NATIONAL BUILDING STUDIES

Technical Paper No. 4

Investigations on Building Fires

Part I. Estimation of Maximum Temperatures

Part II. Colour Changes in Concrete

HIS MAJESTY'S STATIONERY OFFICE

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NATIONAL BUILDING STUDIES

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NATIONAL BUILDING STUDIES

Technical Paper No. 4

DEPARTMENT OF SCIENTIFIC AND
INDUSTRIAL RESEARCH
(BUILDING RESEARCH STATION)

INVESTIGATIONS ON BUILDING FIRES

Part I. The Estimation of the Maximum Temperature attained in Building Fires from Examination of the Debris

BY

T. W. PARKER, M.Sc., Ph.D., F.R.I.C.
and
R. W. NURSE, M.Sc., A.Inst.P.

Part II. The Visible Changes in Concrete or Mortar Exposed to High Temperatures

BY

G. E. BESSEY, M.Sc., F.R.I.C.

LONDON
HIS MAJESTY'S STATIONERY OFFICE
1950

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PREFATORY NOTE

THE study of the structural protection of buildings from fire had its beginning in this country in the valuable exploratory work carried out on a full scale by the former British Fire Protection Committee over the years 1897 to 1921. It was not, however, until the Fire Testing Station at Elstree, Herts., had been established by the Fire Offices' Committee in 1935 that systematic investigation of the fire resistance of structures became possible. In this Station facilities were provided for testing the fire resistance of elements of structures according to the methods described in the British Standard Definitions for Fire-Resistance, Incombustibility and Non-Inflammability of Building Materials and Structures (British Standard No. 476–1932). By arrangement with the Fire Offices' Committee, the Building Research Station assumed responsibility for the staffing and conduct of work on fire-resistance, and the facilities provided were made available not only for the testing of particular structural forms, but also for general research on fire-resistance and related problems. This responsibility remained with the Building Research Station until early in 1947.

The Fire Offices' Committee has for many years carried out systematic work on sprinklers and extinguishing appliances, first at their original testing station at Manchester and later at the Fire Testing Station at Elstree. In addition, following the report of the Riverdale Committee on Fire Brigade Services, a small section concerned with research on fire fighting was set up at the Building Research Station just before the war. This was later merged with the Fire Research Division of the Research and Experiments Department of the Ministry of Home Security which, during the war, assumed responsibility for wartime fire protection. This Division was transferred to the Department of Scientific and Industrial Research after the end of the war.

In order to inter-relate more closely all work on fires in buildings and other fire problems, a Fire Research Organization has now been set up by the Department of Scientific and Industrial Research jointly with the Fire Offices' Committee and this new organization has taken over responsibility within the Department for experimental work on fire, including that previously carried out by the Building Research Station and the Fire Offices' Committee. The time is, therefore, opportune to collect together and publish for the information of the building industry the results of the various investigations carried out over the years 1935 to 1947. These cover not only the work carried out at the Fire Testing Station and the Building Research Station, but also the experience gained during the war from the examination of buildings damaged by fire and of the spread of fire. Much use has been made of the results of these investigations by the Fire Grading of Buildings Committee in the preparation of their first report (Fire Grading of Buildings, Part I. General Principles and Structural Precautions. Post-War Building Studies No 20. H.M. Stationery Office, 1s. 6d., by post 1s. 9d.) and in their later reports that have yet to appear. This renders it the more desirable to make available the actual research data on which the Committee based part of their findings.

One of the most important sections of British Standard No. 476 deals with the methods of testing the fire resistance of elements of structures and the classification of their fire resistance according to their endurance under the test conditions. Much systematic work has been pursued along these lines to determine the behaviour and classification of normal and well-known structural forms and of newer types, to study the individual materials used, and to develop design rules which would enable the performance of specific structural elements to be determined without the need in every case for the large and costly tests at present necessary. Studies have also been made on the extent to which, in suitable cases, simpler and smaller scale tests can be used. The very numerous building fires that occurred during the war as a result of air-raids also afforded a unique opportunity—and one which it is hoped may never recur—for the correlation of the behaviour of structures during actual fires with that found under the test conditions used at the Fire Testing Station. A considerable part of the work has been devoted to these objectives and, while it is still far from complete, a substantial body of information is now available.

The spread of fire within buildings, or from one building to another, throws up another group of problems, such as the effect of the nature of the construction or of the contents of the building on the rate of fire spread, and of the relative spacing and disposition of buildings on the risk of conflagrations. The latter studies have a close bearing on town planning in congested central areas. These have all been touched on in the course of the work and the choice of standard test methods kept under review in the light of the results.

The data and conclusions obtained from this set of investigations are to be published as Technical Papers in the National Building Studies under the general heading "Investigations on Building Fires". The present publication, which is the first in this series, contains two papers which deal with the estimation of the temperatures attained in buildings during a fire, information which is basic to the further development of the general subject.

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Director of Building Research

Building Research Station,
Garston, Watford, Herts.
December, 1949.

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INVESTIGATIONS ON BUILDING FIRES

Part I. The Estimation of the Maximum Temperatures attained in Building Fires from Examination of the Debris

by

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INTRODUCTION

ONE of the difficulties in the way of systematic developments in the fire grading of buildings is that of correlating the behaviour of elements of structure in laboratory tests with behaviour in actual fires. It is true that general experience shows that elements which behave well in fires also behave well in fire tests, while others which have but a short life behave poorly under test, but there still exists a need for more definite data. While a complete similarity in behaviour would hardly be expected when the variables which may be encountered in an actual fire are contrasted with the necessarily standardised condition of a fire test, it is an important step to determine what temperatures are attained in actual fires and what temperature gradients have existed in the building materials.

This part of the paper deals only with the means of estimating the temperatures attained in the fire itself from examination of small pieces of metal, glass and other materials found in the debris after the fire. It must be appreciated that the temperatures so determined are usually quite distinct from the temperatures attained by the various parts, the walls, floors, columns of the building, which in any one fire depend on the nature of the structural element and for any one element on the distance beneath the surface exposed to the fire. These latter temperatures can be obtained from a study of the visible changes that occur in concretes and mortar and which are considered in Part II of this paper. Nevertheless the temperatures determined by examination of debris are useful in the study of the temperatures reached in the structural elements, since they may be used to estimate the surface temperature of the element when the "visible change" technique fails to give a sufficiently accurate measurement.

The work was carried out as a preliminary to a survey of fire-damaged buildings undertaken by the Building Research Station during the winter of 1941, at a time when ample data were available as a result of enemy attack. The intention of the work was to set up a simple scale for routine use during the survey. Suitable debris for study might include anything that is identifiable after the fire, whether from the contents or the structure. Examples that have been found useful are given later in this note, but in general terms "suitable" debris includes mainly material from fittings, glass and ceramic ware, metal articles, and so on.

FACTORS INFLUENCING THE CONDITION OF THE DEBRIS

An important point that has to be considered is that both temperature and time of heating may determine the effect on the various materials that may be found. In some cases the significance of time* may not be very great—the colour changes in concrete described in the second paper are an example—but in others time and temperature may be equally significant over the time periods associated with building fires. In such cases it may be impossible to say with certainty whether an article has been exposed to a high temperature for a short time or to a lower temperature for a long time. Greater precision can of course be obtained when the approximate duration of a fire is known.

Considering any one building as a whole, the possible severity of a fire in it will depend amongst other factors on the quantity and nature of combustible contents in it and on whether or not the structure itself contains combustible material. It is frequently found, however, that the fire loading varies throughout a single room as well as from room to room and floor to floor. This effect, combined with the variable draught due to windows, stairways, etc., leads to very great variations in temperature over quite small distances.

