The Accelerated Drying of Refractory Concrete – Part I: A Review of Current Understanding

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The drying of refractory and *Portland* cement concretes has been studied by engineers and scientists for many years and lately research is driven by the need to understand the damage mechanisms to public infrastructure from fires. The development of high performance concrete (HPC), self-compacted concretes (SCC), low cement refractory concrete (LCC), ultra-low cement refractory concrete (ULCC) and no cement refractory concrete (NCC) by selecting the particle size distribution to improve packing and replacing cement with ultrafine particles such as silica fume and hydrateable alumina has enabled compressive strengths to increase to >100 MPa. This means there is an even greater demand on engineers to understand the forced drying of these materials.

Fig. 1 View of exploded refractory panel (LCC), which occurred during dryout

Introduction

Currently, the drying of refractory concrete is routinely carried out by placing gas burners in process vessels and the burners are controlled such to heat the concrete up at a rate prescribed by refractory material suppliers. It is generally well-known that these heating schedules are based on historical trial and error approach and consequently damage to these concrete structures still occurs.

Understanding the effects of different heating rates on green concrete structures is of primary importance to engineers and industry. This is because heating of concrete and refractory materials can result in serious problems, particularly if an explosive spalling event occurs. If an explosive spalling occurs, projectiles of reasonable mass (1–10 kg) can be thrust violently over many metres. While surface spalling is less violent the extent of damage can still be severe and in both cases repairs will be required resulting in significant costs to industry.

There are two drivers for spalling of concrete – thermal strain caused by rapid heating and internal pressures due to the removal of water. Thus being able to predict the outcome of different heating rates on thermal stresses and internal pressure during water removal is particularly important to industry and other concrete structures.

This research investigated the literature results of concrete drying and the critical parameters that effects drying. In part II of this paper the development of a 1D numerical model and the results are presented.

Since the publication in 1978 by *Bazant* and *Thouguthai* [1] on the theory of concrete drying, considerable research has been undertaken by many researchers. However, the problem of predicting safe heating rates for refractory concrete and the mechanism that causes spalling during drying is still debatable and three possible reasons are favoured [2, 3]. These mechanisms are – localized constraint by a colder zone of a heated plate, which results in compression of the heated surface, the buckling model and the compression splitting crack model. Essentially, these models assume compression of the heated surface combined with internal vapour pressure.

Concrete failure and pore pressure

The mechanisms which can cause concrete spalling accepted by researches are described as:

1) localized constraint of a heated plate by a colder zone which results in compression of the heated surface,
2) shear due to surface compression and internal vapour pressure (moisture clog),
3) buckling of the surface by thermal compression and hydraulic spalling [2]. Also it is generally accepted that spalling occurs when the material's tensile stress is exceeded.

The difficulty in determining the tensile strength of refractory concrete is the lack of

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Fig. 2 Explosive spalling of high performance concrete (Noumowe et al. [7])

published data particularly at high temperatures. While bending strength is well published, it is not the material's tensile strength and if used will overestimate tensile strength.

Explosive failure of concrete is a particularly bad case not only because of the damage to the concrete structure, but because large mass can be thrust over long distances at great speed. With refractory concrete the risk to human life is small because the explosion is confined, but the repair cost can be significant. It seems logical for an explosion spalling event to occur there must be a sufficient instantaneous energy release to thrust a mass through space over several metres. Fig. 1 shows the extent of damage for an exploded refractory panel which occurred during dryout.

A quick check of the force to thrust a projectile through space can be estimated from ballistic theory. This shows that a mass of approx. 1,1 kg can travel a distance of approx. of 35 m at a velocity of 17 m/s. The pressure required is approx. 1,8 MPa. The sudden release of pressurized vapour from superheated water when a crack propagates within a concrete body can release sufficient propellant to ensure a pressure wave can thrust the concrete mass. Thus, it seems quite realistic that vapour pressure and superheated water have sufficient energy to cause an explosion spalling event.

Moore et al. [4] studied the dehydration of 60 mass-% alumina refractory concrete-panels measuring 600 mm × 600 mm × 150 mm with 15 mass-% CAC[1] and 0,05 % organic fibre as part of a large industrial study. The water content was 11 mass-%. The panels were subject to very rapid heating to approx. 250 °C followed by slower heating rates and hold periods up to a max temperature of 600 °C. Moore et al. [4] concluded that spalling was controlled in part by pore pressure which in turn is a function of the material's permeability. It was also reported that flat panels are more problematic than cylindrical geometries. The maximum pore pressure recorded during testing of these panels is reported [1] was approx. 1,7 MPa, measured less than 1 cm from the hot face after approx. 3 h.

