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Assessment of fire damaged concrete using colour image analysis

N.R. Short*, J.A. Purkiss, S.E. Guise

School of Engineering and Applied Science, Aston University, Aston Triangle, Birmingham B4 7ET, UK

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Abstract

Assessment of fire damaged concrete structures usually starts with visual observation of colour change, cracking and spalling. On heating, a change in colour from normal to a pink/red is often observed and this is useful since it coincides with the onset of significant loss of concrete strength. Optical microscopy combined with colour image analysis has been used to quantify changes in colour for concrete subjected to elevated temperatures. Samples were examined in reflected light and measurements of hue, saturation and intensity for colour definition, were taken. The measurement of hue was particularly useful and enabled the quantification of colour at different temperatures. This technique is superior to the subjective visual assessment currently used. The full development of the pink/red colour is coincident with substantial reduction in compressive strength and the method may be used to define the distance from a heated surface where strength degradation has occurred.

Keywords: Concrete; Fire; Colour

1. Introduction

When reinforced concrete is subjected to high temperatures as in a fire, there is a deterioration in its properties. Of particular importance are loss in compressive strength, loss of elastic modulus, cracking and spalling of the concrete; reduced yield strength, ductility and tensile strength of the steel, and the loss of bond between them. To ascertain whether a structure can be repaired rather than demolished after a fire, an assessment of structural integrity must be made. As part of this process it is necessary to assess the extent of deterioration of the concrete itself.

Assessment of fire damaged concrete usually starts with visual observation of colour change, crazing, cracking, and spalling. On heating above 300°C, the colour of siliceous aggregate concrete is said to change from normal to: pink or red (300–600°C), whitish grey (600–900°C), and buff (900–1000°C) [1]. The pink/red discolouration results from the presence of iron compounds, in the fine or coarse aggregate, which dehydrate or oxidise in this temperature range. This colour change is useful since its appearance coincides with the onset of a significant loss of concrete strength as a result of heating. Thus, in practice any concrete which has turned pink/red after a fire is regarded as being suspect of deterioration. Cutting back the concrete should give a good idea as to the depth to which temperatures greater than 300°C have occurred. The colour change to pink/red is less prominent with calcareous and igneous aggregate concretes.

These visual observations may then be supported by various tests which give an indirect indication of the

* Corresponding author. Tel.: +121-359-3611, ext 4535; fax: +121-333-3389.
E-mail address: n.r.short@aston.ac.uk (N.R. Short).

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Table 1
Chemical analyses (wt.%)

Material	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	Na_2O	K_2O	LOI[a]
OPC	64.30	20.20	5.60	2.60	3.20	1.30	0.10	0.76	0.80
PFA	1.45	48.20	32.20	8.02	0.52	0.66	0.98	2.85	3.84
BFS	40.09	35.51	12.59	0.58	0.15	9.11	0.24	0.54	–

[a] Loss on ignition.

condition of the concrete. These tests include: core strength, rebound hammer, ultrasonic pulse velocity (UPV), Windsor probe, BRE internal fracture, and thermoluminescence. The advantages and disadvantages of these are described in detail elsewhere [2–5]. Whilst these tests are valuable aids in assessment, they do not give a complete picture of the extent of deterioration.

Optical microscopy/image analysis applied to polished or petrographic thin sections has been used extensively in investigations of concrete microstructure and whilst this includes phenomena related to mechanisms of deterioration in general, there has been only a minimal amount of work related to fire damaged concrete [6]. The aim of the present investigations was therefore, to assess the potential of colour image analysis for use in investigations of fire damaged concrete. This has involved the analysis and quantification of changes in colour of concrete samples which have been subjected to both steady-state and transient heating regimes.

2. Experimental

2.1. Materials and sample fabrication

An ordinary Portland cement (OPC) and blended cements prepared from OPC and 30% pulverised-fuel ash (PFA) or 50% ground granulated blast furnace slag (BFS) were used. The compositions of the various materials, expressed in percentages by weight of the constituent oxides, are shown in Table 1. The fine aggregate was a medium zone quartz sand. The coarse aggregates were chosen from those used in the UK and were known to show a range of behaviour with regard to colour change. These were (i) siliceous gravel, (ii) crushed limestone, (iii) crushed granite, and (iv) Lytag.

