Existing theories of concrete spalling and test methods relating to moisture migration patterns upon exposure to elevated temperatures : a review

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Existing theories of concrete spalling and test methods relating to moisture migration patterns upon exposure to elevated temperatures – A review

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A B S T R A C T

The present paper reviews some recent research on concrete spalling theories and existing test methods of moisture migration patterns that occur when concrete is exposed to elevated temperatures. Experimental investigations on these systems in fire conditions are not as extensively conducted as under normal temperature conditions. Therefore, only a few representative experimental procedures are discussed in the paper. A summary of small-, medium- and large-scale experimental tests where water pooling was evident is also presented. This is then presented in relation to the design recommendations that are based on previously discussed experiments. Finally, some future perspectives on the subject matter are also presented.

1. Introduction

Concrete can be defined as one of the most commonly used construction materials due to its versatility, stability, durability and high resistance to fire. Compared to steel, which requires protection from corrosion and is vulnerable to melting at high temperatures, and timber, which is combustible, concrete requires less protection and has the ability to withstand higher temperatures. However, even though concrete is regarded as having superior properties at elevated temperatures, it undergoes a phenomenon called 'spalling', which is associated with the flaking, breaking off, or in severe cases, instantaneous loss of cross sections (explosive spalling). If concrete spalling is explosive in nature, it can rapidly reduce the load bearing capacity of the structure, thus, resulting in collapse [1,2].

Spalling is generally categorised based on its nature and severity and is grouped into four categories; aggregate, corner, surface and explosive spalling [3,4]. Jansson defined a 'spall', similar to the definition given by Preston and White [5], as being a flake from a surface, which must form suddenly, with enough violence to make an audible noise (a 'pop' sound) [6]. However, when concrete is exposed to fire, especially in situations where a rapid increase in temperature is experienced, such as in tunnel fires, spalling can be fast and random, and therefore, it is vital to understand the underlying cause(s) of spalling. Research on the effects of fire on the performance of concrete has had several developments over the years [7–12], with researchers striving to develop both experimental procedures and numerical modelling to investigate the fire performance of concrete. When considering experimental procedures, especially large-scale fire testing of concrete elements, they can be costly and difficult to perform, however, numerical modelling can have several variable which can drastically affect the results, and unless these variables are completely understood, accurate simulation of the procedure is difficult to perform [1]. Guerrieri et al. [13] reported, after a series of large-scale fire testing in a proprietary

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furnace, that full-scale testing provided an accurate representation of the behaviour of concrete in fire, while unloaded flat panels did not. Research on a direct comparison of single-phase and multiphase mathematical models revealed that single-phase models could be used to represent experimental results to a considerable level, while the multiphase model could predict water accumulation ahead of the drying front [14]. Correlations between experimental observations and a numerical simulation was conducted [15] where gas pressure/temperature measurements were compared. The thermo-hydro-chemical model developed for concrete at high temperatures showed qualitatively acceptable results allowing for a deeper insight in to the heat and mass transfer of concrete at high temperatures. High strength concretes (HSC) and high-performance concrete (HPC), which are obtained through the modification of conventional concretes, have become more popular owing to their enhanced durability, strength and other engineering characteristics. However, these modified concretes are believed to be more susceptible to fire-induced failures compared to normal strength concretes (NSC), with spalling being the dominant mode [1,16,17]. This is believed to be due to the more dense microstructure and low permeability levels, which constrict the pore pressures, which are built-up during high temperatures, from escaping, thus impacting the physical and mechanical properties negatively [18–23]. Rossino et al. [24] studied the correlation between the microstructural and mechanical properties after elevated temperature exposure of three different concrete mix designs, using a few different testing techniques. It was reported that heating to 500 °C affects the total porosity of all concrete mixes, and different techniques can be used to monitor the development of micro-cracks at different stages of fire exposure. Monte et al. [25] indicated that the magnitude of indirect tensile strength loss per unit value of pore pressure, denoted by a coefficient k, decreased for higher concrete grades, and increased with the addition of PP fibres and when calcareous or silico-calcareous aggregates were used in the mix design, as opposed to using basaltic aggregate. Over time, the incorporation of polypropylene (PP) fibres in concretes were found to mitigate the levels of spalling [10, 26–29]. Pistol et al. [30] reported that the incorporation of monofilament PP fibres is currently one of the most useful method of reducing explosive spalling. The study also reported that capillary channels created as a result of thermal decomposition of the PP fibres, got connected and formed a netlike micro-crack formation. These micro-crack formations help to release the internal stress and allow the transportation of vapour during the increase in temperature. Kalifa et al. [28] reported that the addition of PP fibres in HPC avoid the occurrence of spalling during fire altogether. The PP fibres melt at a temperature of 170 °C and partially gets dispersed in the cement matrix, which form pathways (micro-channels) for the gases to escape, thus reducing the build-up pore pressure, and, in turn, reducing spalling. Khoury [31] reported that PP fibres contributed in reducing the pore pressure through a few different ways such as; (1) through reservoirs, such as air bubbles and micro-cracks, which relieves the expanding steam and; (2) through continuous channels which provide pathways for the moisture vapour to migrate. When considering the amount of PP fibres which can be incorporated into a concrete mix, Debicki et al. [32] reported that a fibre content of 1 kg/m^3 was sufficient to prevent spalling in HPC, while, Kalifa et al. [28] indicated that, under ISO 834 conditions, a dosage of 2 kg/m^3, with a fibre length of 10–20 mm and diameter of 50–200 μm were found to prevent spalling of HPC up to 100 MPa. However, these values are not optimized and a dosage of as low as 0.9 kg/m^3 is effective in reducing spalling. Their study, which was focused on understanding the behaviour of PP fibres at high temperatures of 600 °C, revealed that the pressure is indeed released through the porous system created by the melted PP fibres, and it was demonstrated that the flow uses the largest and the straightest path available [28]. Khoury [31] showed that, along with the characteristics of the PP fibre material, the characteristics of the fibre itself would contribute in releasing the pressure, and that an optimum individual fibre length would allow both interconnectivity as well as good dispersion. Du et al. [10] studied the spalling behaviours of ultra-high strength concretes (UHSC) during fire and found that a PP fibre dosage of 1.365 kg/m^3 prevents the spalling of UHSC (115–135 MPa). Kojima and Koyama [33] suggested that a combination of long and thin synthetic fibres and steel fibres significantly reduce spalling of UHSC (200–300 MPa). Research was undertaken on understanding the effects of recycled tyre polymer fibres on the spalling of concrete [34]. Results revealed that a dosages equal to or larger than 2 kg/m^3 prevented fire spalling damage and protected the steel reinforcement bars as the fibres prevented breaking away of spalled concrete. The authors stated that these recycled tyre polymer fibres could be a sustainable solution to the concrete spalling problem. The influence of adding PP fibres on spalling mitigation was studied [35], by analysing the drying rate and the moisture profiles. It was found that the dehydration front moves about five times faster when PP fibres were incorporated into the concrete specimens, which is assumed to be due to the increased permeability brought about by the melting of PP fibres. Several theories have been put forth by various researchers as contributory factors towards spalling; however, due to the complex physical and chemical processes occurring concurrently, it is difficult to agree to a consensus. Jansson [36] reported that Barret [37] was the first person to make a recorded observation of concrete spalling in 1854, where it was said that when the aggregate used in the concrete is flint, the concrete is seen to split and yield when exposed to fire. Following, from this observation, there have been several major efforts to understand this phenomenon, and hence to reduce the level of damage caused on the structural integrity of buildings [36–38]. There are numerous physical and chemical changes which occur when concrete is exposed to elevated temperatures. These can be mainly categorised as being thermo-hydral and thermo-mechanical changes. Thermo-hydral identifies the changes in the microstructure with respect to the changes in moisture such as, moisture migration, water accumulation and dehydration, and thermo-mechanical denotes the changes in the microstructure with respect to the stresses formed such as, thermal stresses, tensile stresses and compressive stresses [9,21,26,39–42]. The egress of water from the unexposed surface of heated concrete, also known as water pooling, was first recorded in 1905 by Woolson [43], which is a common occurrence, where water can be seen to flow out from the unexposed surface in a 30 cm think slab being exposed to a single-sided fire for just 40 min [36]. This demonstrates the presence of a continuous crack-system within the concrete which could be a collection of old and newly formed cracks before and after the exposure to elevated temperatures [36]. This 'pouring out' of water from the unexposed surface during the gradual increase in internal temperature is recognized as a major contributor that dictates the type and time of spalling [44–46]. Guerrieri and Fragomeni [47] reported the build-up of pore pressure and flexural cracking are the key contributors towards concrete spalling, where the flexural cracking create pathways for considerable amounts of moisture to migrate and egress from the unexposed surface during the exposure to heat flux. Ye et al. [48] also acknowledged that water vapor pressure entrapment is a major reason for concrete spalling. Hedayati et al. [42] stated that at temperatures below 100 °C, the compressive strength decreases due to the increase in energy and the movement of free water. Additionally, during heating, the formation and propagation of cracks are considered to be a crucial phenomenon which can lead to severe spalling conditions [42]. Moreover, these cracks which form with increasing temperature levels, are assumed to occur due to dehydration of the cement paste and/or due to the thermal gradients which form within the concrete, thus causing detrimental effects to the structural stability of concrete [49,50]. However, the factor(s) which govern the movement of moisture and the movement patterns within the concrete are hard to define and are mostly limited to macroscopic or point-wise observations [35], which limits the validation of the proposed models. Hence, more innovative experimentation is required to understand the level of influence moisture migration has on spalling [36,42,45]. Tengattini, et al. [35] used a non-contact neutron imaging technique on concrete specimens during heat exposure, to obtain a full-field distribution of moisture in 3D and in real time. Results from the study shows that the initial moisture content contributes significantly towards concrete spalling, where samples that had higher initial water content spalled to a higher degree.This paper reviews current key theories pertaining to concrete spalling, including innovative ones, which have been developed to understand the moisture migration patterns within concrete. The paper also narrates on existing fire testing with a view to understanding the performance of concrete at small, medium and large-scale, especially, focusing on the influence of moisture migration and the generation of water pooling during exposure to a fire scenario. For the purpose of this review article, the classification of small-, medium- and large- scale tests were based on the sizes of the tested specimens. Where specimens less than 100 mm were considered as small-scale tests, specimens that were larger than 100 mm, such as cylindrical, cubic or prismatic specimens, were considered as medium -scale tests, and specimens larger than 1000 mm, such as wall and column specimens, were considered as large-scale tests. Finally, a critical analysis of the empirical data, where possible, is also attempted.