In the same series of tests *Velez et al.* [5] studied the drying of two refractory concrete types with 8 mass-% and 3,5 mass-% CA cement. The compressive strength of one castable was 51,7 MPa (25 °C) and the other castable was 12,4 MPa (25 °C); one normal strength concrete and one low strength concrete. The diametral tensile strength was 8,27 and 0,09 MPa, respectively.

The main difference between the castables was the cement content and the apparent porosity. One important aspect of this test was that water was pushed out of the cold face indicating pore pressure will drive liquid water from the cold face surface. The pore pressure of the estimated pore was about 1,8 MPa and was lower that steam table values. The general consensus was that pore pressure could exceed the material's tensile strength and is dependent on permeability, firing time, thickness and heating rate.

Hipps and *Brown* [6] carried out experimental study and measured the vapour pressure in hydrated cement mixes using DSC and strain gauge pressure probes. The sample size was 180 mm × 230 mm × 150 mm and one end of the sample was placed into a pre-heated furnace (with a guillotine door) at 538 and 927 °C, respectively. Pressure probes were placed ever ½" from the hot face. The maximum pore pressure recorded for the lower temperature (538 °C) was 1,34 MPa at a depth of 38 mm and 0,83 MPa for the high temperature (927 °C) case at a depth of 25 mm. In these tests "sheet like" spalling occurred in all samples for the 927 °C-case and the explosions were described as *"violent and occurred within a matter of seconds"* (before pressure could be recorded) after placement into the furnace loosing layers of approx. 13 mm thick. It was concluded that resistance to explosive spalling is largely determined by casting water, castable thickness, method of placement and curing temperature and the material properties influencing spalling include permeability, cement bond strength, thermal conductivity and mix design.

Noumowe et al. [7] studied two high strength OPC[2] concretes, one standard high strength concrete with PP-fibre and a lightweight concrete without PP-fibre. During testing the lightweight concrete samples exploded between 290 – 430 °C as shown in Fig. 2 and the concrete with PP-fibres (2 kg/m^3 concrete) did not explode.

Jansson [2] measured the pore pressure in self-compacted (OPC) concrete with a 28 day compressive strength of 37 MPa. The heating schedule followed ISO 834, which means a temperature of approx. 700 °C was reached in about 10 min. The maximum pore pressure measured was 1,7 MPa at a depth of 10 mm and no spalling occurred. Other tests measured only low pore pressure, approx. 0,3 MPa, before spalling. From these tests it was concluded that pore pressure alone does not cause explosive spalling.

The use of microsilica sol bonded refractory (NCC)[3] has gained attention since the bonding mechanism was first published in 1995. Since then, there has been large amount of technical literature published. One of the main attributes put forward for this type of material is the ability to be rapidly fired due to the type of molecular bonding and the material's high permeability. Research by *Myhre* [8] postulates that bonding or stiffening occurs by polymerization of silanol groups that exist on the surface of the nanosilica particles.

Stiffening can also be controlled by pH and the introduction of cations like Ca^{2+} and Mg^{2+}. *Myhre* [8] studied explosion resistance of NCC and LCC[4] samples placed in a furnace and progressively heated for 30 min to a set temperature (specimen size effect ignored). It was found that the NCC exploded at 350 °C while the LCC sample did not explode. It was not until 600 °C did the LCC sample fail. It was thought the NCC sample

[1] Calcium aluminate cement
[2] Ordinary Portland cement
[3] No cement castable
[4] Low cement castable

would not fail due to the lack of bonded water. The test was rerun after the samples were oven dried at 110 °C to remove free water and on this occasion the LCC failed into two pieces at 600 °C and the NCC sample did not fail even when heated to 1200 °C.

Jansson [2] also reported in this thesis that experiments carried out by *Shorter* and *Harmathy* on concrete known to spall when pre-dried did not spall.

The authors` conclusion from these tests is that water of crystallization is not responsible for explosive spalling but free water is and rapidly heated LCC can fail due to transient thermal stresses.

Water removal

The removal of water from a porous concrete plate by heating one surface occurs by diffusion and steam pressure, i.e. due to differences in humidity and vapour pressure. As the temperature at the surface starts to move inwards a number of processes occur. Firstly, the material will dilate as temperature increases, then progressively the material's permeability will start to increase due to thermal structural changes to the cement matrix/aggregate followed by burn out of polypropylene (PP) fibre but this does not start until the temperature reaches approximately 160 – 180 °C.

Eventually the temperature is hot enough and water starts to evaporate and move through the pores towards the heated surface due to pressure and humidity differences. However, the movement of water vapour is impeded due to the capillary size and the fact that capillary water does not evaporate at 100 °C which further restricts gas flow.