The concrete mix was 1:2.1:4.2 cement/sand/coarse aggregate. Mixes were designed to give equivalent workability by varying the water/cement ratio between 0.62–0.66, and 60-day cube strengths typical of good quality structural concrete. Quality control was maintained by measuring slump and fresh wet density. Mixes were cast into standard cubes, beams or cylinders. Thermocouples were embedded at various distances from the surface to measure temperature gradients. Specimens were demoulded after 24 h, cured under water for 28 days and then stored in air with controlled RH and temperature. When samples were 60 days old they were dried in an oven at 105°C for 48 h in order to prevent explosive spalling on firing. This regime provided well-cured samples and minimised any effect of accelerated hydration when heated.

2.2. Steady-state heating regime

Cube and beam samples were heated to equilibrium temperatures of 175, 250, 300, 350, 400, 450, 500 and 700°C in a proprietary kiln type furnace. The rate of heating was approximately 6°C/min. The specimens were heated to the test temperature, soaked at that temperature for 1 h, then allowed to cool. A range of tests were carried out on samples heated at each temperature level and on control specimens cast at the same time. These tests included residual compressive and flexural strength, dynamic modulus, ultrasonic pulse velocity, surface hardness, mercury intrusion porosimetry and differential thermal/thermogravimetric analysis. In this paper only residual compressive strengths are reported and compared with the changes in colour. Other test results and their implications are reported elsewhere [7].

2.3. Transient heating regime

During an actual fire, temperatures within a concrete section do not generally reach equilibrium values. A thermal gradient is established with the temperature of the outside layers being drastically increased, whilst the temperatures of the inner concrete may be comparatively low. As a result of this, development of the pink/red colour is restricted to a surface section. However, the boundary where colour change diminishes is difficult to determine by visual inspection.

A simple electric furnace was constructed with a heating element at one end, allowing the establishment of a temperature gradient along the axis of a concrete cylinder specimen. The furnace was calibrated using a heat flux meter to give rates of heating at the concrete surface equivalent to heat fluxes of 80, 110 and 140 kW/m^2 which are typical of low, medium and high intensity fires [7].

2.4. Colour measurement

The concepts involved in understanding colour and its measurement are complex (see, e.g. references [8,9]) and only a brief description is given here. Different colours can be described and quantified in terms of their components by the use of what are known as colour spaces. There are numerous forms of these but they can, more or less, be divided into two groups which represent specific colours either as combinations of other colours, e.g. the primary colours red, green and blue (RGB) or in terms of hue, saturation and intensity (HSI)

The RGB colour space is widely used in cameras and monitors since it is simple and good for generating and displaying images. Separate signals for red, green, and blue are obtained and then the resultant colour is defined by the percentage of red, green and blue that are present as its constituents. A disadvantage of this system is that people do not think of colour in terms of combinations of red, green and blue.

In the HSI colour space: Hue denotes the kind of colour, i.e. whether it appears as red, yellow or green, etc. It is the attribute by which the eye distinguishes different parts of the spectrum and is measured in terms of wavelength. The hue of a specific colour may then be represented by its position on a horizontal circle (Fig. 1). The zero on this circle depends on the measuring system used. In the present work, the instrument analyser defines pure red as the zero and hue may be quantified as an angle. However, for computer purposes the 0–360° range is re-scaled to fit a 0–255 instrument display, so that pure red is 0 and 255. Saturation refers to the degree to which a pure colour is diluted with white, e.g. a bright/deep red not diluted with any white is said to be highly saturated. As white is added the colour changes to light red, to pink and then white (completely de-saturated). In HSI colour space the circumference of the circle represents 100% saturation with 0% at the centre (Fig. 1). Intensity is a colour neutral value and represents the extent to which a material reflects light, i.e. it describes the relative brightness or darkness. Thus in bright light, red has a high intensity but as the light dims the intensity decreases and the red becomes darker and darker until it fades to black. In HSI colour space it is represented by an axis perpendicular to the circle plane (Fig. 1). The full model is thus represented by a double cone and a specific colour is defined in terms of hue, saturation and intensity by its position on the surface of the cone.