2. Review of concrete spalling theories

2.1. Concrete and spalling

Concrete undergoes complex microstructural changes when exposed to increasing temperature levels, where considerable amounts of strength is lost from temperatures above 300 °C, with the structural capabilities lost after about 600 °C. Table 1 gives the mineralogical changes which concrete undergoes when exposed to elevated temperatures [51].

Concrete spalling is a phenomenon which can lead to the severe damages including the disintegration of concrete particles, element failure, loss of structural integrity, and collapsing of entire structures. Despite concrete spalling having catastrophic outcomes, the numerous studies conducted, are not able to pinpoint the key initiator for the type and phenomenological evolution of spalling process. However, the most prominent parameters have been reported as; heating rate, moisture content, permeability, strength, restraint to thermal expansion, aggregate type, curing regime, geometry and nature and extent of reinforcement [52]. Table 2 gives key some historic findings on concrete spalling presented by Jansson [36].

According to Jansson [36], the first published record of the occurrence of spalling was presented by Barret [37] during a presentation of a paper explaining the system of fireproof construction. In this publication, Barret provided a discussion, when the performance of concrete under the action of a fire was questioned, and it was stated that if the type of aggregate used in the concrete were of flint stones, the concrete would split and yield during fire. Jansson [58] provided experimental observations on spalling, considering spalling in the form of surface flaking and explosive spalling. Fig. 1 shows spalling on the unexposed surface of a 200 mm think concrete section after exposure to fire for 40 min where holes were formed throughout the thickness after continuous flaking.

Woolson [43] provided the first record of liquid water being expelled from the unexposed surface of the concrete in a study which investigated the crushing strength and elastic properties during fire exposure. In the discussion, it was highlighted that when the 15 feet span floor specimens were exposed to fire for two hours a water accumulation of about ½-¾ inch was visible on the unexposed surface. While the main cause of water accumulation of was not explained, the study clearly showed evidence of water pooling. In addition to this, it was stated that the concrete undergoes a sweating process, i.e., water pooling, under the action of heat where the water found in the voids would expand, thus, exerting a force adequate to change the mass. This entrained water would gradually

Table 1
Mineralogical changes in concrete during heating [51].

Heating Temperature°C	Changes Caused by Heating Mineralogical Changes
70 – 80	Dissociation of ettringite
105	Loss of physically bound water in aggregate and the cement matrix commences, increasing capillary porosity
120 – 163	Decomposition of gypsum
250 – 350	Oxidation of iron compounds causing pink/red discolouration of aggregate. Loss of bound water in cement matrix and associated degradation becomes more prominent
450 – 500	Dehydroxylation of portlandite. Aggregate calcines and will eventually change colour to white/grey
573	5% increase in volume of quartz (-to-quartz transition) causing radical cracking around the quartz grains in the aggregate
600 – 800	Release of carbon dioxide from carbonates may cause a considerable contraction of the concrete (with severe micro-cracking of the cement matrix)
800 – 1200	Dissociation and extreme thermal stress cause complete disintegration of calcareous constituents, resulting in whitish-grey concrete colour and severe micro-cracking
1200	Concrete starts to melt
1300 – 1400	Concrete melted

Table 2
Key Historic Findings on Concrete Spalling [36].