This resistance to gas flow means pressure will develop within the concrete body and there will exist a zone where boiling occurs. Depending on the temperature and pressure steam and liquid water can coexist and that starts at 100 °C if the pressure is at 1 atm. Thus on one side of the boiling zone steam exists and on the other side liquid water exists. The "moisture clog" zone [5]. However, at 100 °C very little structural changes to the material have occurred, any PP-fibre has not burnt out and any dilation changes are very small and liquid water is more resistant to flow due to is viscosity. It is these factors that contribute at pressure build up within a refractory concrete.

Thus a material permeability is very important and understanding permeability changes during curing and heating is critical to predict water flow and pressure development. There has been a significant research on permeability and *Innocentini et al.* [10] carried out steam flow rate measurements on a wetted pre-fired refractory concrete[5)] with no PP-fibre and found that the total flow rate increases rapidly (limited by the flowmeter) reaching a peak at approx. 100 °C for a heating rate of 1 K/min. When heated at 5 K/min the hot gas flow rate increases slowly than the 1 K/min case then dramatically increases to a maximum followed by a dramatic decrease and thereafter the measured flow was erratic.

In both cases the peak flow rate occurred at approx. 100 °C. The results also show outlet temperature was constant at 100 °C while the inlet gas temperature continues to increase. The same steady temperature trend was seen at the lower heating rate but to a lesser extent. This constant temperature point was attributed to the heat of water evaporation. Depending on how the temperature was measured at this location the steady state temperature could be liquid water is ponding on the sample surface before evaporation. If evaporation of the water had occurred at or near the sample surface then an increase in the steam temperature would be expected as there should be sufficient thermal inertia in the furnace. The phenomena of water ponding on the unheated surface is not uncommon and has been reported by *Jansson* [2] during their tests on concrete (Fig. 4) and *Velez et al.* [5] who reported that water came out of the cold face during drying/firing of their test panels.

The test undertaken by Innocentini et al. [11] (Fig. 4), for a pre-fired sample[6)], with similar particle packing as described above in footnote 6), was saturated with water and dried in a TGA oven at constant heating rates are shown Fig. 4. The heating rates in this test are similar to the permeability test heating rates but in this case the peak mass water removal rate in this case is approx. 50 and 60 °C for heating rates of 0,9 and 6,4 K/min, respectively.

Fig. 3 **View of water on the cold surface of heat concrete [2]**

Fig. 4 is the mass water loss rate under axisymmetric temperature and internal vapour pressure. The volume water loss sample was more "disc" like in shape (40 mm diameter and 25 mm thick) while the mass water loss sample was "cylindrical" like (40 mm diameter and 40 mm thick). The two tests characterize the differences between water movement within a concrete body under different driving forces.

The tests by Innocentinni et al. [11] show a slow heating rate means the whole sample has time to reach temperature equilibrium linearly. While a rapid heating rate means the sample has a greater temperature differential to the furnace air. Also their experiments the sample temperature remains relatively steady at approx. 30 °C while rate of water loss increases significantly with heating rate. The difference between the sample temperature and the furnace temperature is expected for natural convection.

In the case where pressure and temperature is applied [10] the test shows the majority of the water is removed quite quickly and intuitively it would be expected that liquid water would be pushed through under pressure to the opposite surface as discussed above.

In fact, the physical evidence shows that liquid water, along with steam, is pushed through concrete during drying.

5) High alumina refractory castable with 2 % hydratable alumina binder and *Andreasen*'s packing model coefficient (q) of 0,21. Samples were cylinders of 7,5 cm in diameter and 2,5 cm in thickness with 4 cm surface exposed to air flow. Temperature was measured with K-type thermocouples at the entrance and exit chambers.

6) Samples were 4 cm diameter and 4 cm thick cylinders. A thin K-type thermocouple was inserted at the centre line 2 mm below the upper surface.

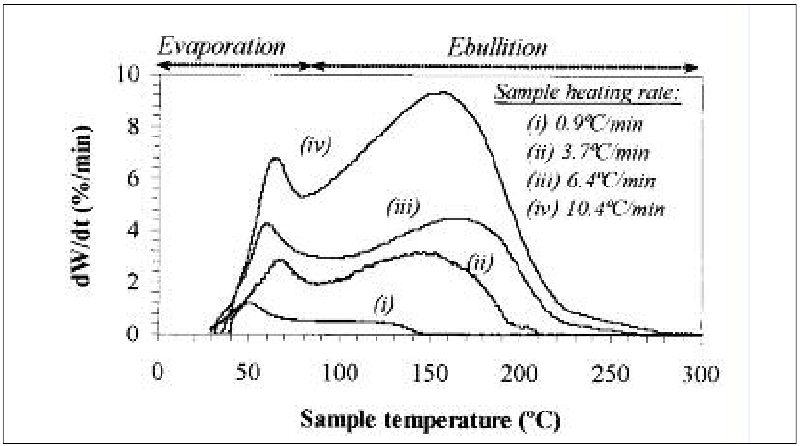

Fig. 4 **Innocentinni et al. [19] removal of free water in a TGA over – sample pre-fired to 800 °C**

