforced concrete beams are given in Tables A2.1 to A2.3. The same mixes have been used for the fibre reinforced concrete.

The 28-day strength given in Tables A2-1 to A2-3 represents the average compressive 28-day strength obtained during the final trial mix tests.

Table A1.1
Mix Proportions of Normal Weight Concrete

<table>
<thead>
<tr>
<th>Mix Code No.</th>
<th>N0.50</th>
<th>N0.35</th>
<th>N0.25</th>
</tr>
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<tbody>
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<td>Cement</td>
<td>360.00</td>
<td>366.37</td>
<td>489.55</td>
</tr>
<tr>
<td>Micro Silica</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Limestone</td>
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<td>1099.22</td>
<td>1174.83</td>
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<tr>
<td>Lytag</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sand</td>
<td>501.00</td>
<td>806.03</td>
<td>636.05</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>1.25</td>
<td>7.0</td>
<td>15.15</td>
</tr>
<tr>
<td>Water</td>
<td>193.59</td>
<td>146.53</td>
<td>137.85</td>
</tr>
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<td>28 day Strength</td>
<td>49.70</td>
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<td>98.92</td>
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Table A1.2
Mix Proportions of Modified Normal Weight Concrete

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<td>366.37</td>
<td>431.82</td>
</tr>
<tr>
<td>Micro Silica</td>
<td>-</td>
<td>-</td>
<td>95.96</td>
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<tr>
<td>Limestone</td>
<td>745.25</td>
<td>604.57</td>
<td>662.13</td>
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<td>383.44</td>
<td>311.16</td>
<td>340.78</td>
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<tr>
<td>Sand</td>
<td>501.00</td>
<td>806.03</td>
<td>619.38</td>
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<tr>
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<td>6.75</td>
<td>10.88</td>
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<td>Water</td>
<td>187.82</td>
<td>138.85</td>
<td>147.19</td>
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<tr>
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Table A1.3
Mix Proportions of Light Weight Concrete

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<td>146.75</td>
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Table A1.4

Properties of plain and reinforced concrete at ambient temperature

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<th>Test day Fail. load kN</th>
<th>28 Days Compressive strength N/mm²</th>
<th>Test day Yield load kN</th>
<th>Test day Fail. load kN</th>
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Table A1.5
Properties of fibre concrete at ambient temperature

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<th>Fail. Load kN Test day</th>
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Figure A1.1 Capillary rise of limestone (N), modified normal (M) and LWA (L) concrete
Lytag beam at high heating rate (L/0.35/HH/00/C2)

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Figure A2.1 Diagrammatic representation of silica rods/transducer location in contact with beam in furnace
Figure A2.2
Relationship between axial displacement and third point deflections vs. Average concrete temperature
Beam L/0.35/HH/00/C2

TYPICAL RESULTS – SERIES 2 FIBRECONCRETE TESTS
(Figures follow Table below)

Modified fibre concrete beam high heating rate

Beam (M/0.35/HH/00/F1)

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**Figure A2.3**
Relationship between axial displacement and temperature
Fibre concrete beam M/0.35/HH/00/F1
Figure A2.4
Relationship between support displacements vs. temperature
Fibre concrete beam M/0.35/HH/00/F1

Figure A2.5
Relationship between central deflection vs. temperature
Fibre concrete beam M/0.35/HH/00/F1
Figure A2.6
Relationship between central deflection relative to support vs. temperature
Fibre concrete beam M/0.35/HH/00/F1

Figure A2.7
Relationship between third point deflection vs. temperature
Fibre concrete beam M/0.35/HH/00/F1
APPENDIX 3

HEATING RATES
AND
TEMPERATURE CONTOURS
Figure A3.1
Time - Temperature Curve for High Rate of Heating
Figure A3.2
Time - Temperature Curve for Medium Rate of Heating

Figure A3.3
Time - Temperature Curve for Low Rate of Heating
Heat Distribution during high rate of heating
NO.5 HHC2
Heat Distribution during medium rate of heating