Samples were impregnated with a colourless resin, cut, ground and polished for examination in reflected light. Using an Olympus polarising microscope combined with a Sight Systems Ltd., colour manager, image analysis workstation and associate software, it was possible to determine values of hue, saturation and intensity for control and fired specimens.

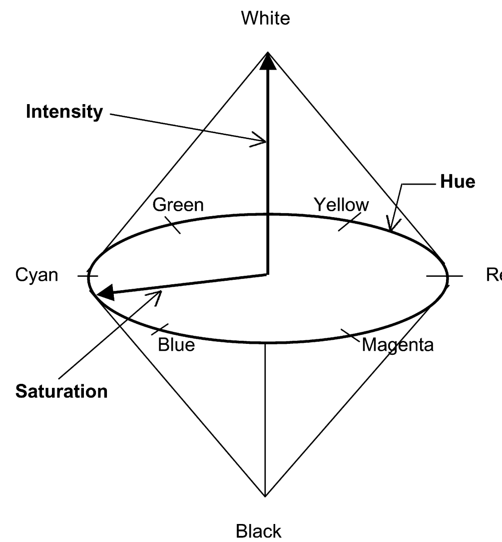

Fig. 1. HSI colour space.

3. Results and discussion

3.1. Visual observation

A polished cross-section of an unheated OPC/siliceous aggregate concrete control sample is shown in Fig. 2a and it is evident that the different components of the concrete exhibit a range of colours. This is also the case for an OPC/siliceous aggregate concrete sample which has been heated to 350°C (Fig. 2b). A difference in colour between these two specimens is discernible, the visual perception being that many of the components of the heated concrete have turned red or become a deeper red colour. Fig. 2c shows a sectioned concrete cylinder heated on the left end face. The surface section has undergone a colour change compared with the interior, although the interface between them is rather indistinct.

3.2. Steady-state heating regime

3.2.1. Siliceous aggregate

Initially measurements of colour were made for a sample area, 50 × 80 mm, typically as shown in Fig. 2a,b thus, including a range of colours. Essentially the analyser records an image of this area and divides it into 512 × 512 pixels, i.e. 262 144 segments. The hue, saturation and intensity for each pixel are then determined.