Not only can the movement of liquid water and steam vapour be aided by vapour pressure gradients the thermal expansion of water can also aid in this process. As discussed earlier, water expansion can cause very high pressures if the constraining volume restricts water movement. In the case of open pores water could be constrained in the circumferential direction but not in the axial direction. It is the relief of pressure in the axial directional that causes the water to be "pumped" through the porous network.

Permeability

Permeability is an empirical parameter, which relates the rate of fluid flow to pressure drop and is defined by *Darcy*'s law. It can be seen that permeability plays significant role in the removal of water as discussed by many authors [1, 4, 12].

It is also the general consensus that the permeability of a concrete must increase with temperature and there are two factors that can contribute to this increase.

Firstly, the thermal mismatch between the concrete constituents from dilation and shrinkage and secondly, by addition of organic fibre. To understand the material effects *Kakroudi et al.* [13] evaluated the thermal effects on two commercial castables, a low cement andalusite castable (And-LCC) and an ultra-low cement bauxite castable (Bau-ULCC). The dilation and elastic modulus curves as a function of temperature for the LCC refractory concrete is shown in Fig. 5 and the ULCC refractory concrete in Fig. 6. The dilation curves show a small but detectable shrinkage during heating at approx 200 °C to 300 °C. The amount of shrinkage in the ULCC is less noticeable than the LCC sample. On the other hand the change in *Young*'s modulus for the LCC sample over the range from 150 °C to 300 °C is strong and occurs due to the dehydration of calcium aluminate hydrates from cement and continues to decrease up to approx. 900 °C. The changes at higher temperatures are of less interest as the drying has finished by this time. A similar trend can be seen in the ULCC castable but the decrease in Young's modulus is less and does not start until 290 °C. Thus, it would be expected that the permeability for the LCC material will increase with fired temperature but less so for the ULCC material. Fig. 7 shows the dilation for one low cement concrete and one conventional concrete when first heated. The shrinkage between 200 – 300 °C for the conventional refractory concrete is significant with some densification most likely due to clay dehydration in the gunning mix, while the expansion of the 45 % alumina LC concrete shows the effect of silica in the mix. In each sample it is expected that damage effect as discussed above could be expected. For a non-cement (NCC) sample tested by Innocentini et al. [10] it was concluded that thermal expansion effects in the high alumina castable with hydrateable binder and no PP-fibre fired at 1350 °C leads to small but perceptible increase in permeability.

In concrete *Bazant* and *Thouguthai* [1] account for changes permeability by proposing permeability as a function of temperature (T) and when T is >95 °C the initial permeability, *a* is expressed as:

$$a = a_o' exp\left[\frac{T-95}{0.881+0.21(T-95)}\right] \text{ and}$$

$$a_o' = a_o exp\left[\frac{Q}{R} * \left(\frac{1}{273+T_o} - \frac{1}{273+T}\right)\right] \quad (1)$$

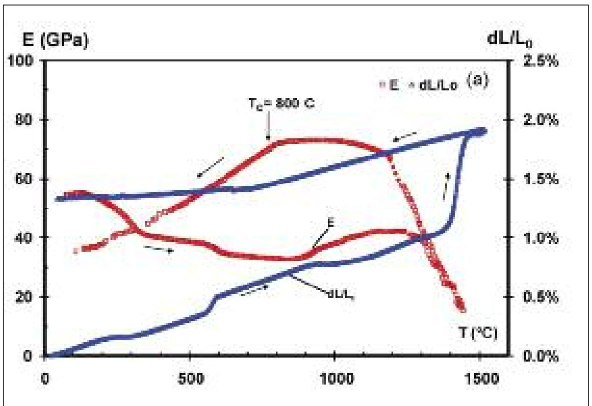

Fig. 5 **Variation of the Young's modulus measured by the ultrasonic technique (Eus) and thermal expansion for castable – And-LCC [6]**