The rate of cooling has a very considerable influence on the character of the debris. If the fire is not extinguished with water, articles may be submitted to intermediate temperatures for very long periods and the effect of this treatment may obliterate indications due to the higher temperature attained at the height of the fire. Loose ash is a good thermal insulator, and in the investigation it was frequently found that piles of ash had either completely protected articles from the fire or had settled round articles already heated and maintained the temperature long after neighbouring unprotected objects were cooled. On the other hand, when the fire is extinguished with water, cooling may be so rapid that the microstructure of metals is preserved in the high temperature form.

The atmospheric conditions during the fire may also have a considerable influence. In a strongly oxidising fire steel objects may be completely oxidised and form a scale having a melting temperature lower than the actual metal. A superficial examination in these cases might lead to the erroneous conclusion that the temperature had been in excess of the melting point of the steel. Cases also occurred where charred wood in contact with steel objects had caused local formation of a cast iron structure of lower melting point than the original steel.

Clouds of dust and ash present during the fire settle out and form a layer which may frequently give the impression of surface melting, particularly of ceramic objects, where the dust often combines with the low melting surface glaze. This dust and ash layer may also affect the scale formed on metallic specimens, and can lower the melting point considerably.

SELECTION OF A SUITABLE TEMPERATURE SCALE

Owing to the many variable factors outlined in the previous section no attempt was made to assess the maximum temperature to a greater precision than ±50°C. In many cases a wider range had to suffice.

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* This relates only to the time factor as it affects the course of the physical or chemical changes. Time of exposure determines equally with temperature the depth to which the colour change penetrates into a structural element (see Part II).

Pure metals are an obvious choice as indicators because of the precision with which the melting points are known and the absence of time-temperature effects. Such metals, however, when used as articles of commerce, are frequently alloyed, and it was considered advisable to check the melting points on samples actually recovered from fires. Similar tests were made on common alloys such as brass. The specimens were heated in a small electric muffle with an air atmosphere from room temperature to the melting point over a period of about three hours. The specimen was considered to be melted as soon as the sharp edges were drawn up into a rounded shape. For alloys this temperature was probably intermediate between the eutectic and final melting points. The temperatures found are given in Table 1 below.

In order to fill in the gap between 600° and 900°C., some experiments were made with common glass objects. Here the time factor was more important, but within the three-hour period the discrepancy in temperature was within the limit of ±50°C. aimed at. Moulded glass objects showed a lower final melting temperature than sheet glass, as might be expected.

Temperatures higher than 1,200°C. are extremely rare. The melting of steel is not a reliable guide in this range, partly because of the wide range of steel melting points (1,350–1,500°C.) and partly because it is impossible to distinguish wrought iron and steel except by a detailed microscopic examination. Laboratory tests on ceramic articles were always made to confirm estimates in this region.

TABLE 1. MATERIALS USED IN ASSESSING TEMPERATURES IN FIRE

SUBSTANCE	TYPICAL EXAMPLES	CONDITION	TEMPERATURE, °C.
Lead	Plumbing fixtures ; damp course ; ornaments, toys	Sharp edges rounded or drops formed	300–350
Zinc	Plumbing fixtures	Drops formed	400
Aluminium and Alloys	Small machine parts ; brackets ; toilet fixtures	Drops formed	650
Moulded glass ..	Corrugated window glass; cosmetic jars ; pepper pots ; opaque as well as clear	Softened or adherent Rounded Flowing easily	700–750 750 800
Sheet glass ..	Window or plate glass including reinforced glass	Softened or adherent Rounded Flowing easily	700–750 800 850
Silver	Jewelry ; spoons	Sharp edges rounded, drops formed	950
Brass	Door knobs ; trays ; spoons ; locks ; buckles	Ditto	900–1,000
Bronze	Window frames ; bells	Ditto	1,000
Copper	Electric wiring	Ditto	1,100
Cast iron ..	Pipes; radiators; machine bases	Drops formed	1,100–1,200

SPECIAL TESTS

MICROSTRUCTURE OF METALS

A number of metal specimens were examined by the Metallurgy Department of the National Physical Laboratory to determine whether temperature indications could be obtained from unmelted specimens. It was possible to give a confident estimate only in a limited number of cases. In iron and steel the criteria used were spheroidisation of pearlite or cementite, spheroidisation of slag inclusions, degraphitisation and the changes in structure at 720°C. and 800°C. In brasses the presence of β solid solution was used as an indication that the temperature had reached 600°C.

Difficulties experienced were:—(1) that no control specimen was available, (2) that specimens were frequently wrought iron, in which the changes on heating cannot be detected, (3) the effects of time and temperature could not always be separated, and (4) a certain amount of cold-working was involved in collecting and preparing the specimens.

Plate 1 shows the microstructure of a specimen of mild steel (·25–·30 per cent C.) reinforcement as removed from the debris. After normalising by heating at 910°C. for 15 minutes followed by air cooling the structure had altered to that shown in Plate 2. In order to restore the structure to the Plate 1 type, it was necessary to re-heat to 760°C. (Plate 3). The pearlite in the original specimen was mostly lamellar but showed some spheroidisation, indicating that the steel could not have been held at temperatures between 650°C. and 720°C. for a long time.

This type of analysis was found to be unsuitable for general use since, in contrast with the scale of Table 1, page 3, no estimate could be given on the site and it was therefore necessary to collect and label a great weight of specimens. Moreover the analysis was costly and no guarantee could be given that any one specimen would be suitable for estimating temperature. The method was however useful as a check on the method of inspection and where there was a scarcity of other types of samples.

CERAMIC WARE

As explained previously, for the range above 1,100°C. it was necessary to rely principally on the evidence furnished by ceramic articles. The main difficulty, as with the metals, was to find a comparatively undamaged sample as a control. The porcelain insulators of electrical fittings were very useful, as it could be assumed with some confidence that the fittings were of similar composition throughout a single room. Some element of doubt always remained however, and since the fluxing action of dust and ash varied from spot to spot it was preferred to base the estimate on heating tests on parts of the actual sample. Plate 4 (A) shows a typical series of test specimens after heating in the laboratory. Plate 4 (B) is the sample as removed from the fire. In this case both melted and unmelted material was available. Occasionally examples were observed in which fusion of bricks or tiles had occurred, and in suitable cases they give a similar guide to that from other ceramic articles. As a particular example from one fire, the ceiling of a room had been constructed of hollow tile blocks and during the early stages of the fire some of the blocks had shattered, the pieces of comparatively unheated tile falling to the floor. Later the temperature rose sufficiently at the ceiling to melt the remaining tiles, which then dripped on to the cooler pieces below. It was concluded in this case that the ceiling temperature had exceeded 1,200°C. Plate 4 (C) is a piece of steel reinforcement taken from the same ceiling. The drops formed on this specimen are molten scale and not steel; laboratory tests showed a melting point of 1,300–1,350°C. Ceramic samples were always used in preference to these scales owing to the possibility of re-oxidation of the scale in the laboratory muffle, with considerable changes in melting point.

CONCLUSIONS

The materials listed as temperature indicators in building fires are not necessarily all that could be used, but they do represent those which have been found most useful in examining a number of buildings. As far as possible those materials which might give an erroneous indication because of time-temperature effects as distinct from temperature effects alone have not been used, but it is impracticable to eliminate them altogether because that would largely reduce the field to the use of pure, congruently melting compounds. Where an alloy or a mixture such as a ceramic body is used, the temperature indication can most accurately be described as " not less than " the particular temperature assessed. Similarly, materials that might be unduly affected by oxidising or reducing conditions have been eliminated or only used when specific indications are present (e.g., drops from molten zinc). This investigation was not specially directed to an interpretation of the results in terms of the course taken by the fire in the cases studied. However, one observation which was frequently made has a direct bearing on the course of the fire : it was that wide differences in temperature had existed during the fire at points relatively short distances apart. In surveying fire conditions from a study of the after effects, the maximum temperature assessment should be made by collecting as many specimens of a suitable type as possible and by keeping as accurate a record as possible of the positions from which the samples were drawn.