N0.5 HMC2
Heat Distribution during low rate of heating

(N0.5HLC2)
APPENDIX 4

ANALYSES OF VARIANCE (ANOVA) for the plain concrete beams tested after curing at RH of 65%, 45% & 0%
Table A4.1
ANALYSES OF VARIANCE (ANOVA) FOR EXPANSION
Concrete (for equal time exposure at a given rate of heating)

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<td>0% RH</td>
<td>L</td>
<td>00</td>
<td>0.5</td>
<td>N</td>
<td>-0.2</td>
<td>7.2</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td>L</td>
<td>10</td>
<td>0.35</td>
<td>LWA</td>
<td>-1.7</td>
<td>5.7</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td></td>
<td>L</td>
<td>20</td>
<td>0.25</td>
<td>M</td>
<td>-2.9</td>
<td>7.8</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td></td>
<td>M</td>
<td>00</td>
<td>0.35</td>
<td>M</td>
<td>1.2</td>
<td>7.1</td>
<td>14.1</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td></td>
<td>M</td>
<td>10</td>
<td>0.25</td>
<td>N</td>
<td>-0.3</td>
<td>8.8</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td></td>
<td>M</td>
<td>20</td>
<td>0.5</td>
<td>L</td>
<td>-5.3</td>
<td>4.9</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td></td>
<td>H</td>
<td>00</td>
<td>0.25</td>
<td>LWA</td>
<td>-3.3</td>
<td>4.3</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td></td>
<td>H</td>
<td>10</td>
<td>0.5</td>
<td>M</td>
<td>-0.8</td>
<td>6.8</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td></td>
<td>H</td>
<td>20</td>
<td>0.35</td>
<td>N</td>
<td>-0.4</td>
<td>3.4</td>
<td>16.7</td>
</tr>
</tbody>
</table>

The expansions (exp) in the last but one column are the values for each test selected at the same average concrete temperature. These values are overall expansion of each beam when exposed to the same period for a given rate of heating.

The last column gives the strain values per unit temperature by dividing the values in the previous column by the length of the beam and the average concrete temperature. Although these strains have the same units as the thermal coefficient of expansion, they also include strains due to shrinkage or non-reversible expansions due to deterioration.

Table A4.2
Main Effects of individual factors

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUM (Xi)</td>
<td>112.2</td>
<td>119.3</td>
<td>96.0</td>
<td>109.3</td>
<td>79.2</td>
</tr>
<tr>
<td>SUM (Xj)</td>
<td>105.0</td>
<td>121.9</td>
<td>114.5</td>
<td>131.5</td>
<td>122.9</td>
</tr>
<tr>
<td>SUM (Xk)</td>
<td>119.4</td>
<td>95.4</td>
<td>126.1</td>
<td>95.8</td>
<td>134.5</td>
</tr>
<tr>
<td>S(Tot)</td>
<td>336.6</td>
<td>336.6</td>
<td>336.6</td>
<td>336.6</td>
<td>336.6</td>
</tr>
</tbody>
</table>

Xi is any individual factor X at level 0
Xj is any individual factor X at level 1
X_k is any individual factor X at level 2

SUM(X_i) = sum of X_i of all 9 values at level 0 (i.e. for factor A strain values 1-9)
SUM(X_j) = sum of X_j of all 9 values at level 1 (i.e. for factor A strain values 10-18)
SUM(X_k) = sum of X_k of all 9 values at level 2 (i.e. for factor A strain values 18-27)

S(Tot) is the sum of SUM1(X_i), SUM1(X_j) and SUM1(X_k)

Table A4.3
Average of main effects (Values used in Figure A4.1)

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUM (X_i)/9</td>
<td>12.5</td>
<td>13.3</td>
<td>10.7</td>
<td>12.1</td>
<td>08.8</td>
</tr>
<tr>
<td>SUM (X_j)/9</td>
<td>11.7</td>
<td>13.5</td>
<td>12.7</td>
<td>14.6</td>
<td>13.7</td>
</tr>
<tr>
<td>SUM (X_k)/9</td>
<td>13.3</td>
<td>10.6</td>
<td>14.0</td>
<td>10.6</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Table A4.4
Interaction Table

