The Accelerated Drying of Refractory Concrete – Part 2 Numerical Modelling

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The aim of this research is to develop a numerical model that can be used to predict pore pressure within a concrete body and the conditions that can lead to faster, safer heating schedules for refractory dryout.
Part 1 of this paper (refractories WORLDFORUM **6** (2014) [2] 75–83) discussed the critical material characteristics that influence the drying or removal of water from a cured (or hardened) concrete body. The current research shows that a material's permeability is probably the most critical parameter controlling the rate of water removal and internal pore pressure within a porous body. It can be deduced from this that a material's homogeneity, including PP-fibre dispersement, and installed concrete quality can also play a significant role in explosive spalling.

1 Introduction

The benefits of numerical modelling are that fast predictions of various concrete thickness, water content and heating rates can be studied and evaluated. The challenge for engineers has been to reliably perform these calculations due to interdependent nonlinear relationships.
One to the most cited theoretical approaches to modelling of concrete drying is Bazant and Thouguthai [1] which uses coupled mass and heat transfer. The equations of state for pore pressure were presented for non-saturated concrete, saturated concrete and the saturation transition.
The results from the numerical analysis conducted by *Bazant* and *Thouguthai* [4] for a 200 mm thick concrete slab heated at 80 °C/min concluded that near the heated surface, the pore pressure tends to push water towards the unsealed surface. Also, the pressure gradient tends to drive water into the wall and in the middle proportion of the slab water is pushed into the specimen creating an oversaturated zone which will impede moisture escape ("moisture clog").

To date the two most widely published causes for explosive spalling are, one, the buckling of a concrete slab due to compressive forces parallel to the heated surface induced by lower temperature surrounds and two, surrounding compressive forces plus internal pore pressure.
Gong and Majundar [5] also developed a numerical model for refractory concrete based on the work published by Bazant and Thouguthai [1]. Gong and Majundar [5] concluded that the pore steam pressure was greatly influenced by permeability and conductivity but the model required experimental validation.
The results from our implicit numerical mass and heat transfer model, based on the Bazant and Thouguthai [1] method but with the Klinkenberg correction added are presented. 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.

2 Historical approach

The current approach to drying and heating of refractory concrete is to follow the manufacturer's procedures, which are conservative, and have not changed in the past 30 to 40 years. It is also known that even following these very conservative heating schedules, explosive spalling of refractory concrete still occurs.
A typical heating procedure is shown in Fig. 1. These schedules show heating rates varying from 20 °C/h to 40 °C/h and lengthy hold periods which can result in schedules taking several days before industrial process is at full production. Such drying schedules are very costly for industry.
The other method used to evaluate drying is casting small laboratory size specimens and studying these specimens under controlled laboratory conditions.
A series of laboratory experiments were undertaken by Crowley and Johnson [6] who reported that curing temperature plays a critical role in the explosive tendency of refractory concretes. They found that concretes, which were inclined to explosively spall, when cured above 70 °F (21 °C) and placed in a furnace preheated to 1600 °F (870 °C) did not explode.

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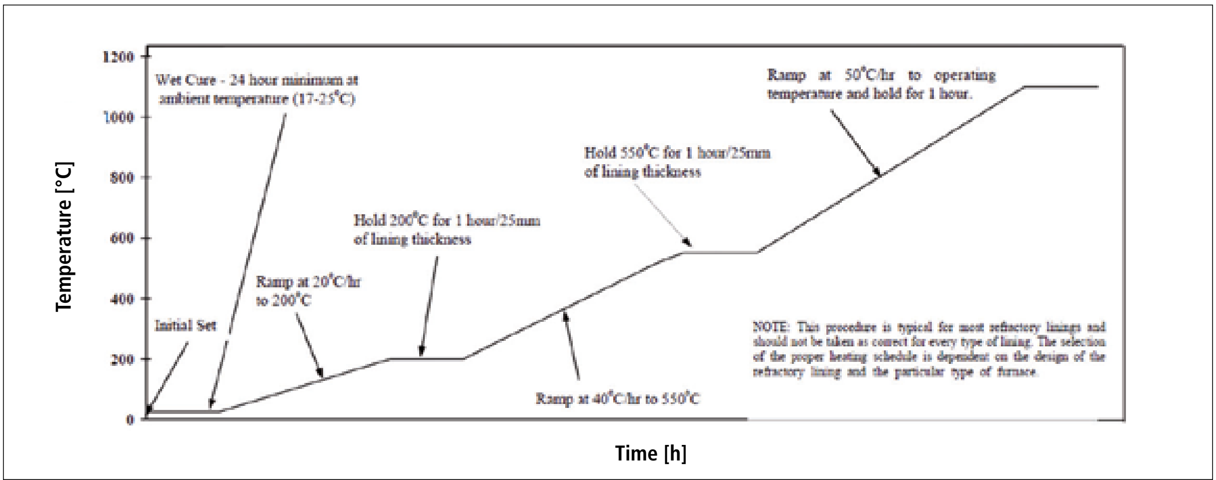

Fig. 1 **Typical heating schedule published by manufacturers**

Crowley and Johnson [6] concluded from their tests that, "there is little need for severe limitation of heating rates to avoid possible damage to refractories. Some caution should be exercised with thick (3 in. and up) linings of materials of very low permeability. Holding the surface temperature at 150 °F (65,5 °C) to 250 °F (139 °C) for long periods, wastes time with little to be gained in drying efficiency. Even air drying may safely be eliminated in most cases." and "heating could be begun immediately following the curing period, proceeding to 1000 °F (538 °C) at increased rates up to 200 °F/h (111 °C/h) depending on the type of concrete. Insulating concretes can be safely heated at a faster rate than dense impermeable concretes. A 200 °F/h (111 °C/h) rate plus elimination of prolonged air drying would result in a time saving of at least 24 h and possibly up to 48 h. Rapid initial heating of dense refractories increased their strength and also their shrinkage slightly but not harmfully."