Part II. The Visible Changes in Concrete or Mortar Exposed to High Temperatures

by

G. E. BESSEY, M.Sc., A.R.I.C.

INTRODUCTION

Visible changes in the appearance of natural stones, cement and lime mortars and concrete after exposure to fire have been observed and recorded on many occasions but no attempt appears to have been made to study their nature or causes. In connection with problems relating to the severity of building fires it is necessary to have available some reasonably reliable method of assessing the temperature and duration of the fires and as direct measurement during a building fire is obviously out of the question, recourse to other means is necessary. In the conduct of full scale fire resistance tests on brickwork, reinforced concrete, etc., at the Fire Testing Station, Mr. C. T. Webster of the Building Research Station had observed that the depth to which certain colour changes occurred in the mortar and concrete varied in a well-defined manner with the duration of heating and it appeared possible that these changes might be adapted for the purpose mentioned above, if it could be established that they occurred at sufficiently well-defined temperatures. The work described in the present paper was carried out to determine to what extent the observed changes were critical and also the temperatures at which they occurred. In the course of the work further changes have been observed which provide a means of assessing the temperatures over a wide range.

Experiments were carried out on samples of aggregates alone and on mortars and concretes.

AGGREGATES

Samples of sands and various types of aggregate were heated in an electric furnace at temperatures from 200°–1,000°C. in steps of 100°C. or in some cases 50°C. for varying periods. The observations and the conclusions drawn are given below.

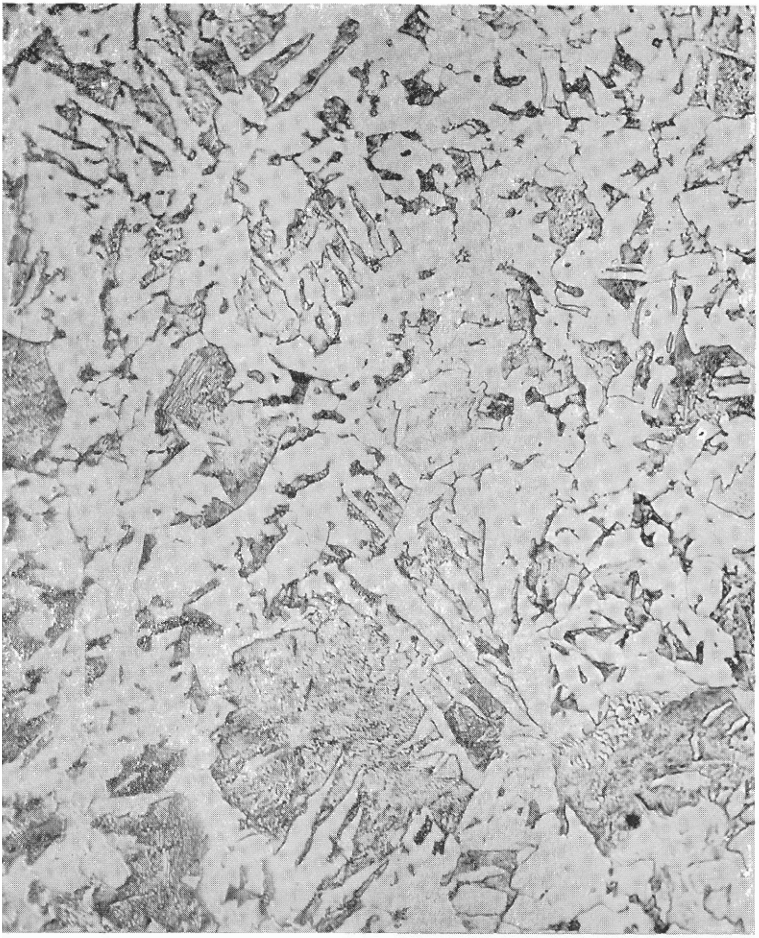
QUARTZ SAND AND SANDSTONES

In all sands and sandstones except the colourless pure quartz sands there was a marked change in colour at 250°–300°C. This colour change, from the normal yellow or brown to a pink or reddish brown is well known, but no previous recording of the temperature at which it occurs has been found. The change is relatively sharp. At 200°C. none is apparent after up to 18 hours heating; at 250°C. the colour develops slowly and is fully developed in 18 hours; at 300°C. it is fully developed in 2 hours. At higher temperatures up to 1,000°C. there is generally little further change although some samples show an intensification of the pink or red colour.

As the original yellow or yellow brown colour of many sands is due to the presence of small quantities of iron compounds it seemed that the colour change was most probably dependent upon the presence of iron compounds in the stone or coating the sand grains, and examination of the literature on the effect of temperatures upon the hydrated iron oxides shows a close agreement between the

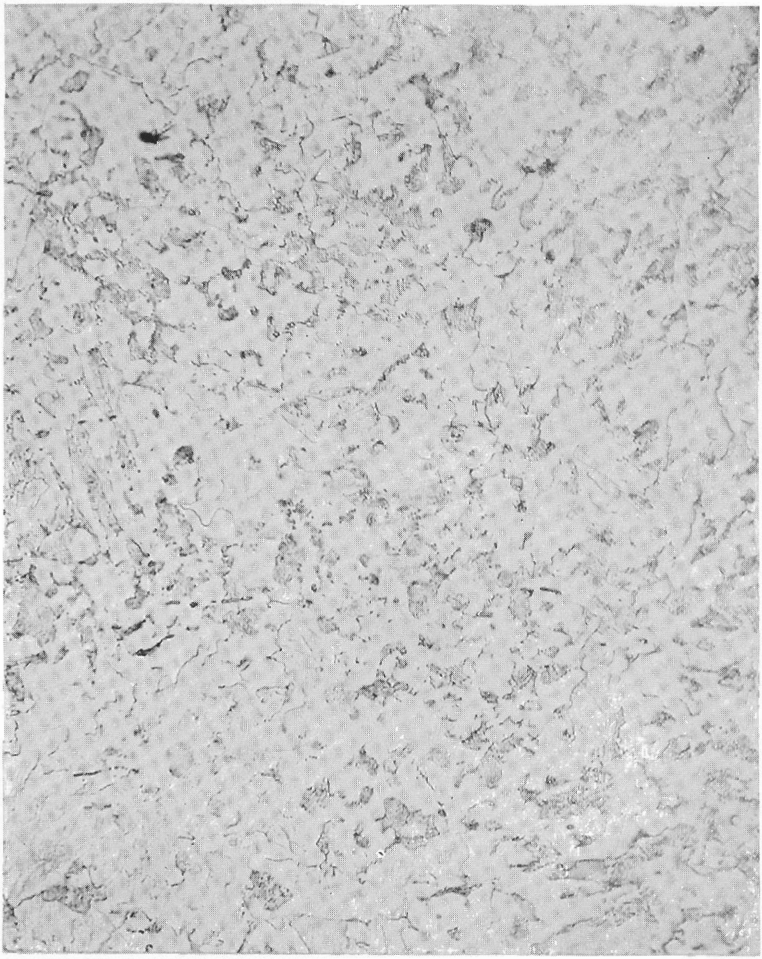
MILD STEEL REINFORCING BAR AS RECEIVED. (× 500.)