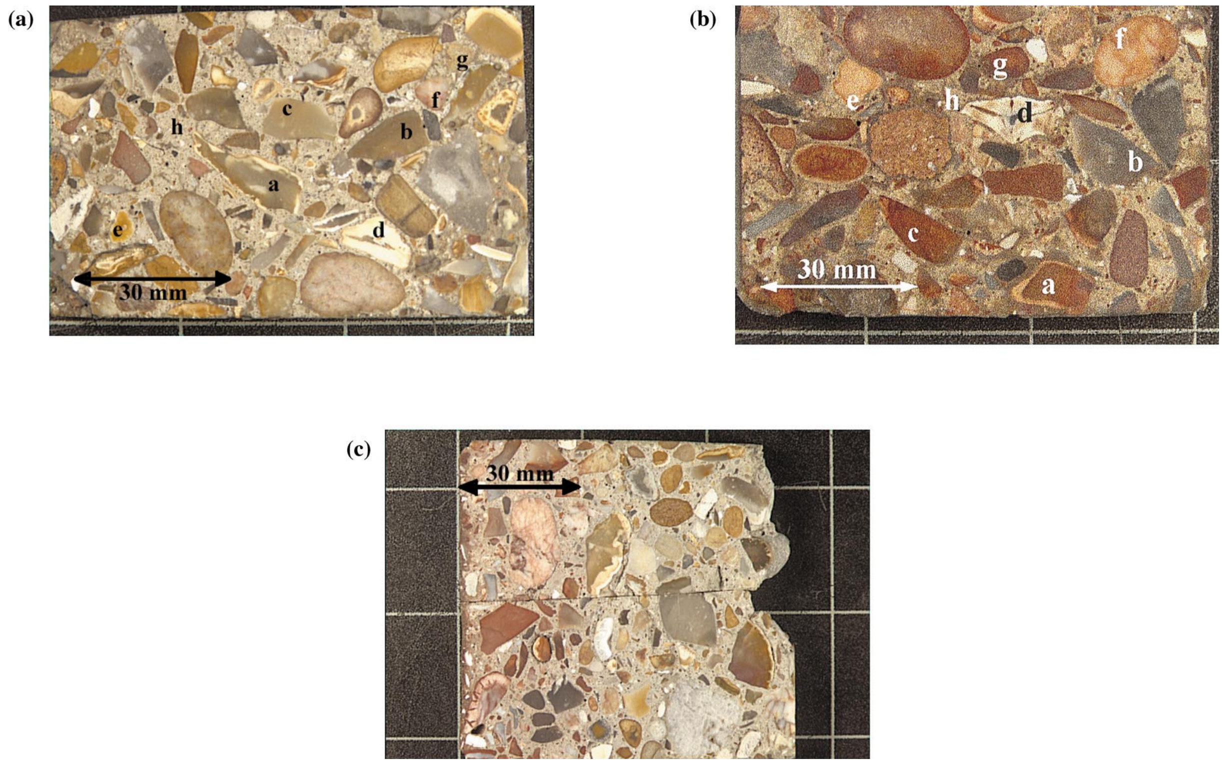

Fig. 2. Polished sections of concrete (a) control (b) heated at 350°C (steady-state) (c) heated from the left end face (transient).

The results presented in Fig. 3, show the frequency of occurrence for the hue levels from 0 to 89, where the different levels represent the red to green part of the visible region of the electromagnetic spectrum (cf. Fig. 1). In order to preserve the clarity of the information the results are plotted as histograms in bandwidths of 10, i.e. 0–9, 10–19, etc. It is evident that for both control and fired samples, the frequency of response is concentrated in the 0–39 levels, representative of colour in the red-yellow region. Values in levels 40–255 were virtually zero. Heating to equilibrium temperatures of 350°C caused a shift in the frequency so that for levels 20–29 there was a drop in frequency of occurrence from 178 000 to 56 000; whilst in the 10–19 levels there was an increase from 76 000 to 203 000. Such a shift indicates a change in colour to a larger red component.

Strictly, an actual colour or colour change should be defined in terms of all three components, hue, saturation and intensity and a more detailed consideration of this is given in [7]. However, since the major changes occurred in values of hue it was decided to present the results only in terms of this parameter. Colour changes occurring on heating are then expressed as frequency of occurrence in the 0–19 levels as a percentage of the total frequency in all levels.

Fig. 4 shows the percentage hue in the 0–19 levels

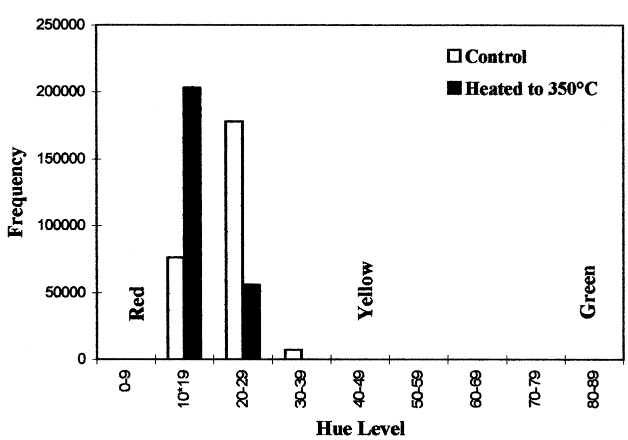

Fig. 3. Frequency of the occurrence for the levels of Hue from 0–89. Control and fired samples.

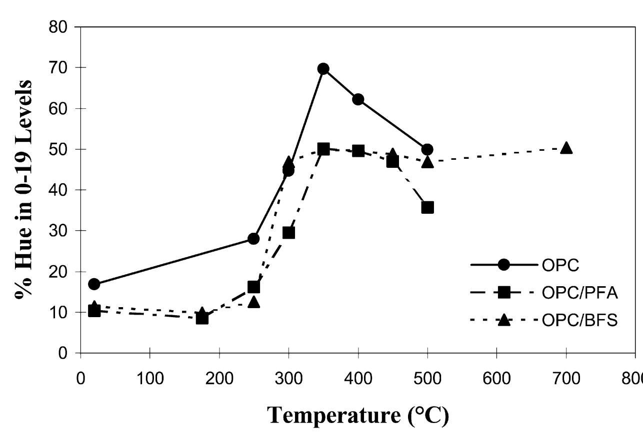

Fig. 4. Hue measurement for samples heated to equilibrium temperature (siliceous aggregate).