Other researchers found that

- Cement dehydration appears to have little effect on the drying profile and drying time for heating rates above 10 °C/min (600 °C/h) but explosive spalling occurred in bodies heated above 20 °C/min (1200 °C/h) [7].
- Rapid heating does not cause damage to high alumina refractory but rapid cooling does cause some damage and combined rapid heating and cooling will also cause refractory damage [8].
- A safe heating rate to prevent fracture for alumina (corundum) of unsaturated refractory was greater than 600 °C/h [14].

Khoury and Anderberg [9] carried out a literature review on Portland cement concrete spalling and reported the effect of specimen size on spalling tendency. It was found that:

- Violent explosions occurred in very dense concrete cylinders (100 mm × 200 mm) subject to a heating rate of 1 °C/min but a reduction of cylinder size by either 50 or 75 % eliminated the explosions.
- Explosive spalling of high strength (60–110 N/mm²) concrete specimens (cylinders 60 mm diameter and 180 mm long) at a rate of 20–30 °C/min was not encountered.
- High strength cylindrical concrete specimens (80 mm diameter, 40 mm length) heated at 20 °C/min did not spall. However, increasing the specimen size (100 mm × 100 mm × 400 mm prisms) resulted in explosive spalling under load.
- Small specimens 40 mm × 40 mm × 160 mm prisms of ultra-high strength concretes (190 to 240 N/mm²) did explode.

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.

Thus it is concluded that using laboratory size specimens to determine safe heating rates cannot be extrapolated to full size industrial concrete slabs. This is most likely due to specimen size effects.

3 Hot strength and pore pressure

As previously mentioned it is generally believed that for spalling of concrete during heating to occur the material's tensile strength must be exceeded and it is known that a material's strength can decrease with fired temperature. Fig. 2 – 3 show hot elastic modulus and hot tensile for refractory concrete with temperature. The graphs show the hot elastic modulus and hot tensile strength decreases with temperature, particularly in the range of 150 – 300 °C.

Depending on the type of refractory concrete the tensile strength is relatively low and varies between 1,5 – 5,5 MPa depending on the type of concrete being heated.

It was reported in Part 1 that measured pore pressure was in the range of 1,3 – 1,8 MPa, which is in the hot tensile stress range of some refractory materials. Thus it is concluded that measured pore vapour pressure can reach values which are sufficiently high enough to fracture refractory concrete.

However, this does not explain how explosive spalling occurs, since formation of a crack could simply relieve pore pressure. In a simple 1D homogeneous isotropic concrete a planar crack would occur at the maximum pore pressure, and result in a layer of concrete of depth "X" which is equivalent to the max. pore pressure. In this case the layer of concrete "X" would fall off. More realistic in concrete panels water can flow laterally which means a pressure is likely to form somewhere in the middle of the panel and if failure was to occur the failure area is likely to have a trapezoidal cone shape.

Physical observations show that when explosive spalling occurs the resultant material varies in both size and thickness. Thus, it seems reasonable to conclude that in an explosive spalling event the material is neither homogeneous nor isotropic due to the

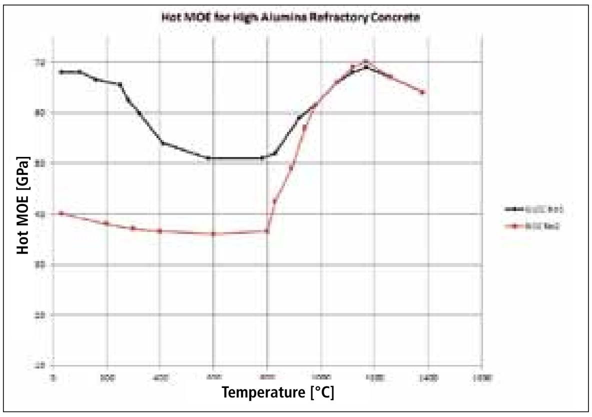

Fig. 2 Variation in hot elastic modulus for low cement and no-cement refractory concrete [12]

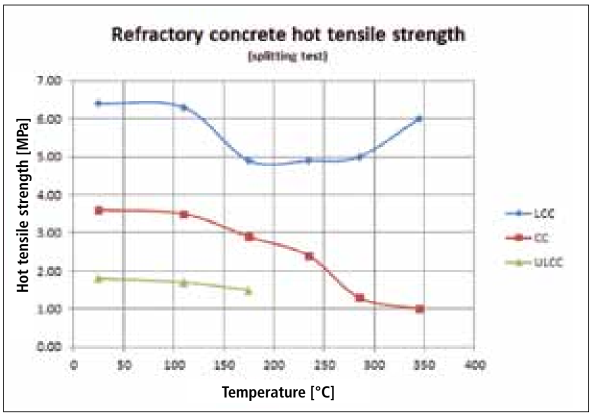

Fig. 3 Variation in hot tensile strength with temperature for different refractory concrete [13]

irregular shape of the spalled pieces. It also seems reasonable to conclude that the installed quality and inhomogeneity of refractory concrete plays a significant role during explosive spalling.