PLATE 1



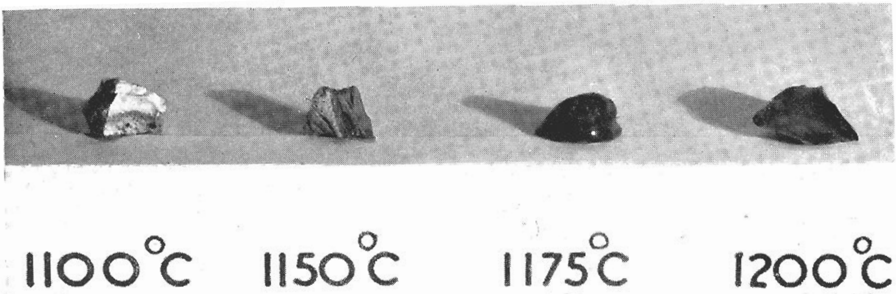
MILD STEEL REINFORCING BAR. NORMALISED 910°C. (× 500.)

PLATE 2

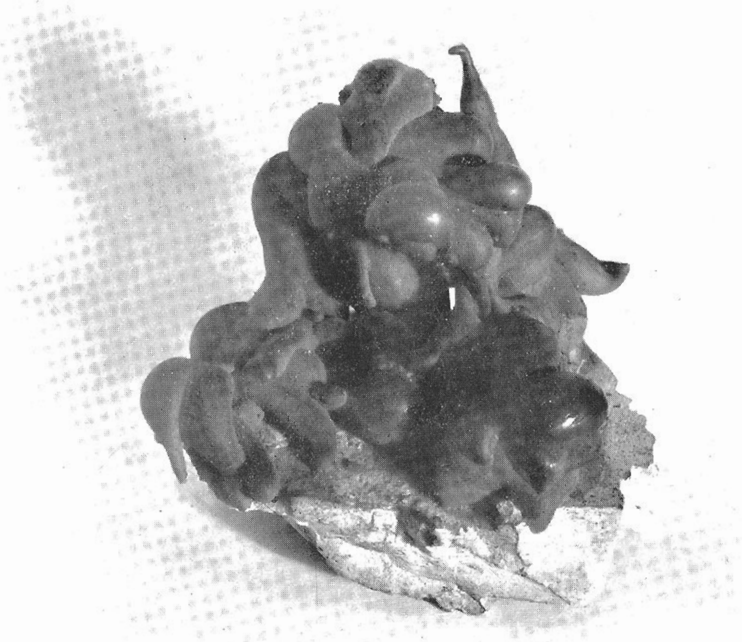


MILD STEEL REINFORCING BAR. NORMALISED AT 910°C, $\frac{1}{4}$ HOUR. SLOWLY AIR COOLED. REHEATED AT 760°C. (×500.)

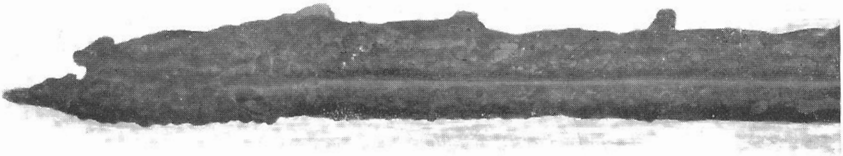
PLATE 3



(*A*) TYPICAL SERIES OF TEST SPECIMENS AFTER HEATING IN THE LABORATORY.



(*B*) SAMPLE AS REMOVED FROM FIRE.



(*C*) SAMPLE OF REINFORCEMENT TAKEN FROM A HOLLOW TILE CEILING.

PLATE 4

dehydration temperatures of all these compounds and the observed colour-change temperature of 250°–300°C. Fischer (1) states that limonite decomposes with a colour-change from yellow to red at 300°C. Williams and Thewlis (2) found Lepidocrite (γ $FeO(OH)_2$) was converted to the γ oxide at 250°–300°C. Posjnak and Merwin (3) also found that Gœthite (α $FeO(OH)$) lost very little water below 250°, but was almost completely dehydrated at 300°C. Hansen and Brownmiller (4) in examining precipitated ferric oxide hydrogel found that it had no structure, as judged by X-ray diffraction after heating at 200°C. but that after heating at 300°C. it had the hæmatite (Fe_2O_3) structure. There can thus be little doubt that the colour change in sands and sandstones corresponds with the dehydration of the iron compounds and that its presence is a reliable indication that the sample has been heated to a temperature of at least 250°–300°C. (the higher temperature with shorter heating periods).

As mentioned above there is no further change in colour of sands or sandstones, but at 573°C., the inversion temperature of the two forms (α and β) of quartz, there is a considerable expansion of the quartz grains. This usually causes internal rupturing of the grains of sand, and weakens sandstones, often making them friable to handle. Samples which are appreciably weaker or more friable than the unheated stone have therefore been heated above 573°C.

FLINT

Flint gravel showed a colour change at 250°-300°C. similar to that observed with sand or sandstone. The amount of red colour developed varied with the initial colour of the flint. At temperatures above 500°C. some shattering of the flint occurred, partly it is thought as a result of removal of combined water from the flint and partly through the high-low quartz inversion ; the absence of such visible effects may not, however, always be a reliable indication that this temperature has not been exceeded. Apart from the visible shattering the lighter coloured fractured surfaces became more white in appearance above this temperature.

Flint that has been held at temperatures above 1,200°C. for any length of time has a lower density than unheated flint, owing to partial conversion to cristobalite. Fig. 1 shows the density of small flint gravel unheated and heated to various temperatures up to 1,250°C. for 2 hours. This is in agreement with previous work by various investigators* ; the density of unheated flint is given generally as 2·55–2·65 and that of cristobalite from flint as 2·22. This change may be used for examination of samples suspected from other indications of having been above 1,200°C.

LIMESTONE

Limestone which contains any hydrated iron oxide was found to develop marked pink or red colours at 250°–300°C in the same way as sandstones. The colour varied considerably but was in practically all cases well defined. It sometimes increased in depth at higher temperatures up to about 600°C. At temperatures above about 700°C. calcination of the limestone occurred, becoming rapid at 850°–900°C. ; when calcination occurs the red colour disappears and the specimen disintegrates slowly on exposure to moist air.

The changes in appearance of a number of well known limestones are shown in Table 1.

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* R. B. Sosman, "The Properties of Silica", Chemical Catalog Co. Inc., New York, 1927.