Table 2
Percentage hue in 0–19 levels for the different components of concrete made with siliceous aggregate before and after firing (codes refer to Fig. 2a,b)

Code	%	Control	%	Heated to 350°C
a	0.2	Grey flint and brownish yellow edge	99.7	Reddish brown flint and pale red edge
b	1.3	Dark grey flint	52.3	Grey flint
c	0.0	Light grey flint	99.4	Reddish brown flint
d	5.5	White flint and brownish orange streaks	48.6	White flint and light brown areas
e	4.4	Orange flint	83.9	Pale red flint
f	64.6	Pale red veined quartz	99.4	Reddish orange veined quartz
g	5.2	Brownish orange sandstone	98.7	Reddish brown sandstone
h	5.1	Yellowish grey mortar	57.7	Brownish grey mortar

for samples heated to different temperatures. It is evident that the red colour started to develop significantly for samples soaked in the temperature range 250–350°C. This colour change developed quickly at 350°C whilst only very slowly at 250°C (bearing in mind the soaking time of 1 h at the equilibrium temperature). Soaking at temperatures in the range 350–500°C showed little change in red colour. It should be noted that the values plotted in Fig. 4 represent a mean red colour for the sample cross-sectional area and that within this area there are differences in colour between the mortar matrix and the various components of the siliceous gravel (see Table 2).

The control samples made with blended cements have a lower base-line red colour compared to control samples made with plain OPC; the reason for which has not been resolved to date. In spite of this, the relative changes in colour are very similar. This observation demonstrates that development of red colour is not greatly influenced by the iron oxide content of the cements, since these vary widely (Table 1).

It is known [10] that concretes made with slag blended cements may develop a dark blue-green colouration. This colour is associated with the release of sulfide ions into the concrete pore solution as the glassy slag dissolves during reaction with alkalis. Exposure to air allows oxidation of the sulfides to take place and the colouration diminishes with age. With cube samples, observation of cross-sections show that there is a light surface zone around an extensive dark core. The action of heat on the cube accelerates the oxidation process and the dark core retreats uniformly to the centre of the cube. In the present work soaking times were such that the blue-green colour had been eliminated before determination of the red colour.

These results clearly demonstrate that this technique can be used to quantify colour changes in concrete as a result of heating and is a considerable improvement on using subjective visual assessment.

Average cube strengths at 60 days for the OPC, OPC/PFA and OPC/BFS concretes were 56.0, 45.0 and 44.0 MPa respectively. The lower values for the blended cements reflect the secondary nature of pozzolanic reactions compared to plain OPC. Fig. 5 shows that for concrete made with plain OPC, there is a slight reduction in the residual compressive strength of samples soaked at temperatures up to 350°C. Soaking at temperatures greater than 350°C leads to a substantial reduction in strength. Comparing Fig. 5 with Fig. 4 it is evident that the substantial change in strength loss coincides with the full development of red colour. With the concretes made using blended cements there is initially an increase in strength indicating some effect of accelerated hydration. However, substantial reduction in strength again occurs at 350°C, and is coincident with full development of red colour. Thus, the full development of a red colour may be used as an indication of significant loss in compressive strength.

3.3. Other aggregates

The results for the limestone, granite and Lytag aggregates were similar to those found for samples made with siliceous aggregate. However, the shift in frequency of occurrence from levels 20–29 to levels 10–19 after heating to 350°C, whilst still evident, was

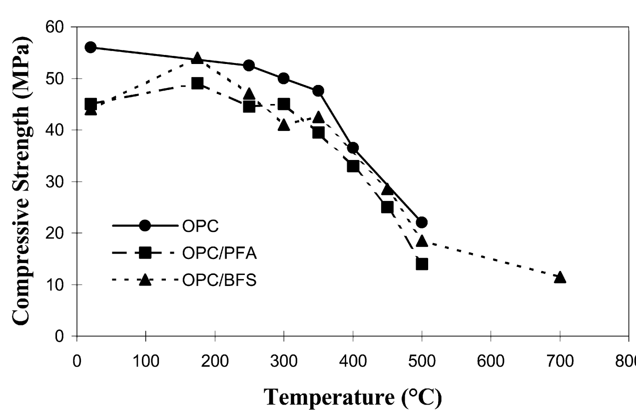

Fig. 5. Change in residual compressive strength with increasing equilibrium temperature (siliceous aggregate).