4 Numerical modelling

The governing equations for heat and mass transfer in concrete can be described by the water mass flux rate due to the pressure gradient and the water released during dehydration as

$$\frac{\partial W}{\partial t} = -div\,J + \frac{\partial W_d}{\partial t} \quad \text{where } J = \frac{a}{g}\,grad\,P$$

where W is the mass of free water, W_d is the mass of water liberated by dehydration during heating, a is the permeability (ms^{-1}), g is the gravity acceleration (m^2/s), P is the pore steam pressure, t is time, and the heat flux rate due to heating of concrete and water (including heat of evaporation) plus heating by convective movement of water as

$$\rho C \frac{\partial T}{\partial t} - C_a \frac{\partial W}{\partial t} - C_w\,J \cdot grad\,T = -div\,q \quad \text{where } q = -k\,grad\,T$$

where ρ and C are the mass density and specific heat (wet) of concrete, C_a is the heat of free water evaporation, C_w is the specific heat of water, k is the concrete thermal conductivity and T is temperature. The term $C_w J \cdot grad\,T$ equals the rate of convective heating due to moving water.

In 1978 Bazant and Thouguthai [1] published a theoretical approach to modelling of concrete drying using coupled mass and heat transfer. The equations of state for pore pressure were presented for non-saturated concrete, saturated concrete and the saturation transition. In their later paper [4] they proposed that the permeability must suddenly increase at 100 °C to explain the physical observations and that the rate of moisture transfer at normal temperature must be controlled by narrow "necks" (gel pores) and water can only pass through the "necks" in the adsorbed state. After the narrow necks have been lost (>105 °C) the moisture transfer is governed by viscosity of steam which changes only slightly.

If hydraulic pressure only is considered then pressure can be calculated from thermodynamic steam tables for saturated concrete assuming a constant pore volume. In that case the water pressure would be approximately 146 MPa (1400 atm) at 130 °C and 258 MPa (2546 atm) at 180 °C.

However, the measured pore pressure in samples tested by Bazant and Thouguthai was only 0,320 – 0,690 MPa. Thus, it was concluded that pore volume must increase significantly. Bazant and Thouguthai [4] also conclude that moisture transfer below 100 °C is not controlled by liquid capillary water, but is controlled by the "necks" which in dense cement paste are only approx. 50 Å wide; this means the "necks" can contain only adsorbed water and no liquid water or vapour.

The results from their numerical analysis for a 200 mm thick concrete slab heated at 80 °C/min concluded that the pressure gradient near the hot face tends to drive water towards the wall and in the middle proportion of the slab water pushed into the specimen creates an oversaturated zone which will impede moisture escape ("moisture clog").

It was concluded there are two possible causes for explosive spalling, firstly, buckling of a wall surface where compressive stresses parallel to the heated surface are induced by the non-heated surrounds and secondly, buckling combined with tension in the microstructure produced by pore pressure.

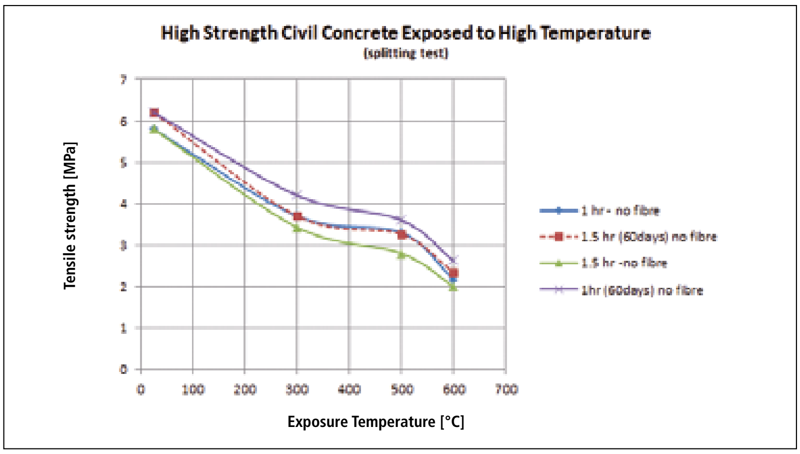

Fig. 4 Variation in hot tensile strength with temperature for high strength concrete [10]

