Fire and Concrete

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ABSTRACT

Concrete structures are frequently exposed to fire. Examples include buildings and tunnels. This imposes a thermal shock depending on the fire. Contrary to common belief, it is not only the maximum temperature that is important but also the rate at which temperature rises (e.g. the heating rate). The former determines the maximum temperatures within the concrete and the latter influences the likelihood that explosive spalling occurs. These are the two key subjects covered by this paper. Compressive strength is the most studied property of concrete in fire. It varies not only from concrete to concrete depending on its constituents and other factors such as external loading, heating and moisture conditions. During heating concrete also experiences thermal strain, shrinkage, as well as load induced thermal strain (LITS). LITS comprises several components such as transient creep. LITS acts to relieve thermal and parasitic stresses. Rapid heating during fire could induce explosive spalling with serious consequences to structure and people. The two mechanisms of explosive spalling are thermal stress spalling and pore pressure spalling. Thermal stress spalling could be reduced by the use of thermal stable aggregates of low expansion, while pore pressure spalling could be reduced by the use of polypropylene fibres in the mix. The fibres effectively induce permeability just when it is required. For existing structures, which a thermal barrier is the solution. Criteria for the thickness of thermal barriers are based on maximum temperatures. A more scientific approach is to consider other criteria such as heating rate and permeability.

KEYWORDS

Concrete, fire, testing, materials behaviour, strain components, modelling

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1. INTRODUCTION

Concrete is considered fireproof on account of its incombustibility and low thermal diffusivity. This is an advantage although concrete can also experience explosive spalling and deterioration of properties during heating which need to be understood and designed against either at the materials level and/or at the structural level. Decades of research have produced a considerable amount of materials data which could lead to confusion if not properly analysed and sorted. Despite the abundance of data, there still remain areas than need further studies and also clarification such as the design of fireproof concrete and also the cost-effective design of structures to withstand fires. There does not exists a universally agreed upon definition of fireproof concrete and the author recommends that an effort in that direction should be made. Numerical methods have made significant advances recently, especially with many authorities accepting performance based engineering design, but sadly numerical methods are still developing faster than the production of materials data that is required for their input. As a result, the outputs of computer models need to be carefully and critically examined to ensure their validity for the application in question.

Concrete structures are frequently exposed to fire. Examples include buildings and tunnels. The nature of the fire varies not only from application to another but also from fire to fire depending upon the fire load (fuel), the geometric configuration and the availability of oxygen. Figure 1 provides examples of deign fire scenarios for various applications. In this set, the least severe is the ISO 834 fire for buildings, while the most severe is the RWS fire for tunnels with a maximum temperature of 1,350^{o}C (i.e. above the melting temperature of concrete).

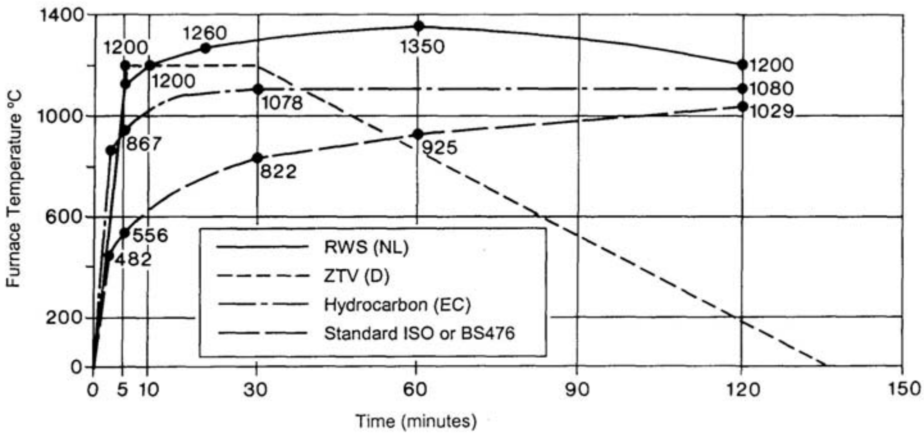

Figure 1. Examples of a few Standard fire scenarios. ISO 834 for buildings. Hydrocarbon for offshore & petrochemical industries, and the Dutch RWS or German ZTV for tunnels.

It should be emphasised that the maximum temperature is not the only or most critical criteria but also the heating rate (i.e. the rate of temperature rise). This provides the degree of “thermal shock” that the concrete is exposed to. For example, in the ISO 834 fire the temperature rises to 800^{o}C in about 20 minutes, while in the tunnel fires it could rise to 1,000^{o}C in about 4-5 minutes. The degree of thermal shock influences the amount of explosive spalling that usually takes place during the early stages of the fire. This is a structural phenomenon that depends upon the amount of moisture present in the concrete prior to heating, the thermal expansion of the concrete and its permeability. Both pore pressures and thermal stresses contribute to explosive spalling as experienced, for example, in the Channel Tunnel fire. The deterioration of mechanical properties such as compressive strength would depend upon the type of constituents used, the physico-chemical reactions that take place during heating and the maximum temperature reached. Therefore effective design of concrete against fire need to consider both explosive spalling and loss of mechanical properties. This is the primary purpose of research work carried out at the materials level. Sometimes, an optimal design cannot be made for reasons such as availability of materials or the fact that a concrete structure already exists. In such

cases, the introduction of a thermal barrier at the appropriate locations needs to be considered as well as a careful structural design to ensure that the structure does not collapse during a fire and that the safety of people is ensured.