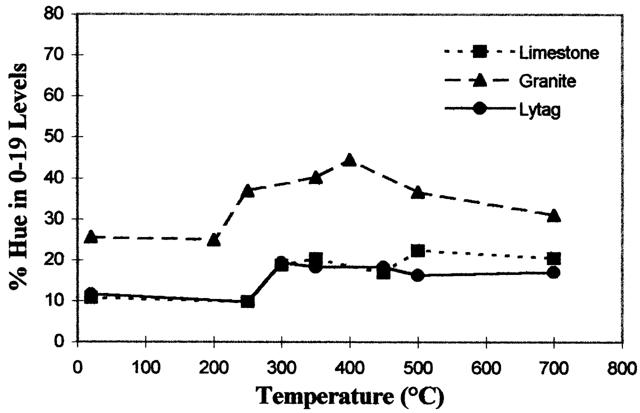

Fig. 6. Hue measurement for samples heated to equilibrium temperature (OPC).

not as great. Thus, the development of the red colour on heating to different equilibrium temperatures is not as distinct, as can be seen in Fig. 6.

Soaking at temperatures greater than 350°C again leads to substantial reduction in compressive strength although the sample made with granite aggregate are slightly more resistant (Fig. 7). Comparing Fig. 6 and Fig. 7 the relation between change in colour and reduction in compressive strength is not as obvious as for the concrete made with siliceous aggregate. Thus, it may be concluded that colour change is not as reliable a predictor with these types of aggregate. However, this problem may be overcome by restricting colour measurements to the mortar matrix, the change in which was found to be independent of the type of aggregate used.

3.4. Transient heating regime

Fig. 8a shows the temperature distribution, immediately prior to cooling, found in the concrete cylinder shown in Fig. 2c. The temperature at the surface reached approximately 680°C and the 300°C isotherm was approximately 30 mm from the exposed surface.

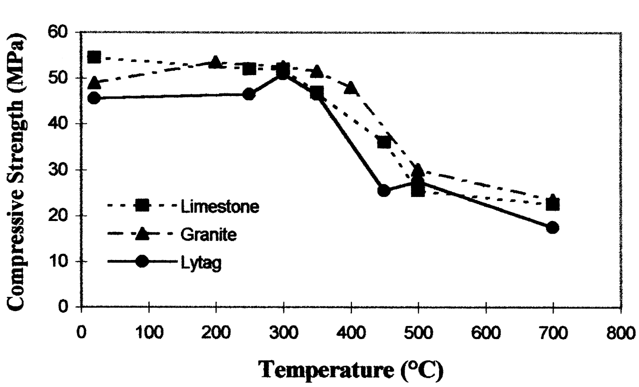

Fig. 7. Change in residual compressive strength with increasing equilibrium temperature (OPC).