<table>
<thead>
<tr>
<th>COMBIN.</th>
<th></th>
<th>AB</th>
<th>AC</th>
<th>BC</th>
<th>DE</th>
<th>CD</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>X_iY_i (00)</td>
<td>42.3</td>
<td>36.6</td>
<td>33.3</td>
<td>23.8</td>
<td>23.8</td>
<td>23.8</td>
<td></td>
</tr>
<tr>
<td>X_iY_j (01)</td>
<td>38.9</td>
<td>33.8</td>
<td>41.7</td>
<td>41.8</td>
<td>41.1</td>
<td>41.1</td>
<td></td>
</tr>
<tr>
<td>X_iY_k (02)</td>
<td>31.0</td>
<td>41.8</td>
<td>44.2</td>
<td>43.8</td>
<td>31.2</td>
<td>31.2</td>
<td></td>
</tr>
<tr>
<td>X_jY_i (10)</td>
<td>37.5</td>
<td>22.3</td>
<td>38.2</td>
<td>30.8</td>
<td>43.8</td>
<td>30.8</td>
<td></td>
</tr>
<tr>
<td>X_jY_j (11)</td>
<td>42.0</td>
<td>39.0</td>
<td>40.7</td>
<td>41.1</td>
<td>30.8</td>
<td>39.9</td>
<td></td>
</tr>
<tr>
<td>X_jY_k (12)</td>
<td>25.5</td>
<td>43.7</td>
<td>43.1</td>
<td>59.6</td>
<td>39.9</td>
<td>43.8</td>
<td></td>
</tr>
<tr>
<td>X_kY_i (20)</td>
<td>39.4</td>
<td>37.1</td>
<td>24.5</td>
<td>24.7</td>
<td>41.8</td>
<td>24.7</td>
<td></td>
</tr>
<tr>
<td>X_kY_j (21)</td>
<td>41.1</td>
<td>41.8</td>
<td>32.1</td>
<td>39.9</td>
<td>59.6</td>
<td>41.8</td>
<td></td>
</tr>
<tr>
<td>X_kY_k (22)</td>
<td>39.0</td>
<td>40.5</td>
<td>38.8</td>
<td>31.2</td>
<td>24.7</td>
<td>59.6</td>
<td></td>
</tr>
<tr>
<td>Tot S(XY)</td>
<td>336.6</td>
<td>336.6</td>
<td>336.6</td>
<td>336.6</td>
<td>336.6</td>
<td>336.6</td>
<td></td>
</tr>
</tbody>
</table>

X_iY_i (00) is the sum of any factor X at level 0 combined with another factor Y at level 0
X_iY_j (01) is the sum of any factor X at level 0 combined with another factor Y at level 1
X_iY_k (02) is the sum of any factor X at level 0 combined with another factor Y at level 2
Tot S(XY) is the sum of each 2 level interactions in each column. This is numerically equal to S(Tot) as this sum is equivalent to the sum of all the 27 results

Table A4.5
Sum of squares for individual factors

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSX_iX_jX_k/9</td>
<td>4196.3</td>
<td>4196.3</td>
<td>4196.3</td>
<td>4196.3</td>
<td>4196.3</td>
</tr>
<tr>
<td>SSTot/27</td>
<td>4207.9</td>
<td>4243.5</td>
<td>4247.4</td>
<td>4268.5</td>
<td>4384.8</td>
</tr>
<tr>
<td>Sa..Se</td>
<td>12</td>
<td>47</td>
<td>51</td>
<td>72</td>
<td>188</td>
</tr>
</tbody>
</table>

SSX_iX_jX_k/9 is the average sum of squares of the individual factors or
\[ \frac{\{(SUM_X_i)^2+(SUM_Y_j)^2+(SUM_X_k)^2\}}{9} \]
SST/27 is (S(Tot)/27)^2 both from Table A4.2

The difference of these two values gives the average effect of each individual factor from A to E as each changes from one level to the other, on the overall average and are equivalent to the deviance (in statistical terms). These values are shown as Sa...Se in the third row of Table A4.6
and Sa… in column 3 of Table 4.8 The degree of freedom Df of each individual factor i.e. 3 – 1 = 2 is also shown on this latter Table.