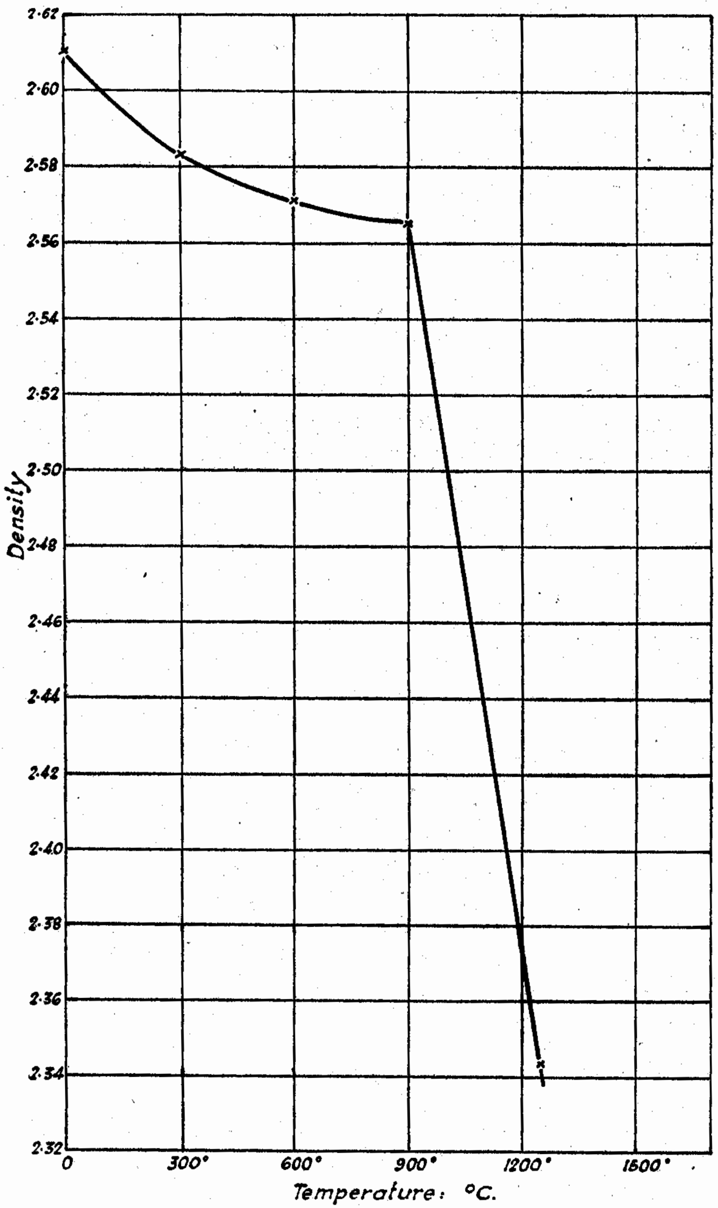

FIG. 1. VARIATION OF SPECIFIC GRAVITY OF FLINT HEATED TO DIFFERENT TEMPERATURES.

TABLE I. CHANGES IN APPEARANCE OF LIMESTONE AND SANDSTONE ON HEATING

	COLOUR OF UNHEATED SPECIMENS	APPEARANCE OF SPECIMENS HEATED* AT TEMPERATURE OF :						
		200°C.	250°C.	300°C.	400°C.	600°C.	800°C.	1,000°C.
Limestone Bath	Dirty white	Unchanged	Tinted pink	—	Pink	Grey (pinkish)	Grey-white, cracked on exposure	Similar, powdered on exposure
Ketton	Buff	Ditto	Brownish pink	—	More red than 250°C.	Chocolate	—	Grey-white, powdered on exposure
Clipsham	Light buff	Unchanged up to 18 hrs.	2 hrs. trace of pink 18 hrs. pink	2 hrs. similar to 250°—18 hrs.	Some grey patches in the pink	Grey-pink	Grey-white, cracked on exposure	Grey-white, powdered on exposure
Ham Hill	Yellow variegated	Ditto	2 hrs. darkened 18 hrs. pinkish brown	Ditto	Darker than 300°	Chocolate and blue	Similar to 600°, cracked on exposure	—
Magnesian Limestone Huddlestone	White	Unchanged	—	—	Slightly discoloured white	Similar to 400°	Pure white slowly crumbling on exposure	Pure white, crumbling on exposure
Anston	Buff	No change up to 18 hrs.	2 hrs. V. slight pink tinge 18 hrs. pink	2 hrs. similar to 250°—18 hrs.	Similar to 300°	Pinkish-grey	Light grey, cracked on exposure	Light grey, powdered on exposure
Sandstone Longridge	Grey	Unchanged	—	—	Brownish pink	More pink than 400°	Similar to 600°	More pink than 800°
Bolham Wood	Buff-grey	Unchanged	Sl. darkening	—	Pinkish chocolate	Chocolate-pink	—	Pink
Whatstandwell	Brownish grey	Unchanged	Unchanged	—	Pinkish tinge with chocolate spots	As 400°	As 400°	As 400°
Yorkshire S.S.	Greyish buff	Unchanged up to 18 hrs.	2 hrs. Sl. darkening 18 hrs. Sl. pinkish tinge	Chocolate pink	As 300°C.	As 300°	As 300°	Pink
Robin Hood	Blue-grey	Unchanged	—	—	Dark grey	As 400° but with pinkish tinge	As 600°	Slightly more pink than 800°

---

* Period of heating 2 hrs. unless otherwise stated.

IGNEOUS ROCKS

Igneous rocks generally have been found to show no colour change on heating. The more acid types (e.g., granite) sometimes crack or shatter at temperatures above 573°C. through quartz expansion; basic types (dolerite, basalt) show no effect at that temperature but may show expansion effects when heated above about 900°C.

SLAG

Blastfurnace slag aggregates in general are unaffected by temperatures below about 1,200°C.

CRUSHED BRICK AGGREGATE

Crushed brick aggregates show no effect at temperatures below sintering temperature. This may vary, for different types of brick; "flow" of the aggregate will rarely occur below 1,000°C. and may in some cases not be observed below 1,200°C.

CONCRETE AND MORTAR

PORTLAND CEMENT—QUARTZ SAND MORTAR

Cement mortar briquettes (1 : 3 Portland cement : sand) made with two different sands, one of high and one of low iron content, were stored for one week in water and one week in air. Individual briquettes were then heated for two hours at various temperatures.

The changes in condition and appearance of these briquettes are shown in Table 2. The appearance of a pink colour at 300°C. corresponds with that observed on heating sand alone, but it is less marked and with a sand of low iron content can only just be observed. Most sands used for building mortar have, however, a considerable iron content and in subsequent observation of mortars in buildings which have suffered damage by fire the change has been clearly

TABLE 2. CHANGES IN CEMENT MORTARS HEATED TWO HOURS AT VARIOUS TEMPERATURES

TEMPERATURE	MORTAR A (PALE COLOURED SAND)		MORTAR B (RED SAND)	
	Appearance	Strength	Appearance	Strength
Unheated	Grey	—	Buff	—
200°	Slight darkening	V. slight drop	No change	V. slight drop
250°	Ditto	Further ditto	Ditto	As 200°C.
300°	V. slight pink	Ditto	Pink	As 200°
400°	Slightly darker than 300°	Ditto	Ditto	As 200°
600°	As 400°	No appreciable strength	Sl. deeper pink	No appreciable strength
800°	Dark, but not perceptibly pink	Ditto	Deeper red	Ditto
900°	Lighter grey	Ditto	—	—
1,000°	Much lighter grey with no pink	Ditto	Pink nearly disappeared	—

distinguishable. Up to a temperature of about 500°C. the strength was not sufficiently affected to modify the apparent condition of the mortar, but at 600°C. it had become conspicuously weak and friable. This change is sufficiently sharp to serve as an indication that the mortar has been heated to at least 550°C. The pink colour was lost at temperatures of 600°–800°C. in the briquettes made with sand of low iron content, but remained with changes in intensity and tint even at 800°C. with the sand of high iron content; this loss of pink colour is discussed later in connection with concretes.

Small blocks of brickwork 12 in. × 9 in. × 9 in., were built with London stock brick and 1 : 3 Portland cement; sand mortar, using an average building sand and cured for 14 days before test. Thermocouples were embedded at various depths from the centre of one 12 in. × 9 in. face and were connected to a temperature recorder. One block was plastered with ¾ in. of cement : lime : sand mortar and ½ in. of gypsum plaster on the face to be heated. The blocks were heated on

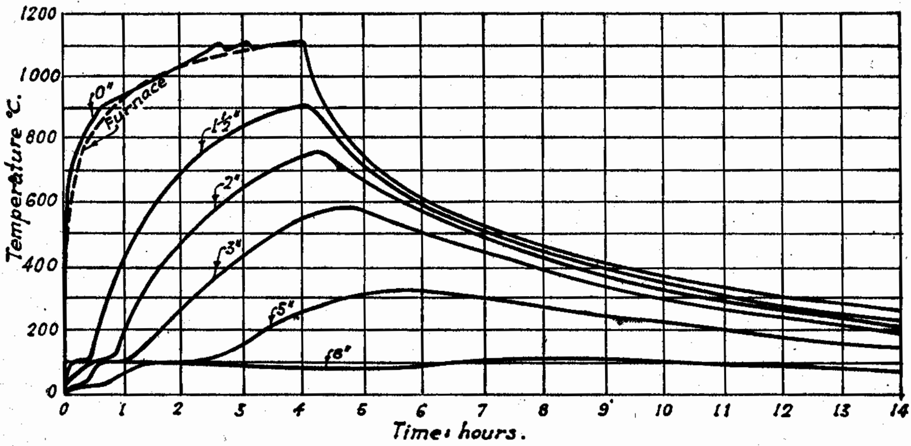

FIG. 2(A). BRICKWORK HEATED FOR 4 HOURS. TIME-TEMPERATURE CURVES AT DEPTH SHOWN FROM SURFACE.