This paper provides an up-to-date global view of the subject, giving a summary of the key issues that require consideration. First, the effect of heating on the mechanical properties of concrete is presented.. The two critical properties being the compressive strength and the strain behaviour. This is at the materials level. Second, the effect of fire on explosive spalling is discussed along with the measures to combat this problem. Between them, they comprise the major components of what fire safety design engineers need to know. In all cases, an in-depth approach is taken whereby the mechanism underlying behaviour are revealed. For information relating to structural configuration, assessment of fire resistance, other properties the reader is advised to read the FIB Bulletin 38 published in 2007 [1].

2. MECHANICAL PROPERTIES

2.1 Compressive strength

The effect of heating on the mechanical properties, and especially compressive strength, is the most studies aspect of the effect of fire on concrete. Compressive strength results shown in Figure 2 indicate an extremely wide variation but a more careful examination indicates that the results depend upon whether the tests were carried out hot or residual and in the sealed or unsealed condition.

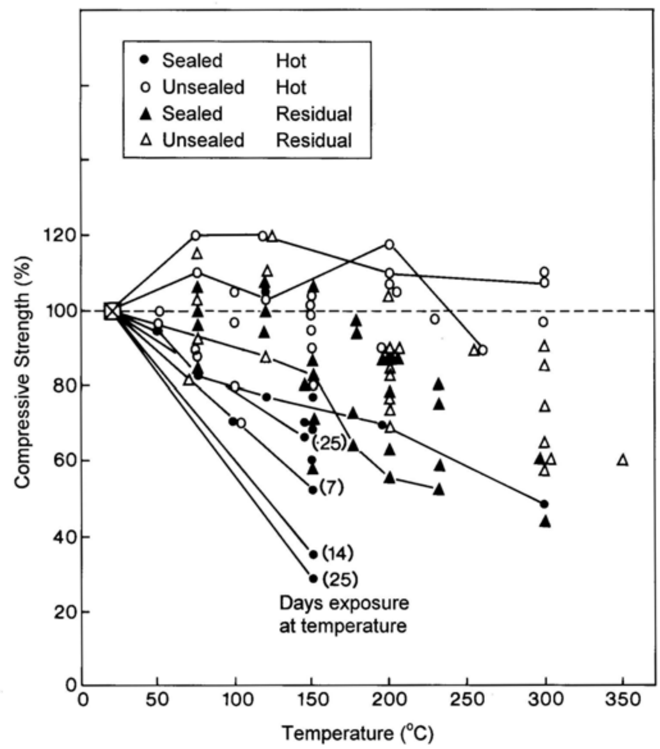

Figure 2. Scatter of compressive strength of concrete at elevated temperature under sealed and unsealed conditions [2].

Figure 3 presents trends rather than data points showing roughly the influence of different parameters. Therefore, Figures 2 and 3 give the reader a guide of the various environmental parameters are likely to influence the data output. However this is half the story, the critical influence is the concrete type represented by the choice of aggregate, cement blend and mix proportions including the water/cement ratio.

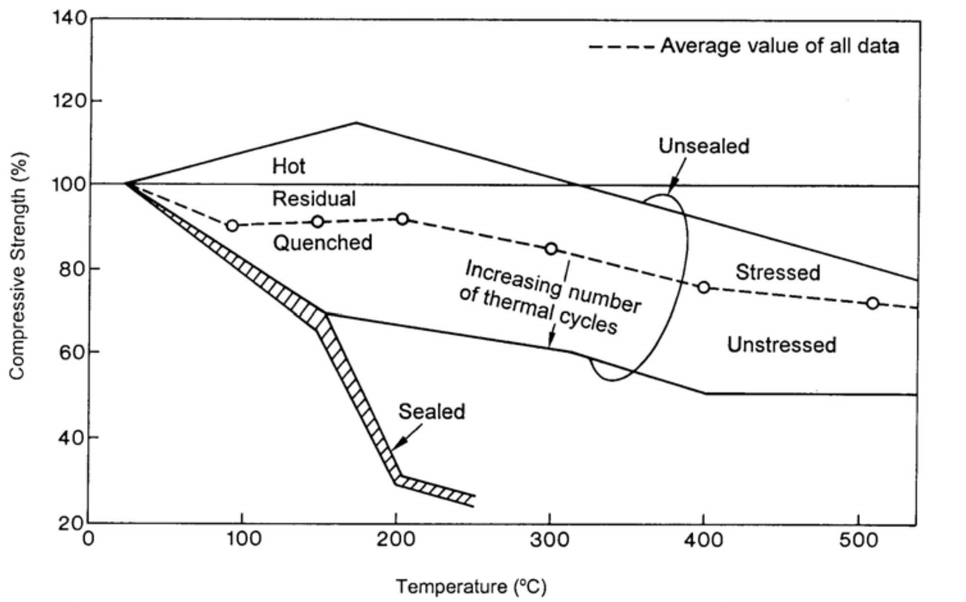

Figure 3. Trends of compressive strength of heated concrete depending upon the moisture, stress and point of test conditions [4].