Year	Ref	Finding
1854	[37]	First record of spalling
1905	[43]	First observation of water being expelled from unexposed surface of concrete during fire
1911	[53]	Early characterization of the types of spalling
1935	[54]	Main factors which govern spalling was updated
1961	[55]	Moisture Clog Theory was brought to light
1966	[45]	Frictional flow theory
1997	[56]	Hydraulic Spalling Theory
2000	[57]	BLEVE theory

Fig. 1. A 200 mm thick cross section displaying severe spalling after 40 min of exposure to the hydrocarbon fire curve [58].

surface on the unexposed face.A summary of the types of spalling occurring in concrete were described by Meyer-Ottens [53] as aggregate spalling, surface spalling, corner spalling and explosive spalling [36]. The time period for the occurrence of these types of spalling after commencing exposure to fire, based on the standard fire curve, where the temperature of the furnace increased from 20 °C to 842 °C within the first 30 min and continued at a slow temperature rise [59], was categorised. The characteristics of these different forms of spalling, which include the main factors affecting each types is given in Table 3 [60] and a graphical representation is provided in Fig. 2 [61].

Hasenjäger [54] disused the main factors which lead to spalling as the thermal stress and water pressure. The study narrowed down the key factors as:

- Rapid heating rate
- Tensile strength being exceeded
- Rapid volumetric changes in aggregates
- Formation of pressure from water vapour and gases

When considering the heating rate and its influence on spalling, Mindeguia et al. [62] reported that generally higher heating rates induce higher amount of spalling. It was found that a lower measure of gas pore pressure was recorded at a more severe heating rate, which was a result of the formation of a large network of cracks due to the higher thermal incompatibilities between the cement and the aggregate. Dal Pont et al. [63] investigated the damage mechanism in high performance concrete when subjected to temperatures of up to 280 °C, and a clear relationship between fissure formation and spalling was presented. Their observations revealed that the cracking mechanism when concrete is heated can mainly happen in two ways; (1) small peaks which are not large enough to allow the escape of free moisture in a sudden way, and; (2) sudden cracking, which increases concrete permeability, allowing the rapid escape of moisture. Although several theories have been formulated, the series of diverse processes occurring simultaneously within the concrete during heating, has made it difficult to distinguish between transformations and accurately discover the main influencer of spalling.

Table 3
Characteristics of the different forms of spalling [60].

Spalling	Time of occurrence (min)	Nature	Sound	Influence	Main Influences
Aggregate	7 – 30	Splitting	Popping	Superficial	H, A, S, D, W
Corner	30 – 90	Non-violent	None	Can be serious	T, A, F_t, R
Surface	7 – 30	Violent	Cracking	Can be serious	H, W, P, F_t
Explosive	7 – 30	Violent	Loud Bang	Serious	H, A, S, F_s, G, L, O, P, Q, R, S, W, Z

A-aggregate thermal expansion, D-aggregate thermal diffusivity, Fs-shear strength of concrete, Ft-tensile strength of concrete, G-age of concrete, H-heating rate, L-loading/restraint, O-heating profile, P-permeability, Q-section shape, R-reinforcement, S-aggregate size, T-maximum temperature, W-moisture content, Z-section size

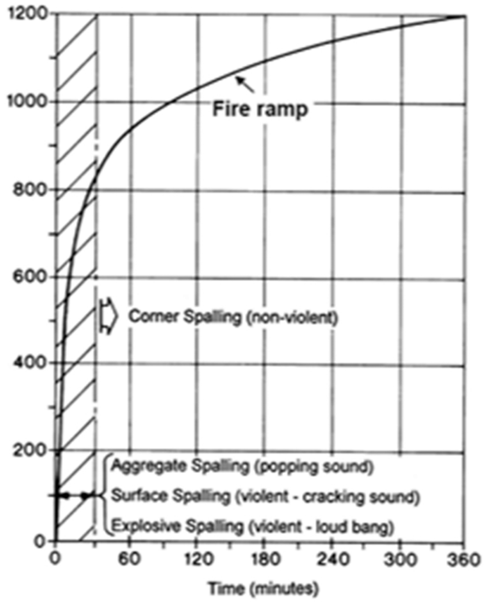

Fig. 2. Time of occurrence of different types of spalling in a fire [61].

The following sections discuss the main theories developed on the causes of concrete spalling.

2.2. Thermal stress theory

McNamee [45] stated that among the various theories brought to light, the stresses caused by expanding concrete layers and the stress caused by restrained moisture are on the forefront as being responsible for spalling. Concrete, being a heterogeneous material, consists of cement paste and aggregate particles, which respond differently when exposed to heat/ fire. The rate of contraction and expansion varies among these two materials, and in conjunction with the dense microstructure and low thermal diffusivity within concrete, high thermal gradients can cause an increase in thermal stress within the concrete, causing micro-cracking [45]. Hedayati et al. [42] defined spalling as being a result of the thermal instability of concrete elements when exposed to elevated temperatures. Choe et al. [46] stated that the spalling mechanism can occur due to the thermal stresses or the vapour pressure, or due to a combination of both [46]. The non-uniform temperature distribution which gives rise to thermal stresses causes brittle fracture and delamination buckling which leads to spalling [42,45]. Bažant and Cusatis [64] stated that the stresses created by thermal gradients cause a brittle fracture and delamination buckling parallel to the heated surface. A schematic description of thermo-mechanical

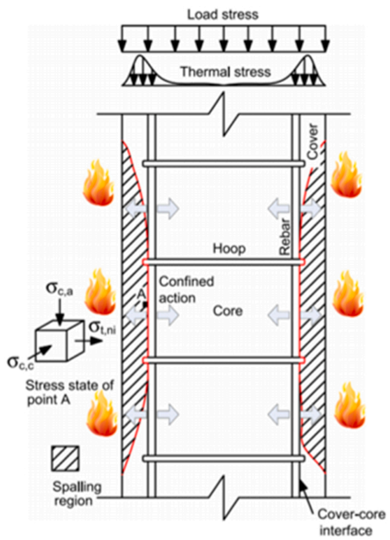

Fig. 3. A schematic description of the thermo-mechanical spalling of concrete [65].

spalling is shown in Fig. 3 [65]. In addition, HSC is reported to display a higher degree of explosive spalling due to the high dense microstructure which restrict the expansions and does not complement the rise in energy. This causes a higher level of thermal stress from forming within the concrete, thus causing spalling [36,45,66].