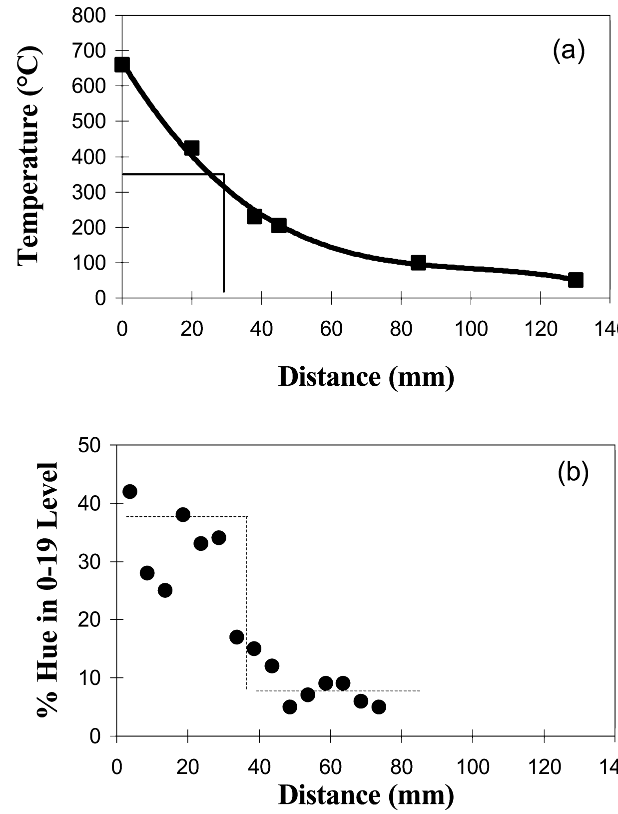

Fig. 8. (a) Temperature distribution and (b) colour development for an OPC/BFS siliceous aggregate concrete heated from one end face.

Fig. 8b shows the corresponding colour change with distance from the exposed surface. Values represent the colour found in consecutive, overlapping, parallel sections, 7.5×55 mm thick. The maximum development of red colour occurred from the surface to depths of approximately 30 mm. At depths of greater than 30 mm, the red colour diminishes rapidly and has essentially disappeared at depths in excess of 45 mm. The transition may be estimated at approximately 35 mm from the surface, i.e. equivalent to temperatures just below 300°C. Although not applied in the present work, the transition depth may be determined by complex statistical analysis as derived by Kriging and discussed in Isaaks et al. [11].

Thus, even if the temperature distribution was not known, then from a knowledge of colour change and an understanding of the relationship between these parameters and compressive strength (as shown in Figs. 4 and 5) it is possible to define the maximum distance from the surface (in this case approx. 35 mm) where significant reductions in residual compressive strength are likely to be found.

3.5. Potential for image analysis

A wide range of microscopes, cameras and image analysis workstations are available for this type of investigation. Specifications for the hard- and soft-ware vary tremendously depending on particular requirements and a suitable suite would probably cost in excess of £50 000. However, in spite of the cost, these facilities are becoming much more widely available, especially in materials research laboratories where they can be employed in a wide range of investigations. In the case of cementitious materials the techniques are now being applied to yield information on, e.g. the quality of concrete such as cement content, water/cement ratio and quantifying the cracks which may result from a wide range of degradation processes.

4. Conclusions

1. Colour image analysis can be used to quantify the colour of fire damaged concrete and this method is superior to the subjective visual assessment currently used.
2. Full development of the red colour coincides with a significant reduction in the residual compressive strength of good quality structural concrete.
3. Colour measurements may be used to determine the thermal history of concrete by providing information regarding the temperature distribution, particularly the 300°C isotherm, that existed at the height of a fire. As such it is possible to estimate the depth of the heat affected zone.
4. The actual colours observed depend on the types of aggregate used to make the concrete. They are most pronounced for siliceous aggregates and less so for limestone, granite and Lytag. In the case of concretes made with the latter it may be better to only analyse the mortar matrix.

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References

[1] Bessey, GE. The visible changes in concrete or mortar exposed to high temperatures. In: Investigations on building fires, Part 2, National Building Studies Technical Paper No. 4, HMSO, London, 1950:6–18.
[2] The Concrete Society. Assessment and repair of fire-damaged concrete structures, Technical Report No. 33, London, 1990:26–30.
[3] Bungey JH. Testing of concrete in structures. Surrey University Press, 1989.
[4] Smith, LM. The assessment of fire damage to concrete structures, PhD Thesis, Paisley College of Technology, 1983.
[5] Chew MYL. Effect of heat exposure duration on the thermoluminescence of concrete. ACI Mater J 1993;90:319–322.
[6] St John DA, Poole AW, Sims I. Concrete petrography. Arnold, 1998:308–316.
[7] Guise SE. The use of colour image analysis for assessment of fire damaged concrete. PhD Thesis, Aston University, 1997.
[8] Clulow FW. Colour — its principles and their applications. London: Fountain, 1972.
[9] Berger-Schunn A, Saltman M. Practical colour measurement. Wiley, 1994.
[10] ACI Committee 226. Ground granulated blast-furnace slag as a cementitious constituent in concrete. ACI Mater J 1987;84:327–342.
[11] Isaaks H, Mohan Srivastava R. An introduction to applied geostatics. Oxford University Press, 1989.