Figure 4 shows tests on concretes using two different thermally stable aggregates and two types of cement blend. A thermally stable aggregate was chosen for scientific purposes in order to eliminate the complications arising from the thermal instability of the aggregate. The results show that even when thermally stable aggregates are employed a significant difference exists in the compressive strength-temperature results which could be explained by the strength of the bond with the cement paste, the better result was obtained with firebrick aggregate. The two cement pastes also showed significant difference with the slag mix registering the best results. Such studies indicate that concrete is a versatile material and its behaviour at high temperatures could be modified by the appropriate use of concrete constituents and proportions thus allowing the engineer to design the concrete fit for purpose.

The results in Figure 4 show that it is possible to design a concrete that retains most of its original strength even up to temperatures of 500^{o}C which in fire is experienced mostly near the surface.

Last but not least, a careful re-assessment by the author of the compressive strength of concrete at high temperatures [3] indicates different mechanisms influence the strength for the 4 stages of the heat cycle (Figure 5): (a) during heating, (b) at constant temperature, (c) during cooling and (d) post cooling. Importantly, contrary to common belief, not all the mechanisms are “degradative”. In fact some mechanisms can be beneficial thus resulting in gain of strength [3].

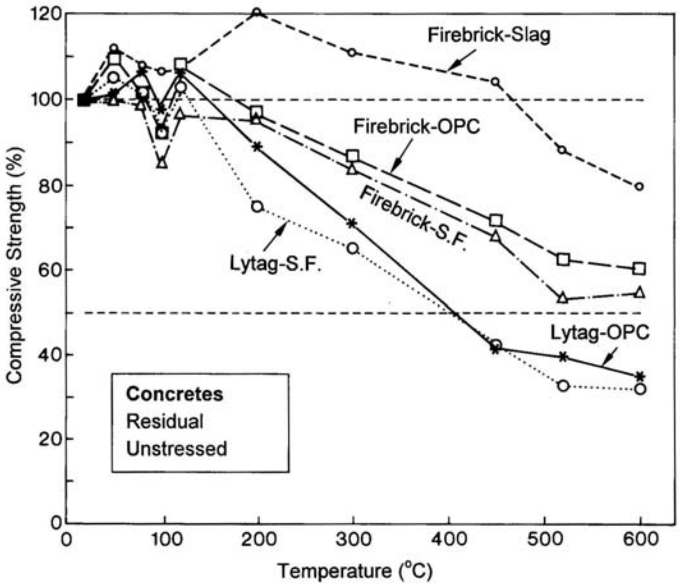

Figure 4. Even when thermal stable aggregates were used large differences in compressive results against temperature were obtained owing to the bond behaviour. The type of cement paste was also important [5].

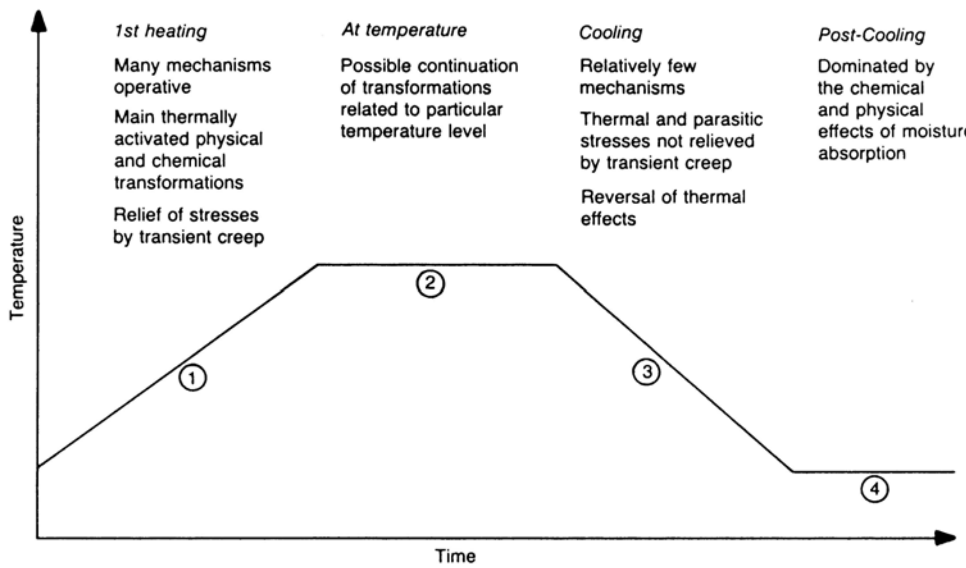

Figure 5. Factors influencing strength during the four stages of the heat cycle [3].

2.2 Strain behaviour

So far the analysis has been confined to one property. An extension of the same thinking to the strain behaviour of concrete during first heating reveals also that different mechanisms are operative. The thermal strain is dominated by the aggregate type while the Load Induced Thermal strain (Strain) is relatively unaffected by the aggregate type as it is seated in the cement paste (Figures 6-8).

The *Load Induced Thermal Strain (LITS)* is the strain that is derived directly from two measurements

on two specimens. It is essentially a measured strain comprising the difference in strain between the strain measured during first heating without load and that measured during first heating under load (Figure 6). It comprises three components of (a) Transient Creep; (b) “basic creep” and (c) changes in the elastic strain with temperature. LITS is irrecoverably on unloading and does not take place during cooling. LITS tends to relieve thermal and parasitic stresses within the concrete. It is for this reason that concrete does not break-up above 100^{o}C despite the very large strain difference between the expanding aggregate and the contracting cement paste. *Transient creep* is often confused with LITS but is in fact a component of LITS, albeit the largest. Some people also call it Transient Strain or Transient Thermal Strain. The key point is that transient creep one of the components of LITS.