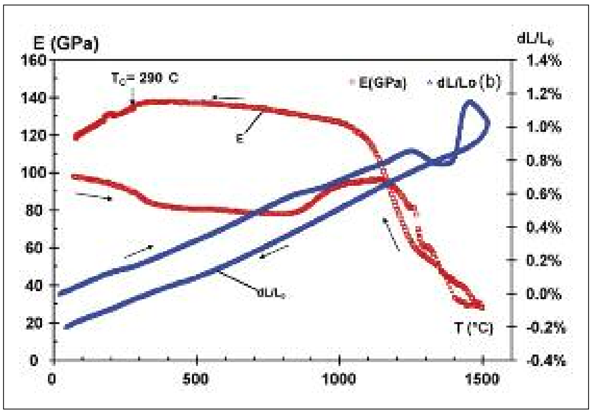

Fig. 6 **Variation of the Young's modulus measured by the ultrasonic technique (Eus) and thermal expansion for castable – Bau-ULCC [6]**

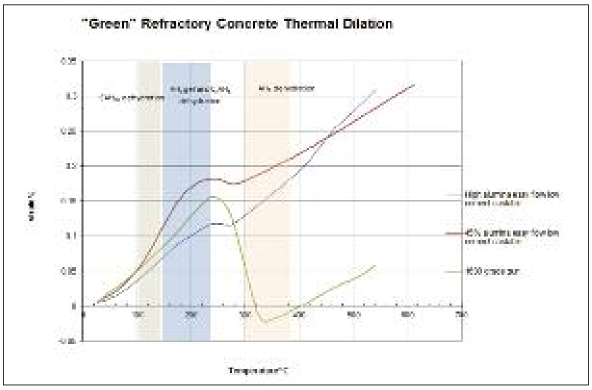

Fig. 7 **Dilation of standard and LCC refractory concrete with temperature**

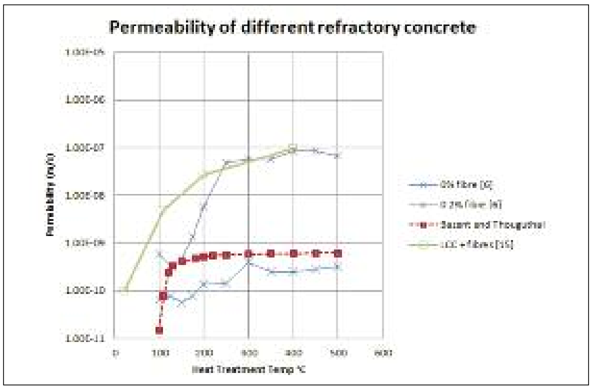

Fig. 8 **Permeability of refractory concrete [1] – civil concrete as predicted by Gong and Mujumdar [14]**

where a_o is the reference permeability at 25 °C, Q is the activation energy for low temperature moisture diffusion (38,912 J/mol) and R is the gas constant 8,314 J/mol·K. This equation was used by *Gong* and *Mujumdar* [14] for refractory concrete permeability. A plot of this equation is shown in Fig. 8 where it is compared other refractory concrete.

Ribeiro et al. [15] measured the permeability for a high-alumina, ultra-low cement refractory concrete, without PP-fibre using standard procedures. The permeability constants determined from *Forchheimer*'s equation:

$$\frac{P_i^2-P_O^2}{P_oL} = \frac{\mu}{k_1}v_S + \frac{\rho}{k_2}v_S^2 \qquad (2)$$

under hot gas conditions [15]. The first term on the RHS of this equation is the viscous energy loss, which is applicable only for slow viscous flow and the second term is the inertial energy loss, normally only applicable for highly porosity material.

The use of the inertial effect in the Darcy equation is used to account for the non-linear effect of the pressure drop is only applicable for high *Reynolds* numbers and in this case the Reynolds number is likely to be <1,67. Experimental studies on flow through porous bodies show that the change from linear (Darcy's law) to nonlinear behaviour is more likely to be gradual and the second term can be expressed as a frictional Reynolds number for many porous materials over a broad range of flow conditions. The deviation of the modified Reynolds number (Re' ≡ $\beta\rho\varsigma/\alpha$) defined by *Andrade et al.* [16] from linear to nonlinear behaviour for a highly porous body is in the range of 10^{-2} < Re' < 10^{-1} and in the region 10^{-2} < Re' < 1,8 the Forchheimer equation generally overestimates the friction factor. *Andrade et al.* [16] concluded that the Forchheimer model is valid for low Re and also for a limited range of high Re numbers, even when inertial nonlinearities can significantly affect the momentum transport at the pore scale.

Ribeiro et al. [15] measured the permeability on prefired samples with temperature and the results are given in Fig. 9. The permeability for the dried sample, 110 °C, shows a strong decrease up to about 130 °C followed by a large increase at approx. 180 °C. The corresponding airflow, shown in Fig. 10, has a strong decrease from approx. 100 – 270 °C, which, from the Darcy equation, suggests the permeability in this area can decreases. The permeability for the 300 °C pre-fired sample shows a general increase over the temperature range to 300 °C. This may be due to the removal of capillary water and alumina gels that may have formed during curing. The 600 °C pre-fired specimen has a slight higher permeability than the 300 °C pre-fired sample but an overall general permeability increase. Thus is it seems clear that permeability can increase and decrease with temperature during the critical drying or water removal stage.