2.3. Moisture clog theory

Harmathy [55] described the moisture clog theory in detail, where it was stated that, at rising temperatures, an increase in the pore pressure in the pores close to the fire exposed surface drives steam not only outwards, but also into the concrete. As this steam reaches the cooler regions within the concrete, it will undergo condensation and become liquid once more. This will create a fully saturated region within the concrete of significant thickness. This saturated layer will create a moisture clogged region, which restricts the movement of additional moisture into the concrete, thus, giving rise to pore pressure. The moisture clog theory states that once this pressure exceeds the tensile strength, pieces spall off [44,45,55,67]. However, while the formation of a saturated region within the concrete during fire testing has been witnessed in on several occasions in previous studies, it is difficult to define a direct experimental approach to support the moisture clog theory [45]. However, newer techniques such neutron imaging has been used to address this issue (see in 3.1.9 Neutron Radiography (NR) and Neutron tomography (NT) for details). Literature simply states that the migration of water entertains the occurrence of a condition called moisture clog, which is assumed to cause an accumulation of water on the unexposed surface of heated concrete. This is referred to as water pooling and a significant contributor to the type and level of concrete spalling [45,66]. Fig. 4 shows a visual representation of the moisture clog theory by splitting a 600 mm × 500 mm × 200 mm slab [58, 68]. Fig. 5 shows the movement of moisture and the formation of the moisture clog region in heated concrete walls [69].

2.4. Fully saturated pore pressure theory

Even though Bažant and Cusatis [64] considered the pore pressure as a secondary factor of spalling, it is reported to be a primary factor causing concrete spalling [45]. Pore pressure spalling, also known as thermo-hygral spalling, is associated with the behaviour of concrete during thermal-hygral processes [65]. Fig. 6 shows a schematic description of the thermo-hygral spalling in a concrete specimen exposed to fire on one side [65]. The saturated pore pressure theory states that when the temperature within the concrete increases, if the closed pore system is partially filled with water at the beginning, this water will expand and force the air into the solids. This will, in turn, build up a hydraulic pressure, and in regions with higher levels of moisture the strength and fracture properties will vary, causing breakage and eventually leading to spalling [6,45,58]. At elevated temperatures, micro-cracks form on the inside and the outside of the concrete due to increased pore pressure and this will entertain the type and level of spalling [42,50].

2.5. BLEVE theory

Ichikawa [57] put forth the boiling liquid expanding vapour explosion (BLEVE) theory, where this phenomenon is assumed to be a contributing factor of spalling in high strength concrete. In this theory, liquid water which will rapidly convert to steam when heated to over 100 °C under pressure will undergo an instantaneous release of accumulate energy, which will lead to spalling. This is identified as the boiling liquid expanding vapour explosion theory.

2.6. Frictional flow from vapor flow theory

Jansson [36] acknowledges that according to Shorter and Harmathy [70], when concrete is exposed to fire, the pressure gradients within the concrete drives some of the moisture into the cooler regions in to the concrete and the rest expels through the heated surface. This moisture which is transported to the fire exposed surface will give rise to frictional forces in the flow path, and this will create tensile stresses on the surface which has already undergone a reduction in strength. Thus, causing the breaking down of these fire exposed surfaces. This is identified as the frictional flow from vapour flow theory, assumed to be another cause of spalling [45].

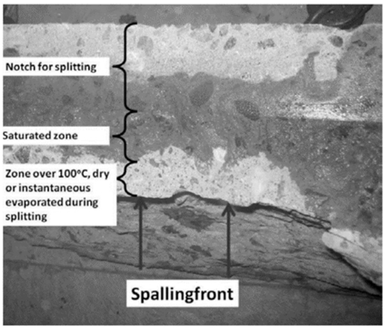

Fig. 4. The moisture clog in front of a spalling front [58].

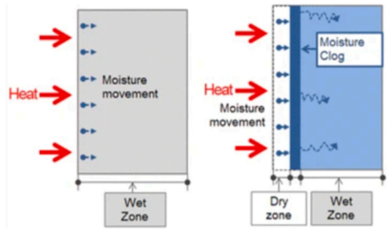

Fig. 5. Sequence of moisture movement in concrete wall specimens [69].

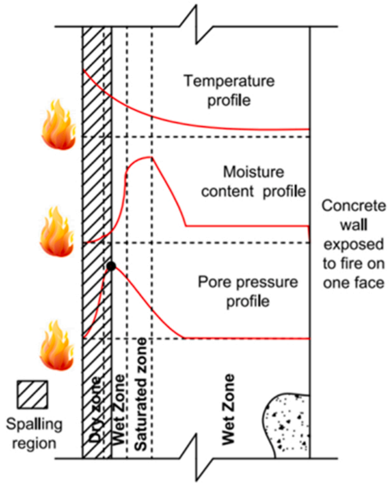

Fig. 6. A schematic description of thermo-hygral spalling in a concrete wall heated from one face is presented [65].

3. Review of the significance of and existing test methods on moisture migration and water pooling in concrete spalling

Jansson and Boström [68] stated that at a higher moisture contents, the risk of spalling is significantly high. A fully saturated region in a moisture clog can significantly alter the mechanical properties of the concrete in areas closer to the heat exposed surface due to the increase in material stiffness and the formation of an unstable growth in cracks. Moreover, the presence of moisture within the pore structure can reduce the compressive strength [6,68]. Vořechovská [71] also conducted testing on plain concrete specimens having various w/c ratios (0.3, 0.4, 0.5 and 0.6) to understand how moisture affects spalling. It was found that specimens having w/c ratios of 0.3, 0.4 and 0.6 were most susceptible to spalling. This could be interpreted by saying that in denser concretes, limited pathways for

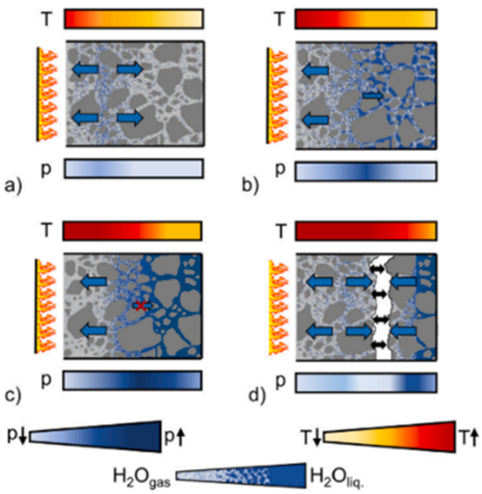

Fig. 7. Schematic drawing of the thermohydraulic spalling mechanism in HPC [32].

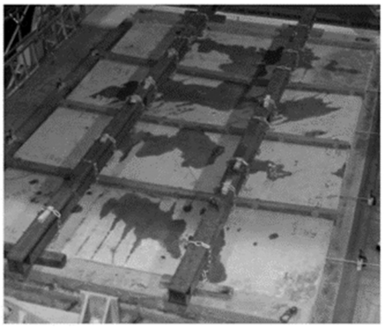

Fig. 8. Water pooling on the unexposed surface of a concrete slab section during heating [58].