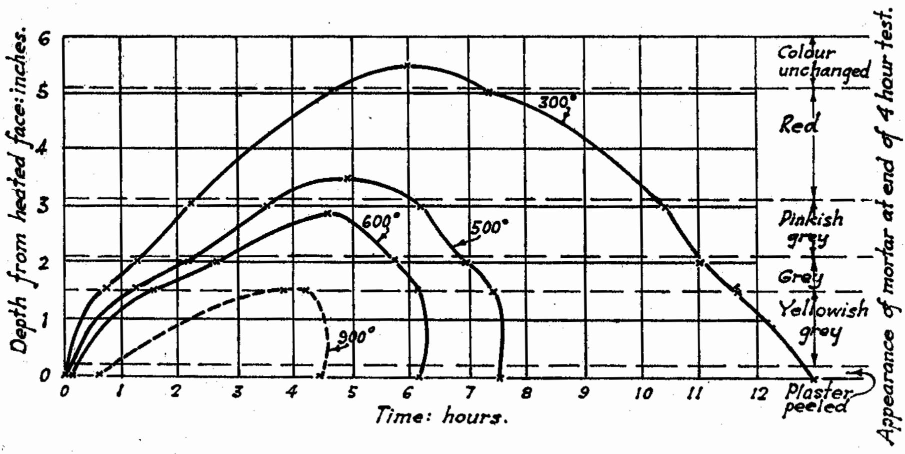

FIG. 2(B). BRICKWORK HEATED FOR 4 HOURS. TIME-ISOTHERMS AND COLOUR CHANGES.

one 9 in. × 12 in. face by a gas-fired furnace, the furnace temperature following as closely as possible the standard curve of the British Standard Definitions for Fire Resistance, etc. (B.S. 476, 1932) and the furnace atmosphere being fully oxidising. After completion of the heating period the furnace and specimen were allowed to cool down together.

The results obtained with the plastered brickwork in a 4-hour test are shown in Figs. 2A and 2B. The temperatures within the block show very clearly the effect of free moisture in absorbing heat and thus delaying temperature rise above 100°C., and also show the markedly increasing lag in attaining the maximum temperature at greater depths from the heated face. The lag in heating and cooling probably

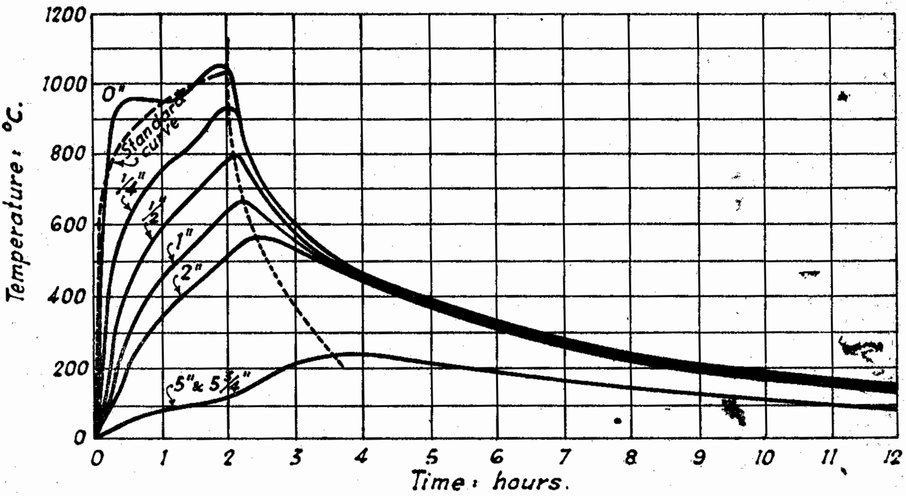

FIG. 3(A). TIME-TEMPERATURE CURVES, AT DEPTHS SHOWN FROM SURFACE, FOR 1 : 2 : 4 PORTLAND CEMENT CONCRETE WITH HAM RIVER SAND AND GRAVEL AGGREGATE. HEATED 2 HOURS.

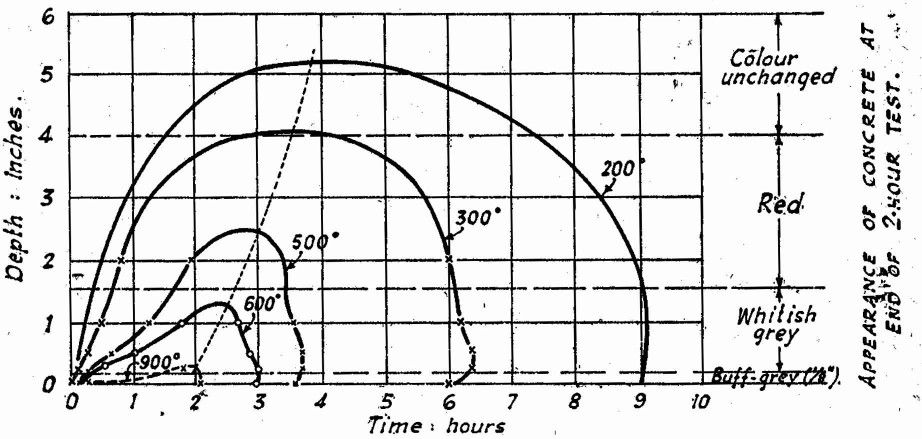

FIG. 3(B). TIME-ISOTHERMS AND COLOUR CHANGES FOR 1 : 2 : 4 PORTLAND CEMENT CONCRETE WITH HAM RIVER SAND AND GRAVEL AGGREGATE. HEATED 2 HOURS.

helps to increase the sharpness of the visible changes in the mortar since it lengthens the period at which any portion of the material is at its maximum temperature. In Fig. 2B the time-depth isotherms are shown, together with the changes in the appearance of the mortar in the brick joints.

The sand used in the mortar had a rather high iron oxide content and the red colour was developed strongly in each test in the mortar heated to above about 300°C. The discharge of the red colour occurred over the range of temperature roughly 550°–750°, giving an intermediate pinkish grey band about 1 in. wide. The width of this band probably results from the high iron content; it was much smaller in the tests on concrete (q.v.). At about 900°C. the grey colour was changed to a buff or yellowish grey.

The plaster fell off the face of the block during the test, and its only effect was to reduce the depth of brickwork heated above 300°C. and 600°C. by about ½ in. as compared with the unplastered specimen.

PORTLAND CEMENT—FLINT GRAVEL—SAND CONCRETE

The experiments on concrete were carried out mainly on slabs 13 in. × 8 in. × 4 in. or 13 in. × 8 in. × 6 in., heated on one 13 in. × 8 in. face. In most cases the slabs were stored initially for 24 hours in moist air, then for 28 days at 65 per cent relative humidity and 65°F. (18°C.). Thermocouples embedded at various depths in the centre of the slab, and a sheathed-thermocouple in the furnace close to the slab, were connected to a temperature recorder, and heating was carried out as described for the brickwork specimens.