Above 900 °C the sample's permeability, while having some variability, is more constant than during the drying temperature range, ambient to 300 °C. Ribeiro et al. [15] concluded that explosive spalling is correlated to the lower permeability and disturbed airflow caused by the dehydration process at low temperatures.

Thus, the results present by Ribeiro et al. [15] suggest that permeability for "green" refractory concrete without PP-fibre is inclined to decrease until dehydration, shrinkage and material expansion mismatch is complete, i.e. till a temperature of approx. 250 °C is exceeded. If this is true then during the dewatering there is an increased risk of spalling due to the formation of an oversaturated zone by impeding moisture escape as suggested by Bazant and Thouguthai [1, 2].

Canon et al. [6] also investigated changes in permeability for refractory concrete with the addition of various quantities of PP-fibre and polyester fibres in a high alumina cement concrete (CAC 5 mass-% with silica fume). The specimens, 100 mm diameter and 25 mm high were cured at 21 °C/95 % RH for 24 h and then pre-fired at various temperatures before testing the permeability. Fig. 11 shows their results. For samples with fibre addition there were three main zones where the permeability changed – below the fibre melting point (180 °C) there was only minor change, above the fibre melting point (~180 °C) a sharp increase in permeability to a temperature of approx. 250 °C and thereafter a slight but gradual increase in the permeability. Canon et al. [17] concluded that the addition of 0,1 mass-% 1,2 denier polypropylene fibre produced the greatest increase in permeability. However, their results suggest there can be a slight decrease in permeability between 100 – 180 °C.

The results by Canon et al. [17] show that permeability increases by approximately two orders of magnitude once the temperature reaches approx. 250 °C. Their results

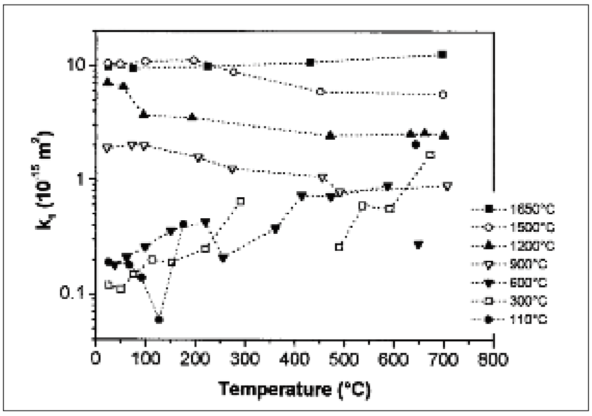

Fig. 9 Permeability results for pre-fired refractory concrete (no fibre) under hot gas conditions [11]

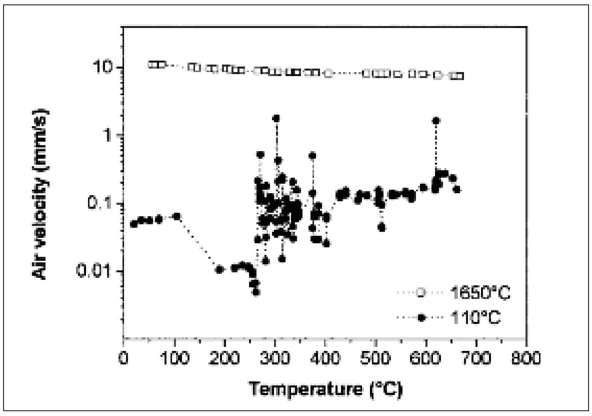

Fig. 10 Gas flow results for two pre-fired refractory concretes [11] at constant input pressure of 2 bar

correlate well with the airflow measurements by Innocentini et al. [18] given in Fig. 12.

Parr and *Wöhrmeyer* [19] also show the effect of addition of PP-fibre on permeability for LCC refractory in Fig. 13. The other very important factor is that the addition of PP-fibre to a concrete will increase the permeability by a factor of 2 to 4. *Long* and *Moeller* [20] found small annular passageways or channels of approx. 1 µm exist around each PP-fibre.

Comparing the permeability of the high alumina refractory concrete sample, Fig. 9, with the permeability of a high alumina CAC concrete with PP-fibre addition, Fig. 11, there is a steady but dramatic increase in permeability in the latter from approx 180 °C onwards.