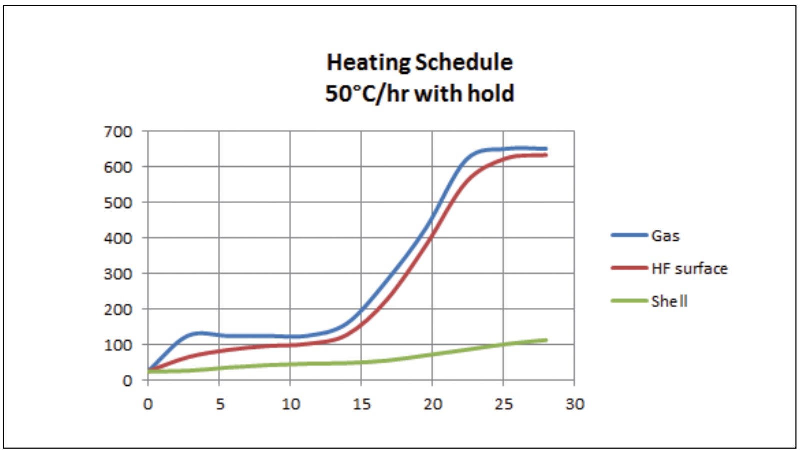

Fig. 5 Heating schedule showing lag between the gas temperature and refractory surface temperature

Gong and Majundar [5] developed a numerical model for refractory concrete based on the work published by Bazant and Thouguthai [1] using equations 1 and 2. While the absolute pore pressure predicted was very low, approx 0,2 MPa, Gong and Majundar [5] found that decreasing permeability increased pore pressure, increasing heating rate increased pore pressure and increasing thickness increased pore pressure.

5 Calculated pore pressure

During the heating and drying of concrete there are two types of stresses that can develop, thermal stresses due to non-linear temperature gradients and internal pressure within the body due to the evolution of steam from free and combined water.

To overcome historical problems, namely explosive spalling, during dry out manufacturer's heating schedules have been very slow and lengthy hold periods have been applied. These schedules have been on the assumption that hold periods lower the risk of explosion and improves drying. The results from our 1D numerical drying model are presented.

The implicit numerical model used to calculate pore pressure was developed following Bazant and Thouguthai [1] 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.

The pore pressure numerical model allows for two material types to be evaluated with different cement content, water content, permeability and thermal conductivity. Relatively good model stability was achieved over a range of cement and water contents. The intrinsic permeability used was taken from Canon, et al. [11] without PP-fibre. All other parameters are kept constant.

Four cases are presented for a two layer lining-dense hotface 100 mm thick and lightweight 130 mm thick for all cases. The total water content (free and combined) was 250 kg/m³ in the hotface and 500 kg/m³ in the insulation. The material permeability for all cases unless specified is for dense refractory concrete with no polypropylene fibre.

The heating schedule is 50 °C/h to 650 °C with and without a 10 h hold period at 125 °C and heating schedule at 100 °C/h to 650 °C with and without a 10 h hold period at 125 °C.

The aim is to demonstrate the effect of hold periods and the commercial impact of different heating schedules on drying. The model assumes that water can flow with minimal resistance at the cold face.

The validity of this assumption when a steel shell is in place is uncertain, while water cannot flow through the shell unless it is cracked or there are holes in place, it is possible water can flow laterally and escape through joints.

Three cases are analysed: 1) heating at 50 °C/h, 2) heating at 100 °C/h, and 3) heating a thick plate at 30 °C/h.

The results for case one, low heating rate of 50 °C/h with the 10 h hold period are shown in Fig. 6 – 8. The graphs show the calculated variable: pore pressure in [MPa] (absolute pressure), water flow flux and temperature with time and thickness.