Fig. 3 showing the results for a Portland cement—natural sand—flint gravel concrete (1 : 2 : 4 mix) slab 6 in. thick heated for two hours, corresponding to the B.S. test for Grade C protection against fire, may be taken as typical of the results obtained. The time-temperature curves (Fig. 3A) are similar in form to those of Fig. 2 with brickwork, but there was practically no free water in these concrete specimens, so the "step" at 100°C. is absent.

The lower set of curves (Fig. 3B) are the time-depth isotherms for the same specimen. The changes in colour observed on breaking the concrete across at the centre are also shown in this figure, with the approximate depths at which the colour changes occurred. As a result of the time lag in heating and cooling the period during which the material at greater depths is held at or near its maximum temperature is greater than the duration of the fire; thus at a depth of 3¾ in. in the present example, the temperature is held between about 300°C. and 330°C. for some 2½ hours, although the furnace was heated for only 2 hours.

Similar slabs were heated for 1, 4 and 6 hours, corresponding to B.S. Grades D, B and A.

The changes observed in all these concrete slabs on breaking them open were similar and differed only in position according to the period of heating. Changes at four distinct temperatures were noted as follows:—

(1) At 300°C. approximately, the red colouration previously described in the mortars replaced the normal grey of the concrete. This colouration is distinctive and the boundary between the red and grey portions could be readily defined. With different sands it was found to vary in intensity and in some cases needed a practiced eye and suitable lighting to determine the depth affected.

(2) At a temperature between 500°C. and 600°C. some cracking of the coarser flint aggregate was observable, and at the upper end of this range the concrete cracked and became friable; this is no doubt mainly a result of the quartz inversion as previously mentioned.

At a temperature similar to or slightly higher than the above a change in colour from the red or pink to grey is observable. This change is most probably due to reaction of the ferric oxide with lime, forming calcium ferrites of lower pigmenting power. This is largely confirmed by the persistence of the pink colouration in the case of materials not containing lime, e.g., sandstones, flint gravel, even at 1,000°C. (see Table 1). Such a solid reaction will be relatively slow and the temperature at which the red colour disappears may therefore depend on the amount of iron oxide present and upon the time of exposure at the maximum temperatures. The range of variation may be taken as approximately 550°–700°C.

The colour change at this point is intensified by treatment of the broken concrete surface with a dilute acid (10 per cent acetic acid is suitable and convenient to use). The concrete above the quartz inversion temperature absorbs water or the dilute acid rapidly and the colour is darkened markedly, with a dull appearance even on drying again. Below this temperature absorption is slower, like that of the unheated concrete, the acid remains on the surface longer, and reacts with the cement giving a more intense colour with a somewhat glossy appearance.

Although the colour change (without acid treatment) does not by itself indicate a very definite temperature, the change in absorption and colour after acid treatment together with the cracking and friability of the concrete above 600°C. are sufficient to define the depth to which this temperature (600°C.) has been attained.

(3) At temperatures near 1,000°C. the colour of the concrete again changed from a cement grey to a buff shade, but the change in appearance is not always as sharply defined as the other changes at lower temperatures. The depth at which this colour change occurs can however usually be seen and may be taken to indicate a maximum temperature of about 950°C.

(4) Sintering of the concrete occurred at temperatures above about 1,200°C. to an extent which depends largely upon the amount of iron oxide present. Incipient sintering is usually seen as a "crackled" surface, with a yellow colour and individual brown spots where there is a higher iron content.

TABLE 3. MAXIMUM DEPTH (IN INCHES) OF CONCRETE SHOWING CHARACTERISTIC CHANGES ON HEATING

CONCRETE HEATED	MAXIMUM SURFACE TEMPERATURE ATTAINED	CHANGE			
		Development of pink or red 300°C.	Fading of red, friability and high absorption 600°C.	Development of buff 950°C.	Sintering 1,200°C.
1 hr.	950°	2¼	¾	0	0
2 hrs.	1,050°	4	1½	¼	0
4 hrs.	1,230°	5½	2½	1	⅛
6 hrs.	1,250°	6¾	3½	1½	¼

The depths at which the four changes discussed above were observed in slabs heated for 1, 2, 4 and 6 hours respectively are given in Table 3 and are plotted in Fig. 4. The maximum temperatures attained in the concrete for these various periods of heating, corresponding to the various grades of Fire Resistance of B.S.D. 476, are shown in Fig. 5. It should be noted that the maxima shown within the concrete are not all attained until after the end of the heating period, the lag depending upon the depth from the heated face.

PORTLAND CEMENT—CRUSHED LONDON STOCK BRICK AGGREGATE CONCRETE

Tests were carried out on slabs of 1 : 2 : 4 concrete with crushed and graded London stock brick coarse and fine aggregate. There were no conspicuous changes such as were observed with gravel and natural sand aggregates, either in colour or in general condition. At about 600°C. there was a slight change in the grey colour, with a tendency for the edges of particles of aggregate to be less visible; at 900°C. a buff colour was noticeable and the fine aggregate appeared to have reacted with the cement. Only the 900°C. change would be of value in ascertaining the temperature to which such concrete has been exposed.

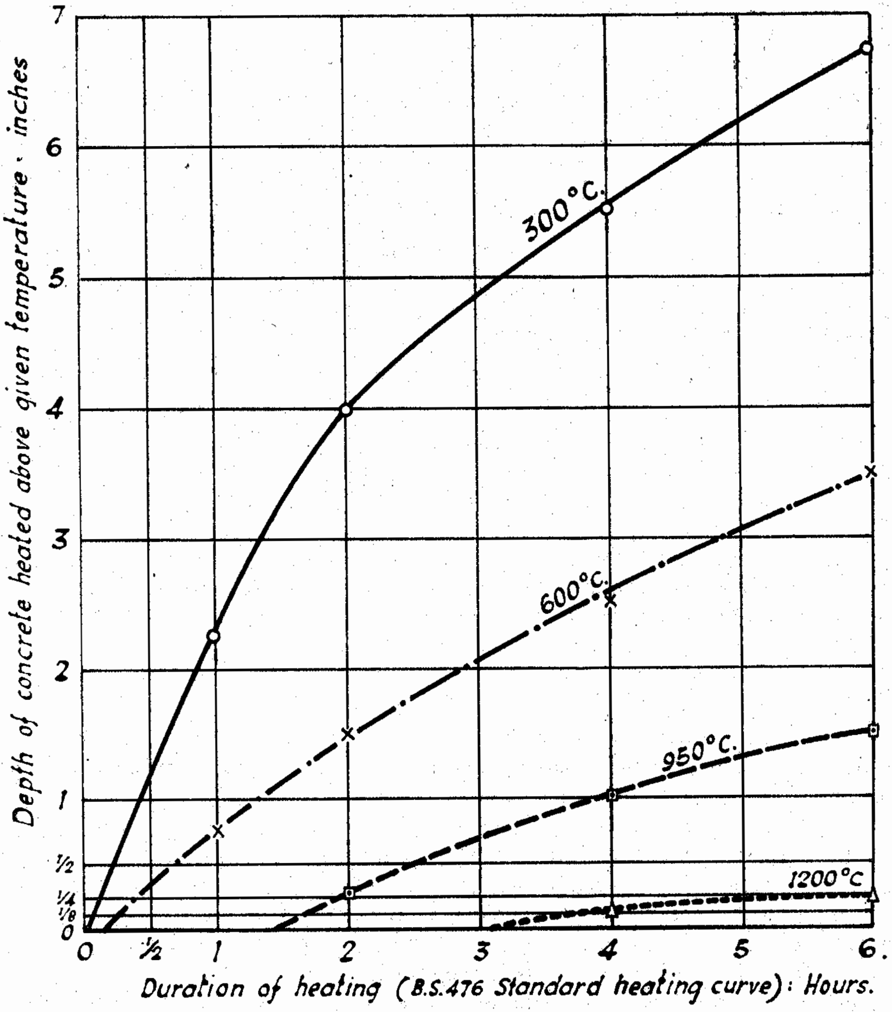

FIG. 4. DEPTH OF CONCRETE HEATED ABOVE CHARACTERISTIC TEMPERATURES IN 'STANDARD FIRE'.