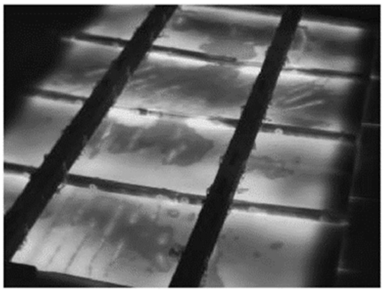

Fig. 9. Thermal imaging showing cracks through which water pooling occurred [58].

moisture movement restricts the release of pressure, and in more porous concretes, moisture migrations create a saturated region and moisture clog. Stelzner et al. [72] explained thermohydraulic damage mechanism (Fig. 7), where an increase in temperature causes the movement of pore water and chemically bound water, bringing about a volume increment that is restricted by the lack of pores. This causes a high vapour pressure which creates pressure gradients within the concrete, thus, resulting in vapour fluxes. The moisture which migrates into the cooler regions of the concrete, condenses and form a condensation zone, which Harmathy [55] explained as a moisture clog. This zone acts as a water-vapour barrier and obstructs the water-vapour flux, which creates a high water-vapour pressure, thus, initiating spalling.

Gallé et al. [73] investigated the impact of different heating rates on both the physical and the mechanical properties of a high-strength concrete after exposure to elevated temperatures. With regards to the water loss (mass loss), it was found that the heating rate does not influence the total water loss, and the lowest heating rate yielded the highest elastic modulus values. In addition, the highest permeability loss resulted from the lowest heating rate, which was determined using gas migration tests. Research conducted by Hertz and Sorensen [40] explored a new test method to understand spalling which occurs due to the stresses formed from restricted thermal expansion at different moisture levels. The loss of moisture was found by measuring the mass loss before and after heating. This sequential drying and weighing procedure determined if the concrete specimen is likely to spall at a given moisture content. While spalling did occur, the addition of PP fibres prevented spalling even when thermal expansions were restricted.

Monte et al. [74] studied three different test scales to try and identify a common key of interpretation of spalling. The authors assessed concrete sensitivity to spalling using; (1) a hot-spot test, where one face of concrete cubes were subjected to a jet flame using propane torch; (2) biaxial loading test, where unreinforced slab specimens were heated at the bottom using the standard fire curve, while being applied biaxial compression, and (3) full-scale test, where real structural tunnel members were exposed to fire at the base while being subjected to the external loads. The steep thermal gradients in hot spot and full-scale test methods had caused specimens to spall at the beginning of heating, however, spalling had been seen to occur at a temperature range of 300 °C–350 °C in all three test methods.

Jansson and Boström [75] reported that the pouring out of water from the unexposed surface of concrete elements is a common occurrence which is believed to be due to the process of vaporisation and condensation occurring inside the concrete. They stated that initially, the presence of saturated regions within the concrete is low, but as the temperature increases, the pressure gradients push the vapour into the concrete which condenses and forms saturated layers. As the transportation of moisture is likely to occur along the cracks and an insufficient amount of moisture is driven into the concrete, an even distribution of the saturated layers will not occur. This explains why water pooling occurs in sections of the unexposed surface [75]. Fig. 8 shows a concrete specimen, which is 8 cm thick, displaying water pooling on the unexposed surface during a fire test [58].

A new test setup was developed to measure the permeability of concrete against room temperature and high temperature [76], on high performance concrete with and without the addition of PP fibres. It was found that the permeability of PP incorporate concretes have a sudden increase in permeability between temperatures of 80 °C and 130 °C. In addition, SEM images revealed that the melted

Table 4
Current small-scale fire test for moisture migration in concrete at elevated temperature-specimen and testing information.

	Farage, Sercombe and Galle 2003	Van der Heijden et al., 2007	Chen et al., 2009	Van der Heijden et al., 2012	Jansson and Boström, 2013	Powierza et al., 2018	Dauti et al., 2018	Stelzner 2019
Specimen Type	Cylindrical Specimens	Cylindrical Specimens	Cylindrical Specimens	Cylindrical Specimens	Rectangular specimens	Cylindrical Specimens	Cylindrical Specimens	Cylindrical Specimens
Specimen Size, mm	40 mm × 80 mm (length) 10 mm thick slices 4 mm thick slice	40 mm × 40 mm (length)	37 mm × 35 mm (length) and 37 mm × 70 mm (length)	80 mm × 100 mm	20 mm × 20 mm x 40 mm	40 mm × 100 mm (length)	30 mm and 50 mm diameters	40 mm × 100 mm (length)
Concrete type and Materials	Cement paste. OPC at a w/c ratio of 0.4	B40 Type concrete	Mortar: cement, sand, 0.5 w/c ratio Concrete: cement, sand, gravel, SP (Glenium 51), 0.48 w/c	NSC cement, sand, gravel, w/c ratio: 0.5	Cement, sand, water (w/c ratio = 0.5) pp fibres	HSC, cement, water, aggregate, silica fumes, SP	HPC, cement, SF, SP, aggregate, w/b ratio= 0.3	HPC of cement, aggregate, SF, SP, with and without PP fibres, w/c ratio 0.3
Curing and Conditioning	Placed at 100% humidity till 24–48 h after casting. Sealed in plastic bags (20°C) for 7 years	Not mentioned	Dry, 3 months at 60% RH, 60% months at 60% RH	3months: water curing 9 months: Humidity at 50%, 75%, 86% and 95%	Mixing - EN 196–1:2005 Curing - water 6 months	Plastic wrapped for 24 h after casting and stored under water for 28 days. Then kept in climate chamber at 20 °C and 65% for 90 days	Sealed in plastic containers and stored in 97% RH and 20 °C	Plastic wrapped for 24 h after casting and stored under water (21 °C) for 27 days. Then kept in humidity chamber at 20 °C and 65% for minimum 2 months
Fire Curve	Not mentioned	Not mentioned	ISO 834	ISO 834	Not mentioned	ISO 834	Not mentioned	ISO 834
Fire exposure	Uniform heating from 80 °C up to a temperature of 300 °C at 0.1 °C/min	Heat exposed up to 250 °C	Constant heating up to 200 °C	One-dimension heating through sealing up to 500 °C	Boiling at 3, 10 and 20 min	Unilateral heating from above up to 300 °C at a heating rate of $10 Kmin^{-1}$. Temperature was held for 130 °C	Heated on the top surface up to 300 °C	Unilateral heating at a rate of $10 Kmin^{-1}$ up to 300 °C and 500 °C and held constant for 130 min
Loading condition	Unloaded	Unloaded	Hydrostatic Loading	Unloaded	Uniaxial Loading	Thermal loading	Unloaded	
Measurements	Porosity Elastic modulus Poisson's ratio	Moisture migration Vapour transportation	Permeability is measured by injecting inert gas at homogenous temperature	Movement of boiling front with respect to temp and time	Effect of moisture and temperature on the compressive strength	Density to identify moisture migration within the concrete	Moisture movement	Moisture migration Temperature
Test Methodology	Mercury intrusion porosimetry (MIP). Non-destructive test method using an ultrasonic testing system used to transmit and capture a pulse of vibration at an ultrasonic frequency	NMR setup placed inside a 1.5-T MRI scanner Model was developed to predict the movement of the drying front	Permeability is measured by injecting inert gas at homogenous temperature	NMR setup	Compressive test	Using X-ray CT scanning on heated concrete	Neutron tomography Thermocouples	X-ray CT scanning 2023 × 2023 pixel image and NMR spectroscopy testing to understand the moisture migration and reconfiguration from small gel pores to macro pores Temperature measured using thermocouples (type K) placed at 1, 10, 20, 30, 50 and 70 mm depths

Table 5
Total water content, lost water, relative lost water (lost water/total water) and released chemically linked water for the tested concrete mixtures [117].

