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Residual fracture properties of normal- and high-strength concrete subject to elevated temperatures

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Contribution by J. A. Purkiss*

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The authors have produced a paper with some very interesting results on the fracture behaviour of concrete subjected to elevated temperatures. There are, however, a number of points which, perhaps, require elucidation.

- (a) In the case of exposure of concrete to a fire the build-up of temperature in the surroundings is relatively gradual. In their investigation the authors chose to place the specimens in an oven or furnace already heated to the required test temperature. This can, certainly, at the higher temperatures used, produce severe thermal shock. Thus any degradation measured will be partly due to the test temperature and partly due to the thermal shock. Do the authors have any indication of the contribution of thermal shock rather than the specific test temperature towards the degradation, as it is likely that the results presented here will possibly be over-conservative if applied to the fire case?
- (b) Could the authors please comment on their choice of siliceous aggregate rather than the more common use of calcareous (or limestone) aggregates for high-strength concrete.

Reply by the authors

Introduction

We would like to thank Dr Purkiss for his interest in our paper, his consideration and comments. The first part of this discussion questioned whether the test results from our thermal shock tests (infinite heating rate) would be overconservative to apply to the fire case because the fire is a gradual heating process. The second part queried the suitability of siliceous aggregates for making high-strength concrete which can sustain high temperatures. Dr Purkiss' discussion focuses mainly on two influential parameters: heating rate and aggregate type. The results presented in our paper were from the preliminary tests in a series of studies on the mechanical properties of high-performance concrete subject to high temperatures. There are many influential factors including mix proportion (water–cement ratio, aggregate–cementitious material ratio), cement type and content, aggregate type, size and content, geometric dimensions, stress level during heating and of course heating regime (heating rate, maximum heating temperature, exposure time, cooling rate, thermal cycle. The mechanical properties in our study

include strength (compressive, tensile and flexural), stiffness (Young's modulus and Poisson's ratio), toughness (fracture toughness and fracture energy) and brittleness. Because much research has been done on strength and stiffness, we paid more attention to toughness and brittleness in our study.

Effect of heating rate

We share Dr Purkiss' viewpoint that a fire is a gradual heating process so a very high heating rate like thermal shock could possibly lead to overconservative results for the fire case. When we first carried out preliminary tests, we could not control the heating rate in the ovens or furnace even though we had realised the importance of its effect. However, we considered that thermal shock might be the worst case and the results obtained would be acceptable for practical use. A new programme-controlled furnace has now been installed at Glasgow University to allow us to further study the mechanical properties of concrete at high temperature. A systematic programme of research is being carried out at Glasgow on the thermal properties of concrete under different heating regimes and on different types of concrete and the test results will be available soon.

Normally, for fire protection, the heating rate adopted is $5^{\circ}\text{C}/\text{min}$ ²³ but in our preliminary tests a nominal infinite heating rate was used. What changes in concrete properties would be caused by such a big difference in heating rate? To answer this question, we would like first to qualitatively discuss the effect of heating rate on the concrete subject to high temperatures and then present some results on the heating rate effect from our latest study.

When the concrete sustains a complete heating–exposure–cooling cycle, then heating rate, maximum heating temperature, exposure time and cooling rate are the four fundamental thermal parameters which influence the mechanical properties of the concrete. The first three parameters affect both *hot* mechanical properties that are tested at high temperatures and *cold* residual properties that are tested after cooling, and the cooling rate affects only the cold properties. During the heating stage, both heating rate and maximum heating temperature affect the thermal behaviour of the concrete. A faster heating rate normally leads to a higher thermal gradient and a higher hygric gradient. The former will cause a higher internal thermal stress but the latter will cause a higher rate of moisture evaporation from the concrete and sometimes forms a higher internal pore pressure especially if silica fume or pulverised fuel ash is used to make denser concrete with reduced porosity and smaller pore sizes. A higher heating temperature will make both gradients even higher. In particular, very high heating temperatures above 300°C can even cause explosive spalling of concrete.

The heating rate does not seem to affect the concrete

very much if it is subject to heating temperatures below 300°C . At the end of this stage, the heating rate will no longer have any effect and only the effect of maximum temperature will be significant. If at this point the concrete does not spall, the concrete properties will depend fully on later heating stages. Thus, maximum heating temperature seems a significantly more influential parameter than heating rate. In practice, an infinite heating rate may just be a nominal environmental rate but not the actual rate on the concrete because the temperature on the concrete surface could be much lower due to the existence of moisture within the concrete.

During the exposure stage, maximum heating temperature and exposure time affect the mechanical properties of concrete. However, exposure time only plays an important role in the early exposure stage. A longer exposure time will gradually reduce the thermal and hygric gradients. If the exposure time is sufficiently long, both thermal and hygric gradients will disappear and final thermal and hygric equilibrium will be reached. Thus, no thermal stress will exist and moisture migration will cease. At this point the concrete properties will not be further affected by exposure time. The exposure time needed for thermal and hygric equilibrium will vary with heating temperature. A longer period of several days may be needed for lower heating temperatures but a period of mainly several hours is sufficient for higher temperatures. Of course the exposure time also depends on the type of concrete and the geometric dimensions of the specimens.

During the cooling stage, both maximum heating temperature and cooling rate play an important roles with regard to concrete properties. A higher cooling rate would cause a higher thermal gradient, with the reverse being the case for the heating stage. Also a higher heating temperature will increase the reverse thermal gradient thereby resulting in more severe cracks due to incompatibility between cement paste and aggregates. This will weaken the concrete. When the maximum heating temperature is not very high, the cooling rate effect will not be as significant. It is clear that the maximum heating temperature dominates all three stages in a heating–exposure–cooling process and that it is a primary influential parameter. The other three parameters are also important but not so significant as heating temperature. In this respect, our test results may be slightly but not significantly conservative for the fire case.