### Table A4.6

**Sum of squares for interacting factors**

<table>
<thead>
<tr>
<th></th>
<th>AB</th>
<th>AC</th>
<th>BC</th>
<th>DE</th>
<th>CD</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSX_iY_i</td>
<td>12839.1</td>
<td>12922.0</td>
<td>12909.4</td>
<td>13590.9</td>
<td>13590.9</td>
<td>13590.9</td>
</tr>
<tr>
<td>Saxb</td>
<td>83.4</td>
<td>111.0</td>
<td>106.8</td>
<td>334.0</td>
<td>334.0</td>
<td>334.0</td>
</tr>
<tr>
<td>Sab</td>
<td>24.6</td>
<td>48.4</td>
<td>94.5</td>
<td>73.3</td>
<td>210.8</td>
<td>94.5</td>
</tr>
</tbody>
</table>

SSX_iY_i is the sum of squares of all the two level interactions or:

\[
\{(X_{ii})^2 + (X_{ij})^2 + (X_{ik})^2 + (X_{ji})^2 + (X_{jj})^2 + (X_{jk})^2 + (X_{ki})^2 + (X_{kj})^2 + (X_{kk})^2\}
\]

SSX_iY_i/3-gives the average sum of squares of the interaction factors

\(S(axb) = SSX_iY_i / 3 - SST/27\)

where SST/27 is \((STot/27)^2\) as before

The average effect of the interacting factors (AB say) on the overall average is Sab

Where Sab = Saxb-Sa-Sb. This value is shown as Sab… in column 3 of Table A4.7 to include interactions AB, AC, BC and DE.

The degree of freedom Df of Sab is 4 as the two factor interactions have each a Df of 6-2 = 4 shown in Table A4.7

**ANALYSIS OF VARIANCE TABLE**

The Table below calculates the variance of each individual and interaction factor from the sum of squares already calculated and the degrees of freedom (df) of the factors. From this the variance of the error factor is estimated. If all the factors are assumed to have an effect, the error factor would be 0 as in column 3 and it would not be possible to test for significance. Column 4 assumes that interaction DE cannot be discriminated from the other factors and is the error factor with df = 4 ie 27-1-5(2)-3(4). Column 5 estimates the Fisher factor F for all the factors with the estimated error. F is then compared with values in statistical Tables, reproduced in Table A4.9, which gives the significance of the effect of a change in level for each experimental factor to a given percentage.

It will be observed, as explained in page 65, that in column 5 factor E or the aggregates has the largest numeric Figure i.e. 5.14. This Figure is higher than 4.32 in Table 4.9 indicating 90 % significance, for a Df of 4 for the error (2nd column) and 2 for the factor (2nd row). To improve the discrimination of the results, the numeric value of the Sum of squares of the error factor has to be decreased and its Df increased. This decreases the denominator in F(a) and increases its value making it more sensitive to check for significance. One way of achieving this is to scan down the Variances (V) column and select the smaller values of the factors and interacting factors. These are unlikely to have an effect on the overall average as the smaller the variance of a factor, the lower is the influence the factor has with a change in level and can therefore be assumed to be due to the error. So Error(2) has been chosen as the sum of A (curing) and interaction factor AB.
This is shown in the 6th column of the Table for all the factors and interacting factors not allocated to the error. This increases the values of F(a) with the result that the significance of a change in level of factor E increases and the remaining factors also become significant to better than 90%.

99% is considered extremely significant, 95% very significant and indicates a real effect in a change in factor level. Over 90% can be considered as just significant.