B325		B350	B400	B450	B500
Total water content (%)	8.72	8.32	7.50	6.67	5.88
Lost water (%)	5.17	5.43	4.67	4.37	3.89
Relative lost water (%)	59.0	65.0	62.0	66.0	66.0
Released chemically linked water (%)	1.37	1.63	1.17	1.17	1.09

PP fibres do not penetrate into the cement paste and only flow into the micro-cracks. These results show that permeability does govern the degree of explosive spalling. Noumowe et al. [77] investigated the effect of applied hydrostatic pressures on the coefficient of permeability (K) to understand the permeability of high performance concrete exposed to temperatures of 600 °C. Studies used the rapid chloride permeability test [78,79] and the measurement of K based on empirical formula [80] to understand the permeability of concrete, as it controls the movement of fluids and hence, gives rise to potential pressure gradients during temperature increase [81].

In providing three experiments to validate a model for concrete spalling, Jansson and Boström [82] stated that thermal imaging can be used to identify the cracks through which water pooling occurs on the unexposed surface of concrete slabs. Fig. 9 shows thermal imaging on the unexposed surface after minutes of exposure to the hydrocarbon fire curve. While the pooling of water can be identified using the test setup, it is extremely difficult to experimentally analyse the amount of moisture migrating away from the heat exposed surface. Hence, no experimentation has yet been defined to understand this mechanism of moisture migration and water pooling which is probably the biggest challenge in modelling concrete spalling.

The following sections provide a collection of relevant experimentation conducted on understanding spalling by focusing on the movement of moisture through heated concretes. Tables 4, 6 and 8 provide specimen and testing information of key research studies conducted on small, medium and large-scale tests, respectively, which are discussed in the ensuing sections.

3.1. Some techniques of measuring moisture in concretes

Various techniques can be found to determine the moisture content in concrete and while no one method is better than the other, the material, type of measurements required, purpose of analysis and required resolution will govern the selection of a particular test method. Additionally, determining the type of moisture, such as physically bound moisture or chemically bound moisture, is recognized as a crucial factor to understand when selecting a technique [83]. The following sections provide an insight to the different principles and techniques that are current being used.

3.1.1. Drying

One of the most common methods of determining the amount of moisture in concrete is using drying techniques. However, while this can be done using several methods, moisture removal through dryings can create a damaging effect on concrete. General method of drying is where a steam of hot air is allowed to circulate through the concrete to heat and remove vapor in an oven. The weight before and after drying is recorded to calculate the mass loss which is considered as the moisture loss. Additionally, in order to reduce the error in calculation due to the re-absorption of moisture from the atmosphere, weights need to be measured before the samples reach room temperature. Evaporable water, which is the physically bound water, is said to be lost at a drying temperature of 105 °C [83].

Thermogravimetry Analysis (TGA) is another method of measuring the moisture where powdered samples of a known mass, extracted from the concrete specimens, are subjected to elevated temperature levels while weighing. While the TGA is similar to oven drying, heating up to temperature far greater than 105 °C can be achieved using TGA (up to 1500 °C). Moreover, additional material compositions and behaviors such as moisture loss, solvent loss, decompositions, oxidation, etc., can be deduced using the TGA as opposed to oven drying. Portable thermo-balances can also be used on site to understand the loss of moisture in powdered samples during heating. Whiles errors could occur due to vibrations or wind effects, these balances are of suitable accuracy. Additional errors associated with using gravimetric analysis (determining moisture using weight measurements before and after drying- see in Fig. 10) to determine moisture can be identified as material loss during handling, incomplete drying, inadequate representation of overall concrete, etc. [83].

3.1.2. Infrared thermography

The Infrared (IR) Thermography can be used in determining the surface temperature of a material. This non-destructive test method records the electromagnetic rays emitted from the eternal surface in the infrared spectrum. The internal properties of a material affect the thermal radiation through the material' such as the moisture content' which also affects the thermal conductivity. Two-dimensional recordings can be obtained using a numeric thermal camera to understand the thermal field on the surface. However, due to the complexity of concrete, which have cements, aggregate, water and/or chemical or physical admixtures, heat transfer though concrete is difficult to identify. In which case, the conduction process can be subdivided through each component [83,84]. While the use of IR thermography in concrete is rare, a study conducted in Montreal, Canada uses this technique to highlight the moisture ingress through a concrete wall specimen. IR-thermography was used to understand the moisture profiles in specimens exposed to capillary

Table 6
Current medium-scale fire test for moisture migration in concrete at elevated temperature-specimen and testing information.

	England and Sharp, 1971	Chapman and England, 1977	Kalifa et al. 2000	Jansson and Boström, 2009	Noguchi et al., 2010	Mindeguia et al., 2010	Mindeguia et al., 2013	Lo Monte et al., 2017	Felicetti et al., 2017
Specimen Type	Cylindrical specimens	Cylindrical specimens	Prismatic specimen	Cube specimen	Rectangular specimen	Prismatic specimens	Prismatic specimens	Slab section	Cube specimens
Specimen Size, mm	Not mentioned	6’’ (152.4 mm) diameter x 5′ (127 mm) length 6" (152.4 mm) diameter x 10’ (254 mm) length	300 mm × 300 mm x 120 mm	150 mm × 150 mm x 150 mm	500 mm × 500 mm x 120 mm	300 mm × 300 mm x 120 mm	300 mm × 300 mm x 120 mm	800 mm × 800 mm x 100 mm	100 mm^3
Concrete type and Materials	Not mentioned	NSC, 1/1/2:4:6, w/c ratio: 0.6	Cement, sand aggregate (NSC 30 MPa), 0.5 w/c ratio Cement, sand, aggregate, SF, water reducers (HPC 100 MPa), 0.34 w/c ratio	Cement, sand, gravel, water, SP, (with and without) PP fibres	R/F concrete at w/c contents of 25% and 50%	Cement, sand, gravel, water, SP, with varying w/c ratios and varying compressive strengths	Cement, sand, gravel, water, SP. w/c ratios: 0.54, 0.3 Varying PP fibre content and varying compressive strengths	HPC: cement, GGBFS, silico-calcareous aggregates, Monofilament PP fibre and water	Cement, sand, gravel, water, with and without 2 kg/m^3 PP fibres
Curing and Conditioning	Not mentioned	Not mentioned	Sealed bags for 6 months	Not mentioned	Air curing at 20 °C and 60% R.H. until heating tests at 91 days	Not mentioned	Stored in air tight bags in ambient air of the laboratory	Not mentioned	Plastic sealed for one week after casting. Then left exposed to laboratory conditions for three weeks
Fire Curve	Not mentioned	Not mentioned	Not mentioned	ISO 834	ISO 834	ISO 834	ISO 834	ISO 834	ISO 834
Fire exposure	Non uniform heating	Sustained heating at the base for varied periods from 401 days to 697 days at temperatures of 105 °C, 125 °C, 150 °C, 175 °C and 200 °C	Unilaterally heated. Thermally insulated from sides	Furnace heating	Single face heating. All other surfaces were coated with a single layer of a coating material resistant to 600 °C, tightly sealed with aluminium tape, and again coated with the heat-resistant coating material	Heated on one face	Exposed to heat on one side with one-dimensional heat flow	Fire exposure from the bottom side of the slab	Heat exposed up to 500 °C on two opposite surface using radiant panels. Insulated using ceramic fibre board to ensure mono-dimensional heat flux
Loading condition	Unloaded	Unloaded	Unloaded	Unloaded and loaded at 2 MPa	Unloaded	Thermal loading	Thermal loading	Biaxially loaded	Unloaded until reaching max. pressure
Measurements	Pore pressure Temperature	Pore pressure Water content	Simultaneous measurements of pore pressure,	Visually identifying the location of the saturation layer	Temperature	Mass loss	Temperature	Movement of the waterfront	Pressure Temperature/ Heating rate