Continuing on the theme of mechanisms, Figure 9 shows that the components of shrinkage and LITS could be separated for the period during first heating and that shrinkage and creep could be separated during the period of constant temperature after heating. The method by which this separation was carried out is explained in references [6-8]. Having separated the strain components it was then possible to develop a strain model of heated concrete as shown in Eq. 1 [8] which should include a cracking strain for concrete heated above the “concrete specific critical temperature” (Figure 10):

$$\varepsilon_{\mathrm{tr,\,tot}}^{\mathrm{T},\,\sigma,\,\mathrm{d}} = \varepsilon_{\mathrm{co,\,el\text{-}pl,\,i}}^{\mathrm{T},\,\sigma,\,\mathrm{d}} + \varepsilon_{\mathrm{tr,th}}^{\mathrm{T},\,0,\,\mathrm{d}} + \varepsilon_{\mathrm{tr,sh}}^{\mathrm{T},\,0,\,\mathrm{d}} + \varepsilon_{\mathrm{tr,\,lits}}^{\mathrm{T},\,\sigma,\,\mathrm{d}} + \varepsilon_{\mathrm{tr,\,crack}}^{\mathrm{T},\,\sigma,\,\mathrm{d}} \qquad (1)$$

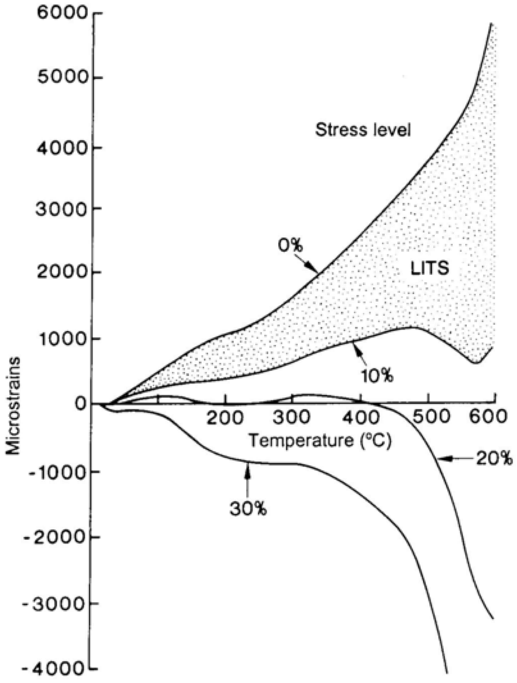

Figure 6. Definition of the Load Induced Thermal Strain (LITS) [6].

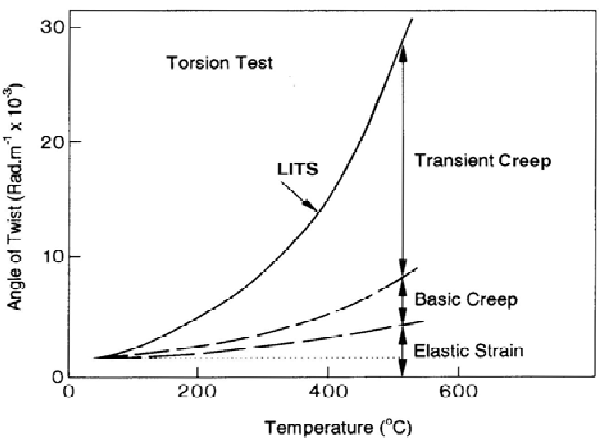

Figure 7. LITS contains three strain components [9]. Transient creep is a component of LITS. Often it is mistaken as LITS.