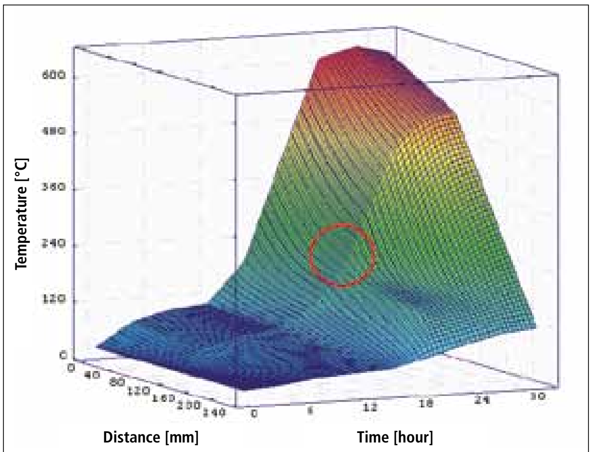

Fig. 6 Temperature with time and thickness – 50 °C/h with hold at 125 °C

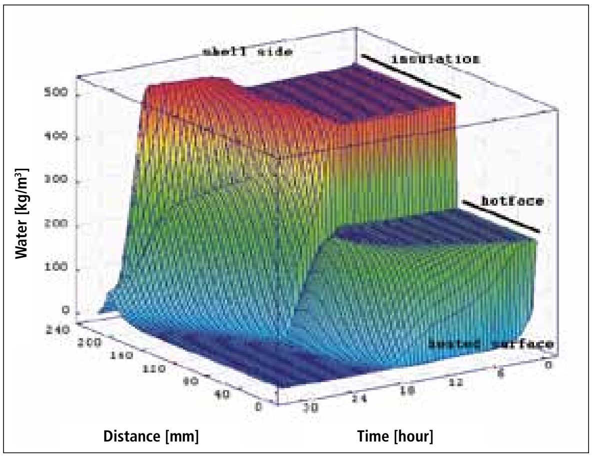

Fig. 7 Water content with time and thickness – 50 °C/h with 10 h hold at 125 °C

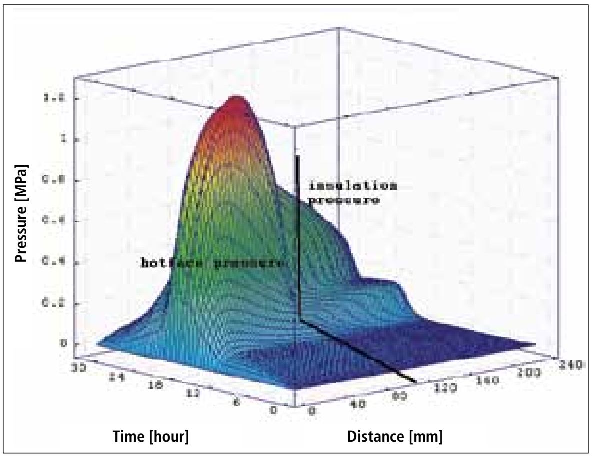

Fig. 8 Pore pressure with time and thickness. Max. pressure reached was ~1,25 MPa at ~19,5 h at depth of ~60 mm – 50 °C/h with 10 h hold at 125 °C

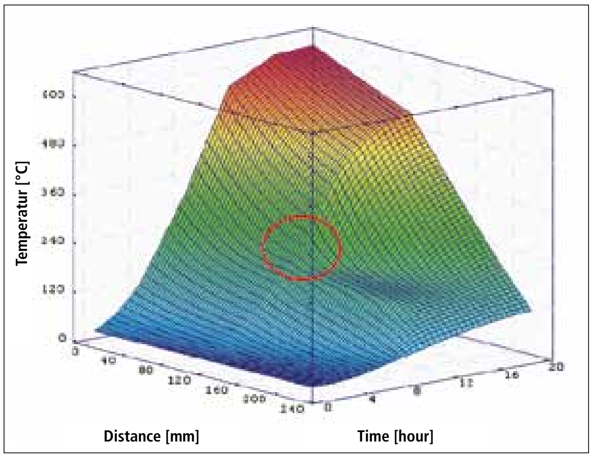

Fig. 9 Temperature with time and thickness – 50 °C/h with no hold

Fig. 6 shows the temperature profile with the slow heating to 125 °C then the applied hold and the increase to 650 °C.

The temperature is first calculated in P-thermal a 1D heat transfer program used to calculate the refractory surface temperature under flow conditions. Fig. 5 shows the temperature difference between the gas and heated surface due to the surface convection boundary layer. This step is used to assist with computational stability.

The temperature curve in Fig. 6 shows a slight deflection (circled), sometime referred to as "a break point" near the interface of the two layers. This decrease in temperature is due to water evaporation and falls in the region of peak pore pressure. Fig. 7 shows the water content in both the hotface and insulation layers. The results show there can be a small accumulation of water near the pore pressure peak. The graph also shows that water is pushed to the shell side and the insulation becomes totally saturated adjacent to the shell. However, the most important issue during the hold period is that there is no change to the model water content. In fact, it is not until the pore pressure starts to develop is there a decrease in the water content. Fig. 8 shows the calculated peak pore pressure and in this case the maximum pore pressure is 1,25 MPa (absolute) which occurs at a depth of approx. 60 mm after 19,5 h. The temperature within the hotface at the peak pressure is 236 °C. Thus introducing a hold period prior to the development of a pressure peak will not reduce the peak pore pressure or reduce the risk of explosive spalling.

The only benefit of this hold period seems to be to allow the hotface to equilibrate the temperature through its thickness which will reduce transient thermal stresses. However, if the hold period does not have a benefit of reducing pore steam pressure, then it is important to check that heating at a constant rate will not increase the steam pore pressure. The results for the heating rate 50 °C/h with no hold period are shown in Fig. 9 – 11.

The temperature heating graph is shown in Fig. 9. This shows a similar "break-point" where the temperature decreases due to water heat of vaporization. The temperature profile through the refractory is similar, except for the hold case.

The water content graph is also similar to the hold case except the duration is reduced.

Fig. 11 shows the water content graph for the 50 °C/h steady heating increase is al-