(*continued on next page*)

Table 6 (*continued*)

	England and Sharp, 1971	Chapman and England, 1977	Kalifa et al. 2000	Jansson and Boström, 2009	Noguchi et al., 2010	Mindeguia et al., 2010	Mindeguia et al., 2013	Lo Monte et al., 2017	Felicetti et al., 2017
			temperature and mass loss						
	Moisture content	Transverse/ longitudinal shrinkage			Moisture content		Pore gas pressure	Temperature and pressure at 6 measuring points	Tensile strength
					Vapour pressure				
Test Methodology	Using mercury manometers, thermocouples, moisture meters and measurement of weights	Thermocouples, moisture meters and pressure tapings located along the length of the cylinders	6 gauges placed at 2, 10, 20, 30, 40 and 50 mm from the heated surface	By sawing a 70 mm notch on the non-fire side	Type K thermocouples at 10, 30, 50, 70, and 90 mm from the heated surface	Mass loss measured during heating using a balance	Using gas pore pressure and temperature measuring probes situated at 10, 20, 30 40 and 50 mm from the exposed surface.	Ground Penetration Radar (GPR)	Probes and thermocouples for measuring the heating rate.
		Scanning Electron Microscope (SEM) was used to obtain photographs of microstructure			Pipes for pressure measurement and electrodes for measuring the moisture content				Indirect split test

Table 7
Results from Pressure Measurements [105].

Main characteristics Concrete mix	Fire curve	With PP fibres		Without PP fibres	
		Pressure (MPa)	Spalling	Pressure (MPa)	Spalling
Tunnel concrete	STD	0.7	No	0.3	Yes
Tunnel concrete	RWS	0.65	Minor		
SCC*	HC	0.45	No	0.15	Yes

* In an additional set of tests on the SCC presented here, with standard fire exposure, the pressures were slightly higher for concrete without PP fibres although spalling behavior was equivalent.

Table 8
Current large-scale fire test for moisture migration in concrete at elevated temperature-specimen and testing information.

	Šelih et al., 1994	Pont, Schrefle and Ehrlacher, 2005	Jansson, 2009	Kang et al., 2016	Guerrieri and Fragomeni, 2019
Specimen Type	Concrete Wall specimens	Hollow cylindrical specimens	Concrete Wall specimens	Concrete Wall specimens	Concrete Wall specimens
Specimen Size, mm	0.2 m thick	1.5 m high, 0.25 m internal radius, 0.55 m external radius	1700 mm × 1200 mm x 300 mm	1300 mm × 750 mm x 150 mm/200 mm/ 250 mm (thickness)	3380 mm× 3360 mm × 100 mm 3380 mm× 3360 mm × 200 mm
Concrete type and Materials	NSC with high moisture content	Ultra high strength concrete specimens used by[26] and encircled y a steel layer of 1 cm thickness.	Tunnel concrete, cement, gravel (granite), superplasticizers, water, w/c ratio:0.4 Self-settling concrete (SSC) cement, gravel (granite), limus (limestone filler) 25 superplasticizers, water, w/c::0.4, w/powder:0.3 Both types of concrete were made with 0 and 1 kg/m^3 of PP fibres	R/F NSC, cement, sand, gravel, admixtures, w/c ratio:0.52	R/F concrete: cement, sand, basalt aggregate, SP, water
Curing and Conditioning	Not mentioned	Not mentioned	Not mentioned	5 month - room temperature	24 hr: cured under polyethylene sheets 27days: moist curing at 23 °C and 100% 2months after casting: room temperature
Fire Curve	Standard fire curve. ASTM E-119 and the Short Duration High Intensity (SDHI) curve (Ellingwood 1991)	Not mentioned	Tunnel concrete: Standard fire curve (EN 1363–1) and RWS curve SSC: Hydro carbon fire curve	ISO 834	The hydrocarbon fire
Fire exposure	Exposed on one side	Heated on the internal face (hollow section) up to a temperature of 250 °C for 30 days. The external face is not heated.	Exposed on one side	One surface fire exposure for 2 h	Single-side exposure-furnace chamber
Loading condition	Unloaded	Unloaded	Loaded on one side with 10% of their compressive strength	Unloaded	Unloaded
Measurements	Temperature Moisture content	Temperature, Pressure	Pressure Spalling	Temperature distribution Moisture Content	Temperature Pore Pressure Moisture content Spalling
Test Methodology	Thermal Analysis using two simplified models	K type thermocouples, pressure sensors embedded into the concrete wall	Pressure measured using oil-filled pipes	Thermocouples to record temperature	Using thermocouples, pore pressure gauges Tramex CME4 for moisture determination and mass loss for spalling

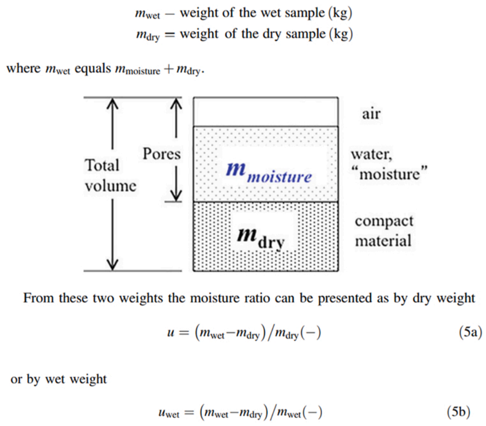

Fig. 10. Principle of Gravimetry [83].

suction from one end. An IR-camera was used to determine the surface temperature profile which was then translated to moisture levels by calibration. However, high moisture content areas produced low resolution images [85].