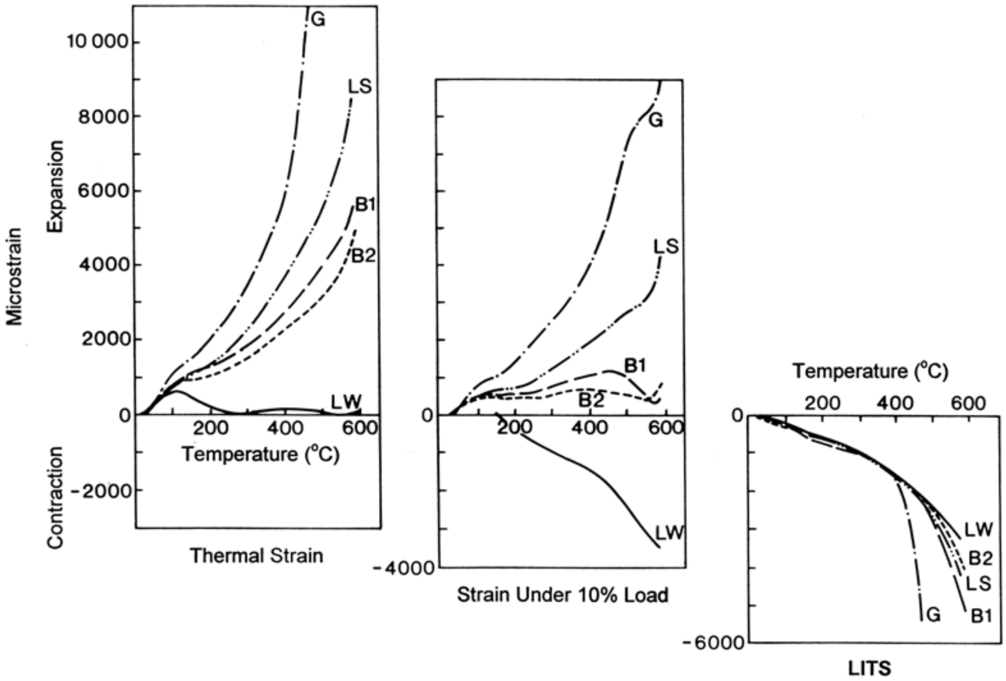

Figure 8. The thermal strain is dominated by the aggregate type but LITS is seated in the cement paste and is relatively unaffected by the aggregate type [6].

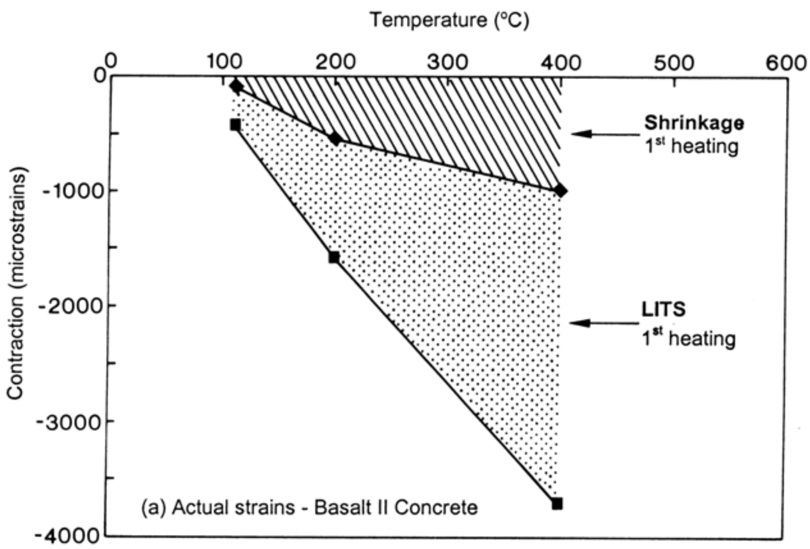

Figure 9. Separation of strain components during first heating [8].

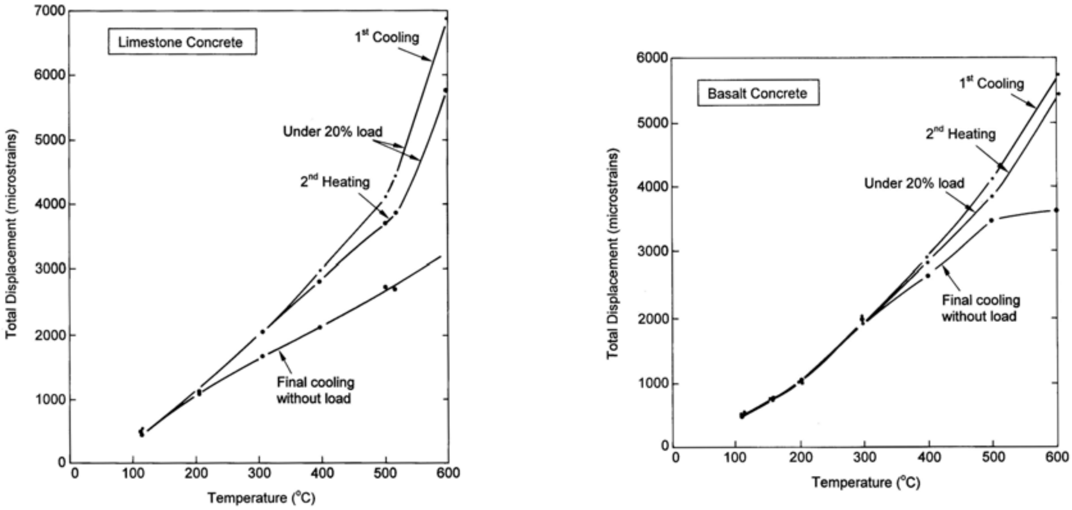

Figure 10. Specific critical temperatures for limestone (left) and basalt (right) concretes indicating that strain measurements are more sensitive that strength measurements [7].

3. SPALLING

3.1 Mechanisms of explosive spalling

Continuing the discussion on trends and mechanisms, a mention should be made of the subject of spalling. While some forms of spalling such as aggregate and post cooling spalling can be regarded as materials behaviour, the phenomenon of explosive spalling is in fact a structural one as it is the outcome of temperature, moisture, and stress gradients within the concrete. There are two mechanisms of explosive spalling:

- thermal stress spalling;
- pore pressure spalling.

Some authorities believe that it is the first and other authorities believe that it is the second. In fact it is a combination of both (Figure 11).

The relative importance of each mechanism depends upon the thermal expansion of the aggregate which contributes to thermal stress spalling and on the other hand the moisture content and permeability of the concrete which contribute to pore pressure spalling. In experiments, it is possible to separate out the two forms of spalling. For example, thermal stress spalling would not develop in a concrete that has zero thermal expansion as experienced with some lightweight aggregate concretes (see Figure 8). This allows the determination of the influence of pore pressure spalling. However it should be noted that lightweight aggregate is highly porous and the additional moisture in the pores would promote pore pressure spalling.