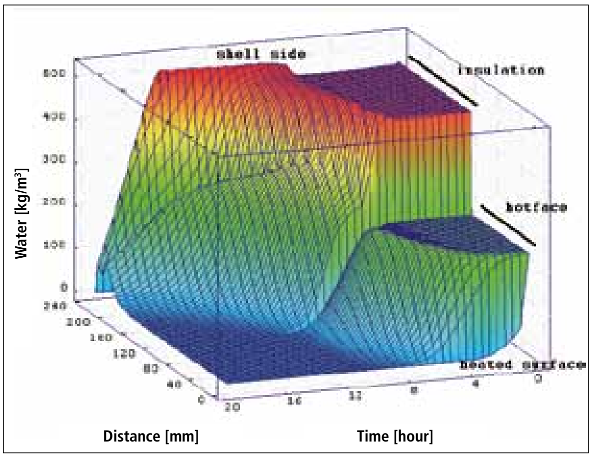

Fig. 10 Water content with time and thickness – 50 °C/h with no hold

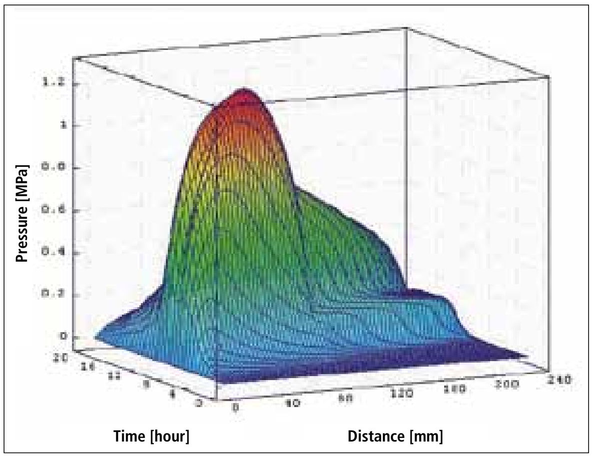

Fig. 11 Pore pressure with time and thickness. Max. pressure reached was ~1,26 MPa at ~9 h and depth of ~60 mm – 50 °C/h with no hold

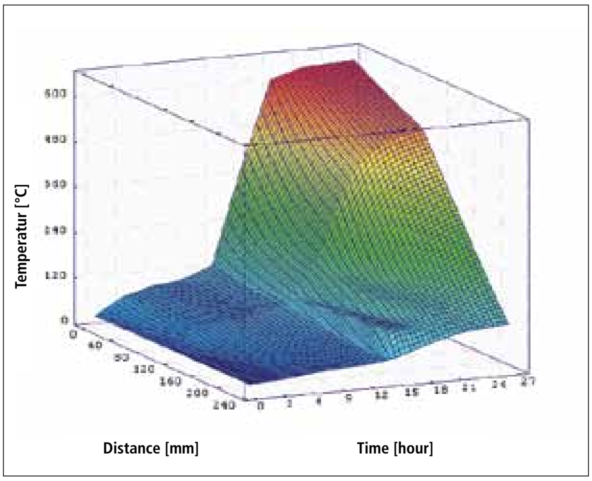

Fig. 12 **Temperature with time and thickness – 100 °C/h with hold at 125 °C**

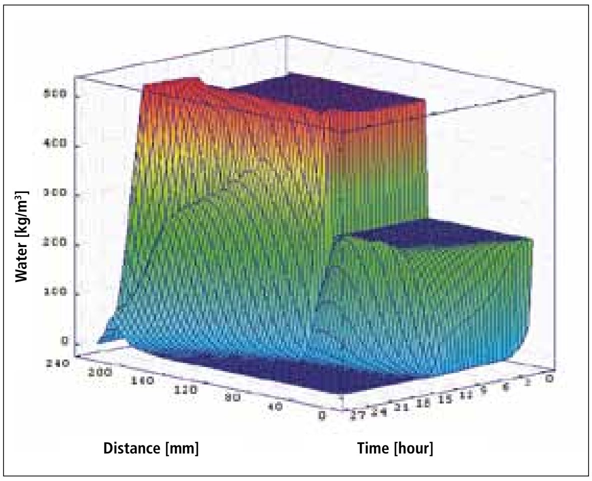

Fig. 13 **Water content with time and thickness – 100 °C/h with hold at 125 °C**

most identical to the 50 °C/h with a 10 h hold period.

The water content in the hotface advances in a parabolic front with time just before the water starts to decrease. At this front there is a small amount of water accumulation. The temperature and pressure at this point is such that the water will be superheated.

Fig. 11 shows the calculated peak pore pressure. In this case the maximum pore pressure is 1,26 MPa (absolute) which occurs at a depth of approximately 60 mm after 9 h. The calculated temperature within the hotface at the pressure peak is 242 °C.

The analysis for 50 °C/h heating rate case shows that using hold periods during dry-outs does not reduce the risk of explosive spalling and does not aid in the drying process. The analysis shows that water removal is driven by pressure not diffusion.

The results for case two, high heating rate of 100 °C/h with the 10 h hold period are shown in Fig. 12 – 14.

The same process to calculate the hotface surface temperature was used. The temperature profile for the faster heating rate with a hold period and final temperature is shown in Fig. 12. The water content graph showing the constant water content plateaus is shown in Fig. 13.

Again, it shows the water content changes slowly with time until near the peak pressure is reached. At this zone the water is superheated. The calculated temperature in the dense concrete at the peak pore pressure is approximately 247 °C. Fig. 14 shows the pore vapour pressure with time and thickness. The graph shows a similar very slow increase in pore pressure until after the hold period and it is not until after the hold period does the pressure start to increase significantly. The predicted vapour pressure is 1,49 MPa after 15,5 h at a depth of 60 mm. The pressure is slightly higher (0,24 MPa) compared to the 50 °C/h heating rate and occurs approx. 4 h earlier.

The pore pressure result for heating at 100 °C/h with no hold period is shown in Fig. 15. The temperature and water content curves are omitted but follow the same trend as previous curves.

With a continuous heating rate the pore pressure rapidly increases to a maximum of approx 1,49 MPa at 60 mm deep after 6 h. The temperature within the hotface at peak pressure is approximately 254 °C.