<table>
<thead>
<tr>
<th>Source</th>
<th>Df</th>
<th>Sa...</th>
<th>V</th>
<th>F(a)=V(a)/V(Er1)</th>
<th>F(a)=V(a)/V(Er2)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Curing)*</td>
<td>2</td>
<td>11.61</td>
<td>5.81</td>
<td>0.32</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B (Heating)</td>
<td>2</td>
<td>47.18</td>
<td>23.59</td>
<td>1.29</td>
<td>3.91</td>
<td>90</td>
</tr>
<tr>
<td>C (Load)</td>
<td>2</td>
<td>51.02</td>
<td>25.51</td>
<td>1.39</td>
<td>4.23</td>
<td>&gt;&gt;&gt;90</td>
</tr>
<tr>
<td>D (W/C)</td>
<td>2</td>
<td>72.18</td>
<td>36.09</td>
<td>1.97</td>
<td>5.99</td>
<td>&gt;95</td>
</tr>
<tr>
<td>E (Aggr.)</td>
<td>2</td>
<td>188.48</td>
<td>94.24</td>
<td>5.14</td>
<td>15.63</td>
<td>&gt;99</td>
</tr>
<tr>
<td>AB*</td>
<td>4</td>
<td>24.57</td>
<td>6.14</td>
<td>0.34</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AC</td>
<td>4</td>
<td>48.36</td>
<td>12.09</td>
<td>0.66</td>
<td>2.00</td>
<td>-</td>
</tr>
<tr>
<td>BC</td>
<td>4</td>
<td>8.61</td>
<td>17.78</td>
<td>0.12</td>
<td>2.95</td>
<td>-</td>
</tr>
<tr>
<td>DE=(e)+</td>
<td>4</td>
<td>73.29</td>
<td>18.32</td>
<td>3.04</td>
<td>&lt;90</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Error)1+</td>
<td>4</td>
<td>73.29</td>
<td>18.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Error)2*</td>
<td>6</td>
<td>36.18</td>
<td>6.03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Fisher distributions with the values of significance have been reproduced (17) in extract form as Table A 4.8. Explanation of the Table with an example for assessing significance has also been reproduced from the same publication. In the example and the Table the probability point in the first column is the tail fraction of the complete distribution and the significance derived would therefore be the tail fraction subtracted from the whole distribution (i.e. 1)

In the Table A4.7 Analyses of Variance:

Column 1 shows the source or the factors to be investigated

Column 2 gives the degree of freedom Df of each source. It should be observed that the Df of the complete 27 experiments is 27-1 = 26. If therefore all the sources from A to DE are taken for the analyses, the Df of the error, calculated from (26 - Df) of all the sources, would be 0, as indicated in the last but 2 rows. The calculation procedure includes division by the Df of the error, which would defy analyses. Therefore the next row in the Table assumes DE as the error shown as (Error)1. The reasons for initially choosing this source as the error factor is that with the principal fraction of the factorial experiment selected, the factors towards the end of the Table are more prone to be aliased (or confused with other interactions).

The 3rd column gives the effect of individual Sa... and interacting factor Sab... on the overall average as derived from Tables A4.5 and A4.6.

Dividing the values of the 3rd column by the degree of freedom of each source gives the variance V shown in the 4th column. The higher the variance the greater is the influence of a change in level factor has on the overall average.
The result of this division for Error(1) gives the Fisher factor Fa in the 5th column. A copy of the appropriate page from a Table of statistical data (17) is shown in Table A4.9 below. The calculated values in this column for the Df’s of the factors and the error selected have to be higher than those in the Fisher Table for the percentage of significance quoted in the Table to apply to our results. Comparing the Figures in the 5th column for factor E (5.13) with value (4.32 for 90% significance) in the Fisher Table for the Df’s of the sources and the error selected gives 90% significance for factor E, with the remainder giving inconclusive evidence of significance.

By inspection the variance V for curing is small indicating that a change in the level in curing has little or no influence on the overall average and should be close to 0. Also interaction AB has a low value of V. Therefore these values arising from curing and its interaction with heating can be replaced as the error. This is what has been done in the last row with the result that the Df of (Error)2 has increased and the variance of the error decreased. Since the variance of the error is the divisor in the calculation of F(a), the values in the last but one column increase, thus increasing the sensitivity of the analyses.

The significance in the last column expresses the percentage probability of the effect on a change in level of a source or a factor on the overall average. Traditionally 95% is considered as significant and 99% as highly significant.

Another way of looking at the sequence of the analysis is that the variances are calculated to assess the influence of a change in level of each factor on the average. The next stage (of calculating F(a)) compares this latter influence with that of the error. If the influences are of the same order as the error, then the variation is probably due to the error of the experiment rather than a real effect and the factor is said to be not significant.