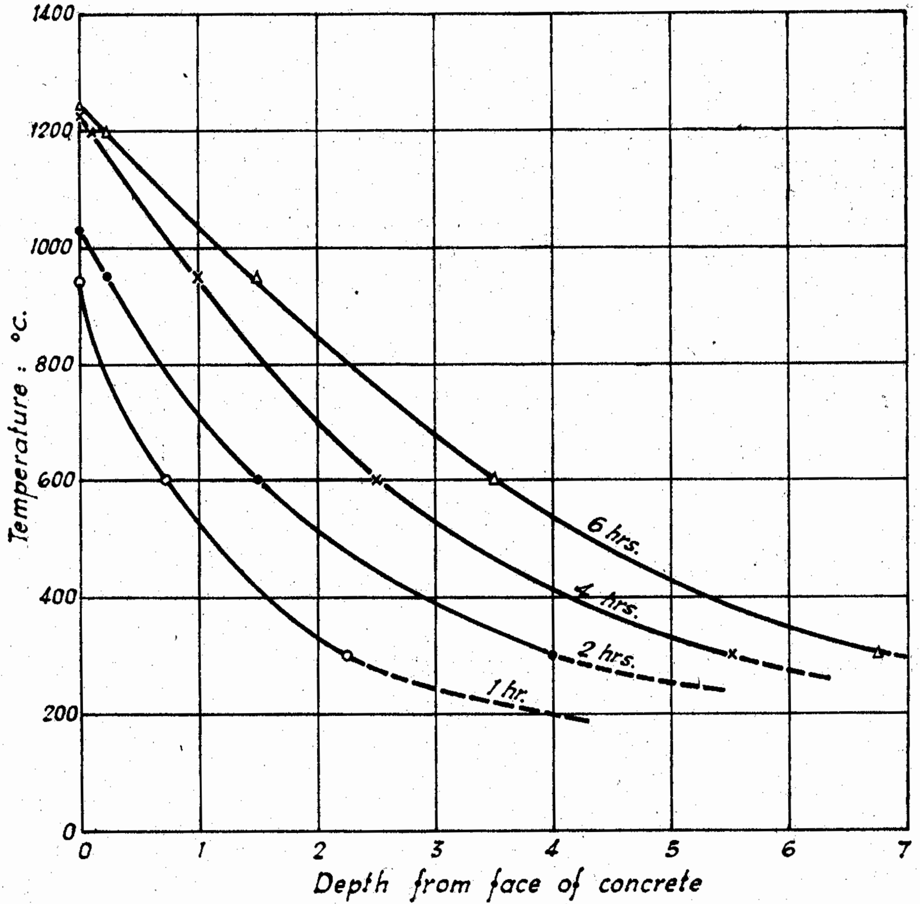

FIG. 5. MAXIMUM TEMPERATURES ATTAINED IN CONCRETE HEATED ON ONE FACE FOR VARIOUS PERIODS IN ACCORDANCE WITH THE TIME-TEMPERATURE CURVE OF B.S. 476. (DEPTH IN INCHES).

HIGH ALUMINA CEMENT—FLINT GRAVEL—SAND CONCRETE

One test was carried out on a 13 in. × 8 in. × 6 in. slab of 1 : 2 : 4 high alumina cement with flint gravel and natural sand aggregates. Three colour changes were observed.

(1) The development of the red colour at 300°C. caused by the iron compounds in the aggregate was clear, but as the cement is darker in colour than Portland cement it would not be so easily distinguished with aggregates low in iron content.

(2) At about 600°C. the red colour is replaced by a purple-grey which is quite distinctive and probably represents the first stage of reaction between the iron oxide and calcium compounds of the cement.

(3) The purple-grey only persists over a narrow temperature range, and at about 750°C. is replaced by a buff or pale yellow.

These changes with high alumina cement are less well-defined than with Portland cement.

REPRODUCIBILITY AND INTERPRETATION OF OBSERVED CHANGES IN TERMS OF TEMPERATURE

In the experiments already described the various characteristic changes in appearance of the concrete were found to occur within a fairly short temperature range, the range being due primarily to the duration of exposing of the concrete to the temperature. Further experiments were carried out in a similar manner to determine whether the duration of steady maximum temperature, or the rate of cooling had any effect; no significant differences were found. The effects of carrying out the test with thoroughly wet concrete instead of dry were also found to be not significant.

The following conclusions were drawn with regard to the accuracy with which the changes in appearance can be used to judge the temperatures to which a sample of concrete or mortar has been exposed.

THE RED COLOURATION (300°C.)

The development of the red or pink colouration in concrete or mortar containing natural sands or aggregates of appreciable iron oxide content occurs at 250°–300°C. Unless the period of heating is known to have been prolonged over 6 hours or more the upper limit of this range can be taken as the transition temperature. The demarcation between changed and unchanged concrete or mortar is usually sharp and the depth which has been heated above 300°C. can generally be judged to ±⅛ in. if a good section is available, or ±¼ in. in less favourable circumstances. Greater accuracy is usually possible in the case of cement mortars than with concrete, and with small depths of penetration the demarcation can generally be estimated after some practice to within the lower range.

THE SECOND GREY COLOUR AND CRUMBLING (600°C.)

The second definite change or series of changes occurs around 600°C. with siliceous aggregates, but is less sharp than the 300°C. change. The disappearance of the red or pink colour with return to a grey occurs generally between 600°C. and 700°C., depending upon the time of heating and other factors; expansion effects such as cracking of flint gravels, and general weakening or friability of the concrete or mortar are evident at 500°–600°C. Observation of these effects together, in doubtful cases, with confirmatory observations by acid treatment of the exposed section, make it possible to judge the depth heated above 600°C. to ±¼ in., or in less favourable cases ±⅜ in.

THE BUFF COLOUR (950°C.)

The change from the second grey colour to a buff is often rather ill-defined and its temperature varies with the rate of heating and other factors from about 900°–1,050°C. If it be assumed that this change corresponds to a temperature of 950°C. the error in judging the depth of penetration of this temperature may be only ±⅛ in. where the penetration is small and the temperature gradient steep, or up to ±¼ in. where the penetration is greater.

THE SINTERING POINT (1,200°C.)

Only in cases of exposure to the most severe and prolonged fires is mortar or concrete likely to reach a temperature of 1,200°C. to any significant depth.

Sintering above this temperature is generally well marked and the depth affected, if it remains on the concrete or mortar surface and does not spall away on cooling, can often be judged to within ±1/16 in.

CONCLUSIONS

It is concluded from the results of the tests on aggregates, mortars and concretes that changes in the appearance of concrete or mortar at approximately 300°C., 600°C., 950°C., and 1,200°C., are sufficiently reproducible and well defined with most siliceous aggregates to make it possible to assess with reasonable accuracy the temperatures attained by sections of concrete or mortar that have been subjected to heat above any of these temperatures. The change at 300°C. (development of red colour) is probably the most useful, but where the depths can be ascertained at which two or more of the above changes occur, it is possible to obtain the temperature gradient.

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