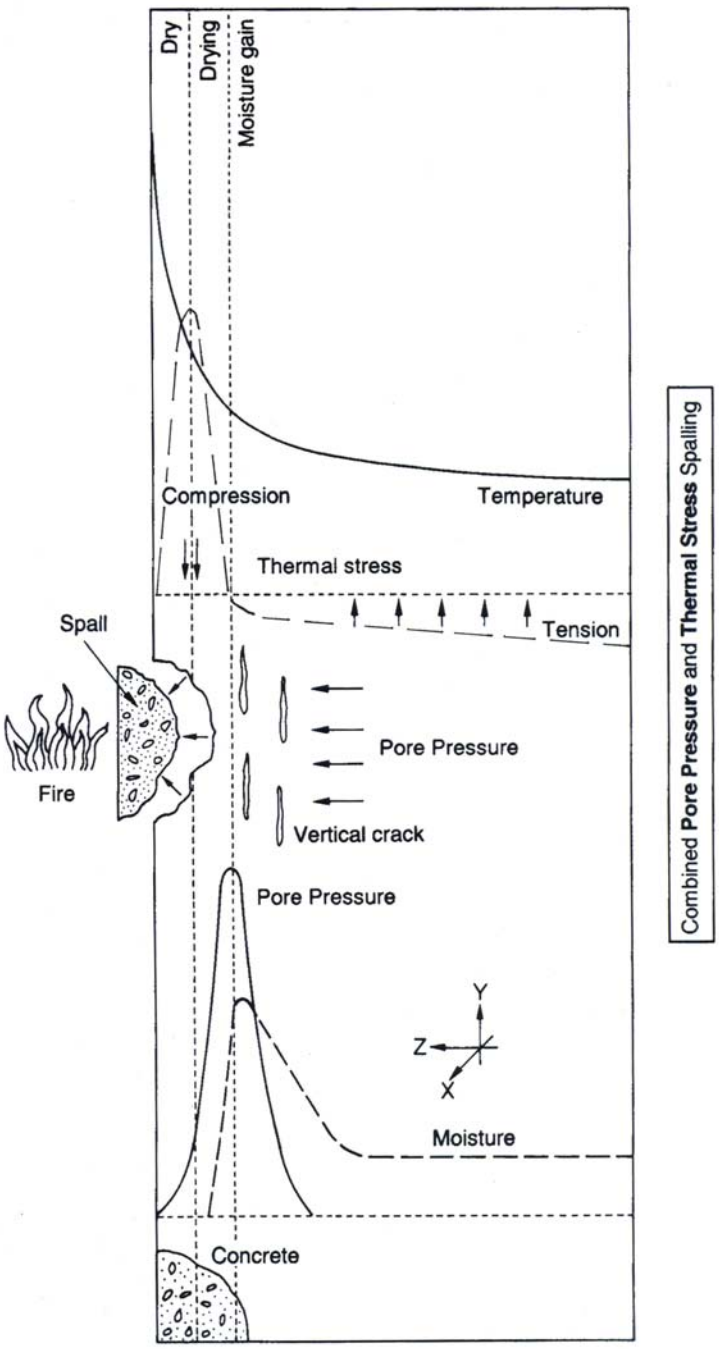

Figure 11. Explosive spalling as influenced by pore pressures and thermal stresses. Schematic, not to scale [10].

3.2 Preventing explosive spalling

Here again, in terms of prevention, the correct approach would be to address the mechanisms when it comes to the design of the concrete, or alternatively use a thermal barrier which could be significantly more expensive but which would also provide benefits in preventing the deterioration of mechanical properties owing the lower temperatures of exposure to the substrate concrete.

3.2.1 Thermal barriers

Criteria for determining the thickness of thermal barriers are currently based on specified maximum temperatures at the barrier/concrete interface. While this is acceptable in terms of limiting the deterioration of the mechanical properties of the concrete it is fundamentally flawed in terms of combating explosive spalling of concrete. This is because explosive spalling usually occurs in the early stages of a fire during rapid heating of the surface that induces both high thermal stresses and pore pressures. Explosive spalling is, therefore, more a function of the heating rate (i.e. rate of temperature increase) than the maximum temperature.

The author proposes in this paper that authorities should consider a heating rate criteria for determining thicknesses of thermal barrier instead of specified maximum temperatures. More comprehensively, other parameters should also be brought in - such as type of concrete (e.g. aggregate type, strength-permeability and silica fume content) as well as initial moisture content.

3.2.2 Concrete mix design

Design of the concrete mix is possible in new structures and logically not in existing structures. Should existing structures be found at an unacceptable risk of spalling and/or concrete damage then upgrading by employing a thermal barrier is the only solution.

For new structures, the concrete mix could be designed bespoke to limit the extent of the deterioration of mechanical properties with temperature and reduce the risk of explosive spalling. Design of the concrete mix against explosive spalling could be achieved by the use of polypropylene fibres which act in a complex manner to reduce pore pressures and hence the pore pressure mechanism of explosive spalling. Low thermal expansion aggregates would be useful in combating thermal stress spalling but these may not always be readily available locally at the best price. This may leave only PP fibres which are of significantly lower cost per surface area than thermal barriers but which do not reduce temperatures in any appreciable sense nor address thermal stress spalling.