Figure A4.1
Change in deterioration with factor level for plain concrete
(RH = 65%, 45% & 0%)
# Table A4.8

## Probability Points of the Variance Ratio (F-Distribution)

| Probability point | ϕ₂ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 12 | 14 | 15 | 20 | 24 | 30 | 40 | 60 | 80 | 100 |
|-------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|------|
| 0.01              | 1  | 3.22 | 4.65 | 5.83 | 6.90 | 7.80 | 8.56 | 9.20 | 9.70 | 10.1 | 10.5 | 11.0 | 11.4 | 11.8 | 12.1 | 12.3 | 12.5 | 12.7 | 12.9 | 13.0 | 13.1 |
| 0.01             | 10 | 29.99 | 37.06 | 42.61 | 47.10 | 50.95 | 54.58 | 57.83 | 60.74 | 63.27 | 65.45 | 67.33 | 68.92 | 70.24 | 71.34 | 72.22 | 73.00 | 73.64 | 74.20 | 74.68 | 75.05 |
| 0.01             | 25 | 105.90 | 125.33 | 134.58 | 143.64 | 152.49 | 160.98 | 169.16 | 176.98 | 184.44 | 191.56 | 198.35 | 204.84 | 210.90 | 216.63 | 221.98 | 226.91 | 231.39 | 235.42 | 238.99 | 242.09 |
| 0.001            | 10 | 34.60 | 43.38 | 49.10 | 53.80 | 57.40 | 60.80 | 63.96 | 66.84 | 69.46 | 71.81 | 73.96 | 75.86 | 77.57 | 79.12 | 80.50 | 81.74 | 82.87 | 83.88 | 84.78 | 85.59 |
| 0.001            | 25 | 158.93 | 186.83 | 203.30 | 218.42 | 232.21 | 244.75 | 256.13 | 266.38 | 275.53 | 284.58 | 293.43 | 301.15 | 307.74 | 313.20 | 318.54 | 323.75 | 328.84 | 333.80 | 338.64 | 343.35 |
| 0.0001           | 10 | 38.11 | 47.07 | 52.80 | 57.41 | 61.89 | 65.26 | 68.52 | 71.69 | 74.76 | 77.70 | 80.51 | 82.21 | 83.77 | 85.22 | 86.55 | 87.77 | 88.88 | 89.89 | 90.82 | 91.66 |
| 0.0001           | 25 | 174.91 | 204.15 | 223.40 | 239.72 | 254.51 | 268.20 | 280.80 | 292.37 | 303.85 | 314.24 | 324.47 | 334.54 | 344.44 | 353.20 | 361.84 | 369.37 | 376.78 | 383.08 | 389.27 | 395.35 |

For explanation and examples see below.
TABLE OF THE VARIANCE RATIO (F-DISTRIBUTION)

The illustration shows the distribution of the variance ratio for 4 and 16 degrees of freedom. The shaded area, expressed as a proportion of the total area under the curve, is the argument in the first column of Table D.

The variance ratio is always calculated with the larger estimate of variance in the numerator, and $\phi_1$ and $\phi_2$ are the numbers of degrees of freedom in the numerator and denominator respectively.

EXAMPLE

Let $F = 4.60$, $\phi_1 = 5$, $\phi_2 = 24$. The 5\% and 1\% points are 2.62 and 3.90, and the result is significant.

In calculating confidence limits for the variance ratio we require the upper and lower tail areas of the $F$-distribution. The levels actually tabled refer to the single upper tail area $F_\alpha(\phi_1,\phi_2)$.

However, the value $F_{1-\alpha}(\phi_1,\phi_2)$ (i.e. the value of $F$ below which a proportion $\alpha$ of the whole curve lies) is given by

$$F_{1-\alpha}(\phi_1,\phi_2) = \frac{1}{F_\alpha(\phi_2,\phi_1)}$$

EXAMPLE

To obtain the 90\% confidence limits for the variance ratio we require the values $F_{0.05}(\phi_1,\phi_2)$ and $F_{0.05}(\phi_1,\phi_2)$.

If $\phi_1 = 4$ and $\phi_2 = 20$, then

$$F_{0.05}(4, 20) = \frac{1}{F_{0.05}(20, 4)} = \frac{1}{5.80}$$

and $F_{0.05}(4, 20) = 2.87$

The required values are thus 0.172 and 2.87.