However, it is important to note that Jansson [2] found that the addition of PP-fibre to self-compacted concrete resulted in a small amount of shrinkage over the temperature range of 200 – 250 °C due to fibre burn out. While not stated it seems that the volume expansion of the aggregates may be taken up by the space left by the PP-fibre.

Even though there may be some volume shrinkage occurring during fibre burn out it can be concluded that the addition of PP-fibre to concrete dramatically increases a material's permeability after burn out by approximately two orders of magnitude.

One of the difficulties with refractory concrete is the wide range of products on the market and the variability of product permeability. For example, the permeability for hydratable alumina binder (HAB) and low cement castable (LCC) refractory can have significantly lower permeability [19]. The results are also in line with data published by Canon et al. [17], Fig. 11, for permeability for a high alumina low cement refractory concrete.

Fig. 14 is the permeability for high strength and lightweight concrete[7)]. While the number of test points are limited it shows that high strength civil concretes permeability is similar to ULCC castable and colloidal silica refractory concrete.

The comparison of refractory concrete with civil concrete can also help with understand the drying and spalling characteristics. While the cement used in civil concrete is different (mainly calcium silicates: C_2S, C_3S, C_4AF, C_3A) the properties of high performance concretes with added silica fume are similar in strength and porosity to refractory concretes. The two concretes prepared by Noumowe et al. [7] show permeability increases with exposed temperature, Fig. 14. The surprising point this data is just how

7) Only the aggregate type was changed to an expanded lightweight, all other mix constituents were the same including water content.

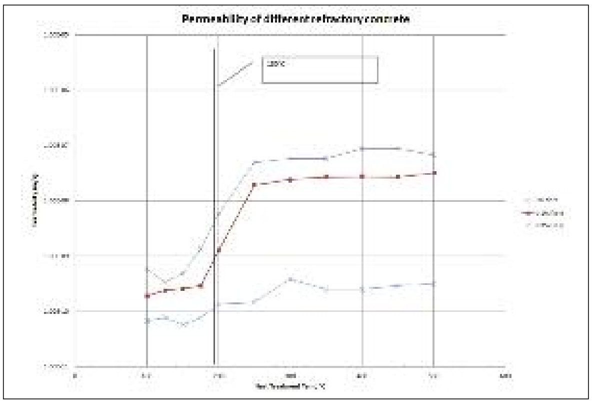

Fig. 11 Permeability results for refractory concrete as determined by Canon et al. [7]

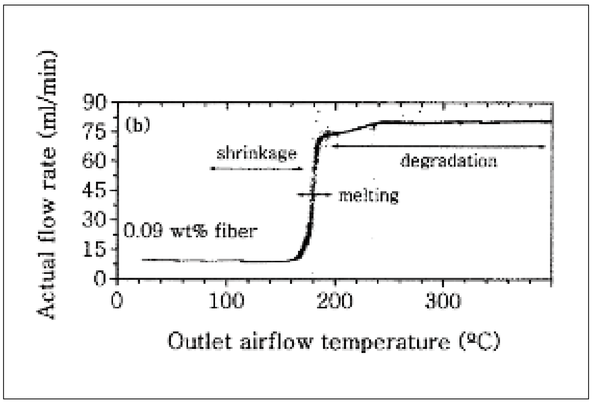

Fig. 12 Airflow increase due to fibre burn out (Innocentini et al. [13])

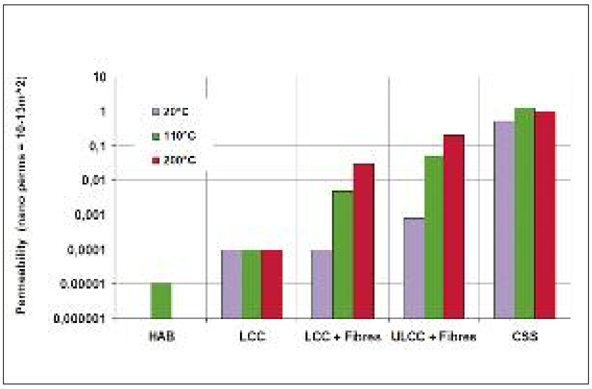

Fig. 13 Permeability of LCC and ULCC refractory concretes [15]

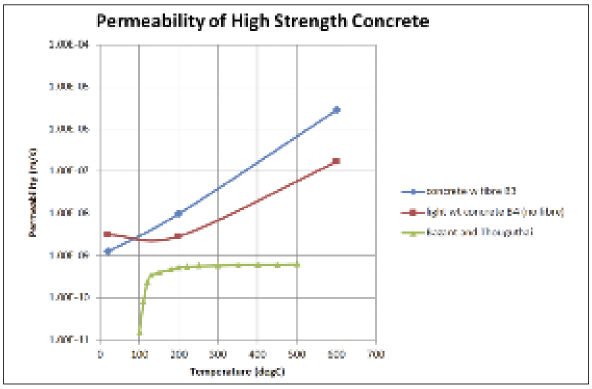

Fig. 14 Permeability of high strength concrete fired at 1 °C/min to 600 °C [7]

permeability the insulation concrete is compared to refractory concrete. The other point worth noting is the permeability of the insulation concrete does not seems to change over the lower temperature range (up to 200 °C) which is critical for dewatering.