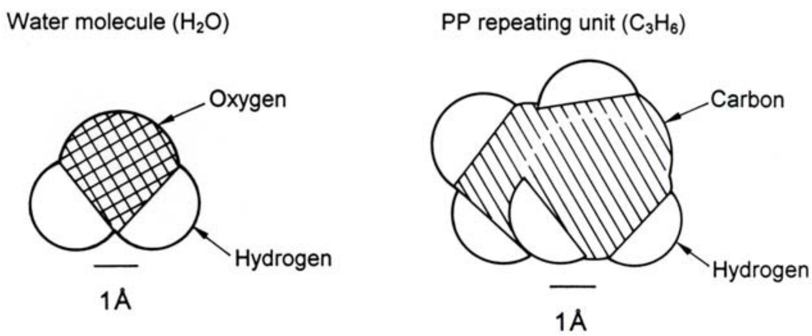

Figure 12. Representation of a water molecule and a polypropylene repeating unit (C3H6) in the space filling format. Units in Angstroms [11].

To date, it has been generally assumed that the mechanism by which PP fibres reduce pore pressure is by vacating channels upon melting through which steam would escape. This is erroneous because the melted fibres are hydrophobic, have large entangled molecules and very high viscosities. It is only when the melted fibres vaporise to low molecular size hydrocarbons of irrelevant polarities that flow of the hydrocarbon becomes easy through the concrete pore structure.

Given the hydrophobic nature of PP fibres and very low elasticity compared with concrete, a possible mechanism is via the creation of vapour pressure induced tangential spaces (PITS) of micron capillary size induced by the rupture of the weak fibre-concrete interfaces to allow water-steam to migrate within the concrete at temperatures above about 100^{o}C even before the fibres melt. It should be noted that explosive spalling usually originates from the part of the concrete that is at about 150-250^{o}C, i.e. before the start of pyrolysis. So the important pressure reduction mechanisms, such as PITS, are those that operate within the temperature range of 100^{o}C to about 250^{o}C. This mechanism is a function of

the total surface area of the fibres within the mix.

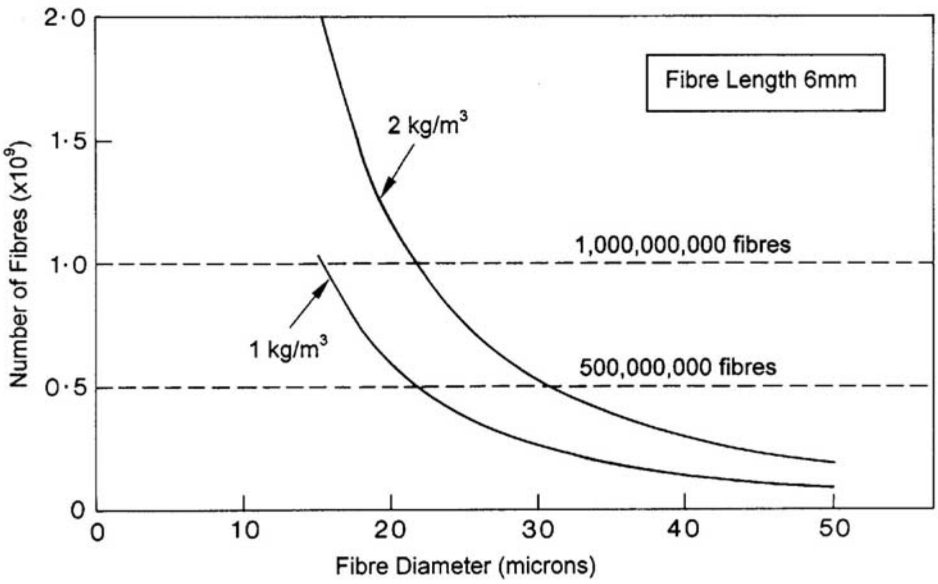

Figure 13. Total number of fibres as a function of fibre diameter for 1 and 2 kg/m3 fibre content of concrete and 6mm fibre length [10].

Other mechanisms contributing to pressure reduction include “reservoirs” such as air bubbles and microcracks induced by the presence of the fibre to accommodate the expanding steam. The aspect ratio of the fibre that is often mentioned is in fact meaningless while the important parameters are the fibre diameter and length which influence the number of fibres and the cumulative total surface area. However, there is a critical fibre length below which interconnectivity would not be possible. If the fibre is too long then there will also be a problem with dispersion and mixing. Last but not least a note of caution should be given relating to the results of microstructural and other tests carried on the composite after cooling. Such residual tests would not necessarily pick up all the hydro-thermo-mechanical transformations that take place dynamically during the heating process and which contribute to explosive spalling. An example is permeability, microscopy and in the extreme case pore pressures. Conclusions of pore reduction mechanisms based on residual properties could, therefore, be limited and even misleading.