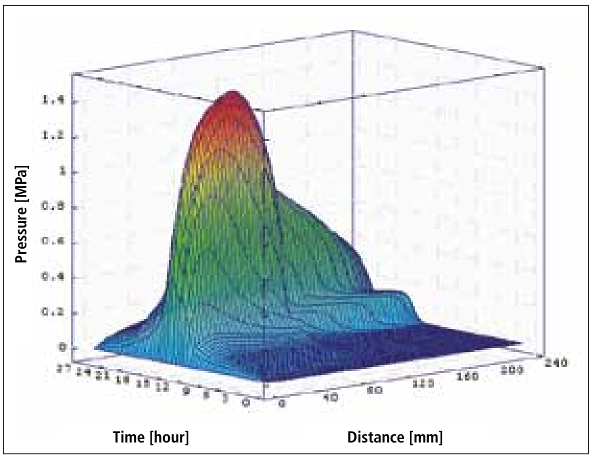

Fig. 14 **Pore pressure with time and thickness. Max. pressure reached was ~1,49 MPa at ~15,5 h and depth of ~60 mm – 100 °C/h with 10 h hold at 125 °C**

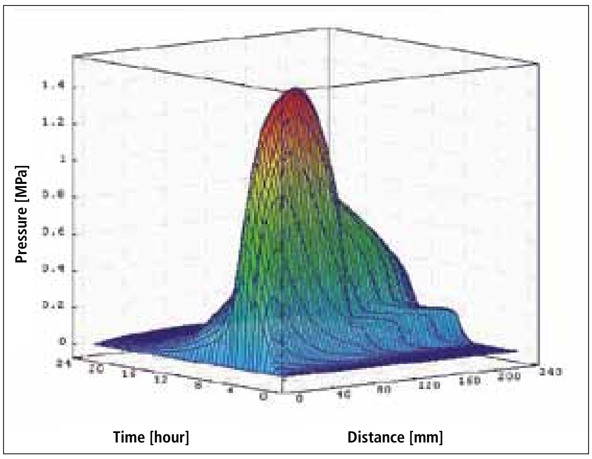

Fig. 15 **Pore pressure with time and thickness. Max. pressure reached was ~1,49 MPa at ~6 h at depth of ~60 mm – 100 °C/h with no hold.**

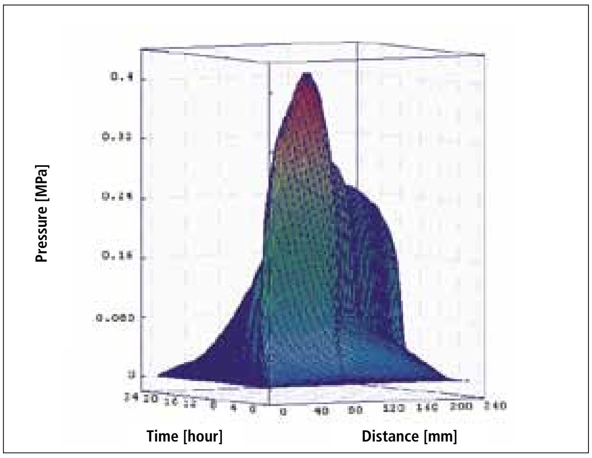

Fig. 16 **Pore pressure with time and thickness with hotface permeability equal to 0,1 % polypropylene fibre content. The peak pore pressure was ~0,42 MPa at 4,83 h and depth of ~68 mm – 100 °C/h with no hold.**

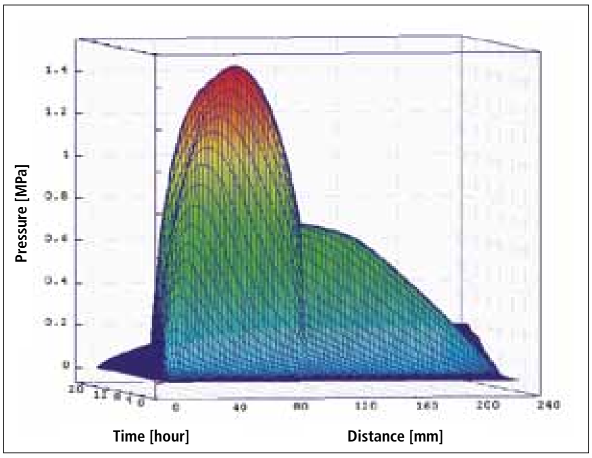

Fig. 17 **Vapour pressure graph showing peak pressure for heating 100 °C/h, no hold and zero mass flow at the cold face – peak pressure is ~1,48 MPa at 5,7 h at depth of ~55 mm**

The previous results are for dense concrete with a permeability equal to concrete with no polypropylene fibre addition. The pore pressure results show that spalling or explosive spalling of the hotface is possible with and without hold periods.

The results also show that a temperature hold at low temperatures, just above normal boiling point, will not reduce the risk of spalling or explosive spalling.

The model for the 100 °C/h with no hold was re-run but with a hotface permeability equal to a dense concrete with 0,1 % polypropylene fibre content.