The permeability results presented above are for gaseous permeability, which does not adequately consider two phase (liquid and vapour) flow or a liquid water flow during drying due to dynamic viscosity of water.

It is well documented that gas permeability measurements are higher than those for water permeability [20, 21]. The major reason for the differences between water and gas permeability is the theory of gas slippage, i.e. the gas close to a wall has a finite velocity whereas water has zero velocity at the wall. The theory of slip flow of a gas was proposed by *Klinkenberg* [1941] and the flowing relation between water and gas permeability was derived:

$$K_l = \frac{K_g}{1+\frac{b}{P_m}} \quad (3)$$

where K_l is the water intrinsic permeability for concrete and K_g is the gas intrinsic permeability of concrete and P_m is the mean pressure at which gas flows. The parameter b is equal to $\beta_1 K_l^{\beta_2}$ where the constants $\beta_1 = 1{,}635 \times 10^{-6}$ and $\beta_2 = -0{,}5227$ [*Bamforth*] for concrete.

Classie et al. [20] report the permeability for cement mortar under low pressures (0,5 atm) and report the constant values $\beta_1 = 3{,}5 \times 10^{-9}$ and $\beta_2 = -0{,}48$. *Chung* and *Consolazio* [21] report the constant values of $\beta_1 = 4{,}963 \times 10^{-9}$ and $\beta_2 = 0{,}5818$ for cement based material.

In this paper, the intrinsic gas permeability is corrected for gas slippage, before being converted to water hydraulic conductivity.

Another factor that should be considered is very low permeable of cured concretes. In these cases the effect of flow through capillary and gel pores may be applicable. *Cui* and *Cahyadi* [9] investigated the relationship between cement paste pore structure and water permeability using the *Katz* and *Thompson* permeability theory. The theory has been applied to porous cement paste but not successfully to concrete. When water has to pass through capillary pores less than a critical value, then gel pores control water permeability. However, if the cement paste is very porous then capillary pores control water flow. If the porosity is low then both capillary and gel pores should be considered. This can be done using the general effective media (GEM) theory which considers two phases – one of high permeability and the other of low permeability consisting of gel phases. Cui and Cahyadi [9] found that the Katz and Thompson permeability theory cannot be applied to cementitious material because in very porous material water will flow in the capillary pore network and in less porous material capillary pores are blocked by hydration products.

The authors` conclude that the presence of liquid water and steam affects a material's permeability and during drying, at low temperatures, the permeability can decrease.

Numerical modelling

Explosive spalling of refractory concrete during heating can be a serious problem which can result in extensive damage to process equipment. To reduce the probability of explosive spalling during dry out lengthy heating schedules with very slow temperature rates and lengthy hold periods have been applied. However, rather than rely on trial and error approach and small laboratory samples to determine drying schedules to be able calculate or simulate drying conditions and predict internal pore pressures and thermal stress would be a significant benefit to industry.

The second part of this work discusses the results predicted by our implicit numerical pore pressure model which follows Bazant and Thouguthai [1, 2] method but with the Klinkenberg correction added. The model was modified to allow the permeability function to be a user input. This means that published material-specific intrinsic permeability for various materials can be utilized to study a wide range of material combinations. The model corrects the intrinsic permeability by applying dynamic viscosity and mass density to the fluid when calculating the mass transport.

Conclusions

The aim of this review on the current research on drying concrete was to identify issues that need to be considered for modelling.

Literature shows that testing of various concrete samples found the presence of high amounts of free water content in concrete increases the risk of explosive spalling. It was also found that undried microsilica gel bonded castables, which has a very low level of hydrated bonds can explosively spall when rapidly heated.

The addition of polypropylene fibre increases concrete permeability as does thermal expansion differences between the matrix and aggregates.

It is concluded that the free water content of concrete is responsible for explosive spalling, not hydrated water. Also, hydraulic spalling of concrete is unlikely with the correct addition of PP-fibre.

The following issues were identified and need to be considered in a numerical modelling:

- Accurate permeability measurements are required to define a material permeability as a function of temperature.
- It appears the permeability between ambient and 160 °C may decrease and further research in this zone is required.
- The difference between liquid and gas permeability must be considered when modelling concrete drying.

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