4. THE AGGREGATE

The importance of the aggregate is often seriously underestimated. It is clear from the foregoing discussion on compressive strength and thermal strain that the aggregate is a dominant factor in concrete behaviour at high temperatures and during fire. This is clearly shown in Figures 4, 8 and 10. Yet people often refer to “concrete” in a generic sense when in fact “concrete” does not exist in a generic form during fire since the behaviour is dominated by aggregate type. This serious error is also extended to structural analysis where the simplified isotherm method is mistakenly referred to as the 500^{o}C isotherm method in the Eurocodes when in fact the 500^{o}C refers to siliceous concrete but cannot be extended to refer to river gravel concrete which could break up at 350^{o}C or flint concrete which could break-up at 250^{o}C. Such errors will result in unsafe analysis of fire design of concrete structures.

5. OVERVIEW

Finally, A summary of the physico-chemical processes that take place in concrete during heating [12] is represented by the author in a thermometer analogy starting from ambient temperatures up to melting as shown in Figure 14.

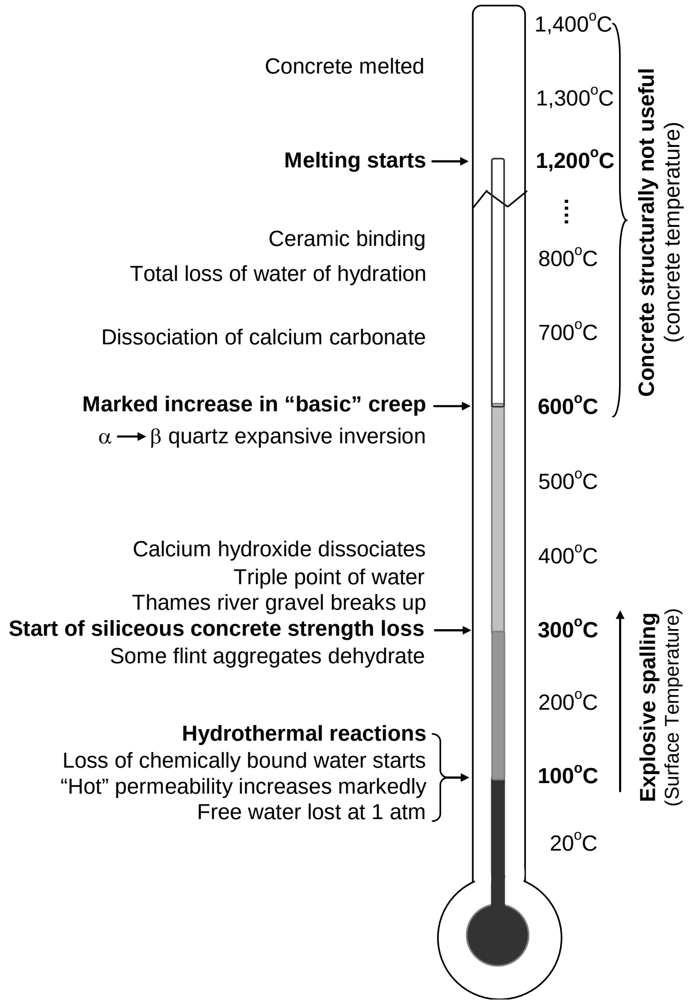

Figure 14. Simplified global presentation of physico-chemical processes in Portland cement concrete during heating in a "thermometer" analogy – for guidance only [12].

6. CONCLUSIONS

Fire exposes concrete to thermal shock depending on the fire scenario which could be more severe in the case of a tunnel fire than building fires. Contrary to common belief, it is not only the maximum temperature that is important but also the rate at which temperature rises (e.g. the heating rate). The former determines the maximum temperatures within the concrete and the latter influences the likelihood that explosive spalling occurs.

All mechanical properties of concrete are influenced by heating. The compressive strength, for example, varies not only from concrete to concrete depending on its constituents (e.g. aggregate and cement blend) but also on other factors such as external loading, heating and moisture conditions. Furthermore, the measured compressive strength of concrete depends on the point at which it is measured. Usually, "residual" strength measured after cooling is lower than "hot" strength.

During heating concrete also experiences thermal strain, shrinkage, as well as load induced thermal strain (LITS). LITS comprises several components such as transient creep which is irrecoverable and

above 100°C is essentially a function of temperature rather than time, “basic” creep which is a function of time and temperature and changes in the elastic strain with temperature. LITS acts to relieve thermal and parasitic stresses without which concrete would break-up during first heating.

While compressive strength as the usual measure of the quality of heated concrete, strain measurements provide a more sensitive indication and can reveal the concrete specific critical temperature which depends on the concrete constituents, but chiefly the aggregate. Cracks begin to dominate the strain above this critical temperature.

The strain model of concrete in fire should consist of a crack-induced component as well as the LITS, thermal strain, shrinkage and the elasto-plastic components.

Rapid heating during fire could induce explosive spalling with serious consequences to structure and people. There are two mechanisms of explosive spalling, thermal stress spalling and pore pressure spalling. The former essentially depends upon the thermal expansion and thermal stability of the aggregate, while the latter depends upon the initial moisture content and the permeability of the concrete – essentially the cement paste. Thermal stress spalling could be reduced by the use of thermal stable aggregates of low expansion, while pore pressure spalling could be reduced by the use of polypropylene fibres in the mix. The fibres effectively induce permeability just when it is required (i.e. during the fire). Concrete mix design cannot be considered in existing structures, for which a thermal barrier is the solution. Criteria for the thickness of thermal barriers are based on maximum temperatures. A more scientific approach is to consider other criteria such as heating rate and permeability.

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