Fig. 16 shows the pore pressure with time and thickness. The results show the addition of PP-fibre significantly lowers the pore vapour pressure from approx 1,49 MPa to 0,42 MPa. This analysis shows the risk of explosive spalling due to high pore pressure is significantly reduced by the addition of PP-fibre. An analysis was also carried out to evaluate pore vapour pressure when the cold face boundary has a zero mass flux, i.e. no flow through the cold face.

The pore pressure result for this case, i.e. no cold water flux at cold face boundary is shown in Fig. 17. Only the pressure graph is shown for this case.

The results show that there is no change in maximum pore vapour pressure when compared to the case above for the lower cold surface boundary flux. The maximum pore pressure reached was 1,48 MPa at a depth of ~55 mm after 5,7 h. The analysis of our results indicates the water vapour that is pushed into the insulation progressively evaporates with time or is pushed back through the hotface. The amount of water vapour leaving by the hotface is dependent on its final permeability.

Thus it is concluded that having zero water flow at the cold face boundary has little effect on the maximum water vapour pressure.

One further analysis was carried out to study the effect of a hold period during the ascending part of the vapour pressure curve. The same conditions as for the 50 °C/h model with a 10 h hold at 125 °C were used except there was a second hold at 300 °C for 7 h. The pore vapour pressure curve is shown in Fig. 18. The maximum pressure calculated was 0,82 MPa at a depth of 57 mm after 20,5 h. The analysis shows that a second hold period within the ascending section of the vapour pressure curve can decrease pore vapour pressure.

The analysis shows that for both heating rates spalling is possible for both conventional and ULC castables as the material tensile strength was exceeded. If spalling was to occur it would happen after approx 9 (50 °C/h) or 4 h (100 °C/h) for the no hold temperature cases at a depth of 50 – 60 mm.

It was also found that a superheated water front (build-up of water) can develop due to the increased pore pressure which is equal to the vapour pressure. Given that the development of pore vapour pressure is relatively fast it can quickly lead to fracture and explosive spalling. It seems reasonable to conclude an explosive event is initiated by the pore vapour pressure propagating a crack and the release of pressurized steam when liquid water pressure drops. It is this steam which acts as the propellant.

The analysis shows that temperature hold periods prior to or after the pressure peak have no effect of reducing the magnitude of the

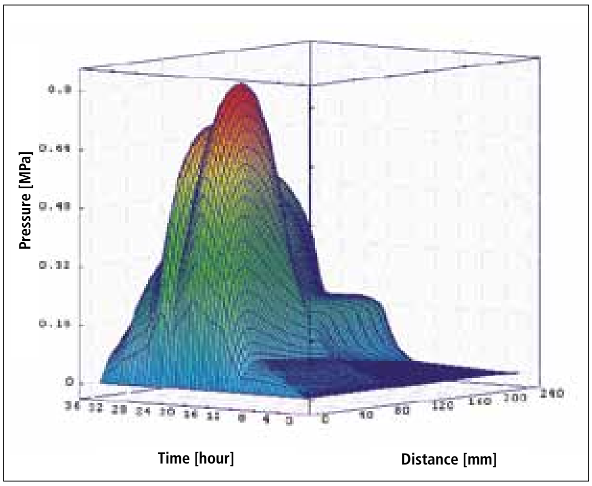

Fig. 18 **Vapour pressure graph showing peak pressure for heating at 50 °C/h, first hold at 125 °C and second hold period at 300 °C for 7 h – peak pressure is ~0,82 MPa at 20,5 h at depth of ~57 mm**

pore vapour pressure and the pressure front will change with materials, thicknesses and heating schedules.
The results show the addition of polypropylene fibre can increase permeability and reduce pore vapour pressure. The corollary is that poorly distributed PP-fibre can change the permeability zone. We have found that a decrease in the permeability by 10 % for whatever reason can increase the peak pore pressure by almost the same amount. In that case the pressure peak will tend to move towards the centre of a square shaped panel.
While thermal expansion of liquid water is not considered in the model it is clear that expansion of water would occur, in which case it would act as a "pump" and push a small amount of water towards the cold face.

6 Conclusions

The 1D heat mass transfer has been used to study the drying and water migration in refractory concrete. The 1D model is considered the worst case condition as water movement through the side boundaries or thermal stress cracks are not considered.
The following conclusions are made from this study:

- Existing manufacturer's heating curves are unreliable and will not prevent explosive spalling.
- Increasing the heating rate can increase the maximum pore vapour pressure.
- The use of thermal hold periods during drying does not aid nor will it prevent spalling if the hold period is not within the pressure peak curve.
- A thermal hold period can decrease the maximum pore pressure if it is correctly placed within the pressure peak zone.
- Explosive spalling starts when the peak pore vapour pressure initiates a crack and the sudden release of the pressurized liquid water into steam that acts as the propellant.
- If explosive spalling occurs then the failure area is likely to have a trapezoidal cone shape into the concrete.
- Concrete installed in large panels without expansion joints will be more susceptible to spalling than smaller panels. In smaller panels water and steam can escape laterally through the side boundaries and lower the pore vapour pressure.
- Impermeable surfaces at the cold face can slightly increase the pore vapour pressure in the hotface. However, if the insulation layer separates during drying then the

hotface pore vapour pressure will not increase as vapour can escape along these boundaries.

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