The following presentation can confirm our explanation but the full results will be published in separate papers. This study was carried out on crushed siliceous dolerite basalt concrete rather than natural siliceous gravel concrete. The effects of heating regimes on the mechanical properties of concrete were investigated using a three-zone Vacua-Therm Sales (VTS) programme-controlled furnace. The heating regimes include different heating rates ($dT/dt = 1, 3$ and $10^{\circ}\text{C}/\text{min}$), maximum heating temperatures ($T_m =$

105°C and 150–450°C with an interval of 50°C), exposure times ($t_h = 4, 8$ and 16 h) and cooling rates (slow and fast cooling).

Fracture energy G_F and modulus of rupture f_r were tested on both hot and cold concrete beams, but compressive strength f_{cu} , splitting tensile strength f'_t and Young's modulus E were only tested on the cold specimens. The dimensions of the concrete specimens were the same as those in the original paper. The concrete was made of ordinary Portland cement, pulverised fuel ash, calcareous quartz sand, 10 mm and 20 mm dolerite aggregates, tap water and plasticiser with a weight ratio of 1:0.33:2.45:1.39:2.78:0.56:0.006. The specimens were cured in the water tank for 28 days after casting and removed from the tank but kept in the curing room for at least a further 60 days before heating to reduce the effect of curing age. At the time of testing, the material properties of the concrete at room temperature were obtained as: $f_{cu} = 67.1$ MPa, $f'_t = 4.47$ MPa, $f_r = 6.24$ MPa and $E = 35.6$ GPa. Figs 23–26 present these four residual properties of concrete heated for $t_h = 16$ h and with slow cooling to show the effect of heating rate together with maximum heating temperature.

The trends of these residual mechanical properties with heating temperature for dolerite basalt concrete are similar to those for siliceous gravel concrete shown in the paper under discussion. However, both f_{cu} and f'_t sustained a decrease–recovery–decrease process with T_m (Figs 23 and Fig 24). They first sharply decreased at 105°C and then slightly recovered; thereafter they continuously decreased with T_m . Further, f_r sustained an increase–decrease process with T_m (Fig. 25). At 450°C, f_{cu} , f'_t and f_r reduced by 20, 45 and 27% respectively for a heating rate of 3°C/min. It can also be seen that, in general, a higher heating rate would lead to a lower concrete strength but the decrease due to a higher heating rate was much smaller than that due to a

Fig. 23. Compressive strength plotted against heating temperature for different heating rates

Magazine of Concrete Research, 2001, 53, No. 3

Fig. 24. Tensile strength plotted against heating temperature for different heating rates

Fig. 25. Modulus of rupture plotted against heating temperature for different heating rates

Fig. 26. Young's modulus plotted against heating temperature for different heating rates

higher heating temperature. Meanwhile, the strength differences between 1°C/min and 3°C/min were much smaller than those between 3°C/min and 10°C/min. Here we consider the worst case where the heating rate increased from 1°C/min at 450°C: f_{cu} , f_t and f_r only decreased by 2.8, 6.1 and 1.7% for 3°C/min and by 3.8, 9.8 and 3.5% for 10°C/min, respectively. These figures are much smaller than those caused by decreasing heating temperatures. E almost linearly decreased with the heating temperature regardless of heating rates, down by 72% (Fig. 26). Again, these latest results confirm that maximum heating temperature is always the most dominant influential parameter and that the effect of heating rate as a secondary influential parameter on the mechanical properties of concrete is limited. Thus, the application of our results from thermal shock tests to the fire case will not be over conservative.

Effect of aggregate type

The type of aggregate is of great importance and significantly influences the mechanical properties of concrete at high temperatures due to its chemical composition and thermal property. In our study, we had planned to use several different types of aggregate: gravel, dolerite basalt, limestone and lightweight aggregates. These aggregates are quite extensively used in the manufacture of concrete for prestressed concrete reactor vessels and other industrial and domestic buildings. Gravel was chosen in the preliminary tests. As the initial aim was to compare the difference in mechanical properties of normal- and high-strength concrete, we tried to use the same ingredients but only varied the proportions to avoid the effect of aggregate type. We also planned some later studies for other normal- and high-strength concrete using different types of aggregate.

We agree with Dr Purkiss that uncrushed siliceous gravel might not be the best choice for making high-strength concrete compared with uncrushed calcareous limestone, but the former can still be used to make concrete with reasonably high strength for general purposes. As shown in Fig. 23, crushed siliceous dolerite basalt can make high-strength concrete subject to high temperatures. Generally, natural siliceous gravel sustains expansive cracking at about 350°C and thereafter causes severe damage that makes concrete less stable.²⁴ Siliceous and calcareous quartz sand sustains an inversion of quartz at 573°C, from α -phase to β -phase, which degrades the mechanical properties of concrete. Limestone sustains a dissociation of Ca(OH)_2 at 550°C and makes limestone concrete less stable. Limestone aggregates and calcareous quartz sand also undergo decarbonation at even higher temperatures. Basalt aggregates do not undergo phase change up to at least 800°C. Lightweight aggregates are very stable even at 600°C as they are manufactured at above 1000°C. Therefore, the utility of aggregates for high-strength and high-performance concrete to sustain high temperatures is very much dependent on environmental temperatures. Gravel concrete can be used for up to 350°C; limestone concrete can be used for up to 600°C; basalt concrete and lightweight concrete can be used for even higher temperature, say 800°C.

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