3.1.3. Gas permeability

The amount and distribution of moisture present in a porous material can significantly change the gas permeability [83]. This gas relative permeability depends solely on the concrete saturation in a cementitious material [86–88]. Liu et al. [89] used a method called the 'Pulse Test Protocol', to determine the in situ moisture content of concrete. A schematic diagram of the pulse measurement protocol is given in Fig. 11. However, the method of gas permeability can have several errors such as an overestimation of intrinsic permeability due to high water saturation or a considerable increase of apparent gas permeability due to micro-cracking which may be caused by drying shrinkage [90].

3.1.4. Pore water pressure and hygrometry

Pore water pressure (P_W) is related to the relative humidity (RH) found in the pores, and P_W in saturated and unsaturated concretes can be determined using pressure gauges, traditional manometers and simple pressure transducer. [83,91]. Mugume and Horiguchi [92] examined the effects of different pore pressure measuring techniques on HSC. The study used three different gauges; 1) a tube; 2) a tube having a metal cup brazed on its top and; 3) a tube having a metal cup brazed on its top and a sintered metal encapsulated in the metal cup (Fig. 12). Each of them had silicon oil or air, as the two media inside the pipe which transforms pressure to the outside of the concrete specimens based on the pore pressures measured. It was observed that the pore pressure readings measured using air filled pressure gauges were lower and unstable when compared to the readings obtained using the silicon oil filled gauges. Additionally, sintered metal gauges (type 3) showed higher amounts of pore pressure compared to the other two types of gauges. The author stated that the pressure measuring system has a significant effect on measured pore pressures and that sintered metal gauges having silicon oil as its medium is the most effective gauge setup for taking pore pressure measurements in concretes subjected to elevated temperatures [92].

Ye et al. [48] conducted an experimental study to determine the accuracy of pore pressure measurements. The accuracy was measured by using twelve designs of pore pressure gages having different types of pressure-gage heads, different placements of thermocouples and different mediums to fill the tube to transfer pressure. UHSC specimens were subjected to one-dimensional heating, and results had revealed that different designs did not affect temperature measurements. However, pressure measurements had been affected and misleading results had been obtained by factors such as too much free space and filling silicon oil.

Hygrometry is the principle of using an instrument to measure the relative humidity (RH) to determine the moisture condition of a material. Generally, several electronic RH-probes are utilized to measure the RH in concretes. These RH probes have a sensor material (the most crucial part) which can measure the electrical resistance or capacitance. This provides a determination of the moisture

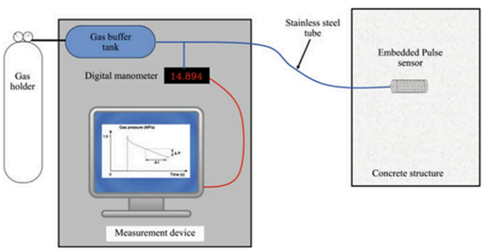

Fig. 11. A schematic diagram of the pulse measurement protocol [89].

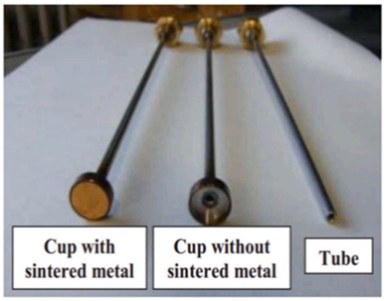

Fig. 12. Three different types of gauges [92].

content of the sensor material which can be translated into RH. Most humidity measurements currently being done are conducted using small electronic probes which reacts to the surrounding humidity. Hygrometers are used to measure the RH of air and then placed within the concrete specimen until equilibrium conditions are obtained in measured readings [83,93]. Fig. 13 shows a view of RH probes inserted into concrete specimens through drilled holes.

The changes in temperature between the sensor and material surface is an important factor when measuring RH, which can cause systematic errors. Ozawa [9] reported systematic errors where HPC having a very low moisture capacity measured a repeated difference of − 0.6% RH for each measurement when the same concrete sample was tested. Large systematic errors were recorded from concrete samples having low w/c ratio which were found to be due to the initial drying of specimens before testing and the very low moisture capacity [83].

3.1.5. Time domain reflectometry (TDR)

Time Domain Reflectometry (TDR) uses the measurement of the time taken for an EM signal along a probe moving there and back, through which, the mean relative permittivity can be derived. This mean relative permittivity can then be used to understand the volumetric water content and its changes. The non-destructive nature of this test, along with high spatial resolution, high precision and stability make this moisture determination technique advantageous. The TDR apparatus consists of mainly three parts: a reflectometer (pulse generator), reflected signal analyzer, and a probe (waveguide). Reflection pictures can be presented in terms of volumetric moisture contents. TDR techniques are now being implemented to understand the volumetric moisture contents of different types of concretes [83,94–96].

3.1.6. Nuclear magnetic resonance (NMR)

Nuclear Magnetic Resonance (NMR) spectroscopy, NMR relaxometry (relaxation measurements) and MRI (Magnetic Resonance Imaging) are non-destructive techniques (Fig. 14) which can be used to understand the amount of moisture within concretes [83]. This is the only method available in determining both the capillary and physically bound water. Moreover, factors such as pore sizes can be identified using NMR instruments. The number of hydrogen nuclei, measured using NMR, can be indicated by the amplitude of the NMR signal and this is proportional to the total water content. Koptyug [97] stated that properties such as the transportation, moisture characteristics, formation and shape of moisture front can be identified using MRI. However, temperature changes influence the accuracy of the results, and therefore, the environmental conditions must be kept constant. NMR imaging can be used to monitor and measure semi-quantitatively and non-destructively, the moisture content variations within concrete during heating [98,99]. Van Der Heijden et al. [67] stated that moisture distributions within building materials can be directly measured during heating using an NMR setup. Modern NMR instruments are small and can be easily carried and placed on concretes for moisture detection.

3.1.7. Ground penetration radar using the microwave reflection principle

The Ground Penetrating Radar (GPR) technique is a methods available under the microwave reflection principle which can be used to examine moisture. The GPR consists of an antenna which is connected to a processing unit having a wave transmitter and receiver. The transmitted waves will reflect when they strike different boundaries, and can be captured using the receiver antenna. The

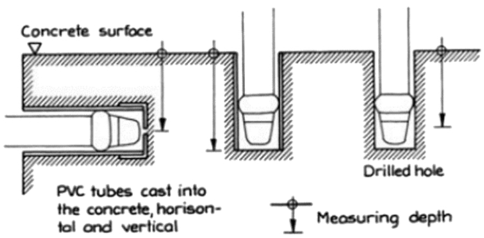

Fig. 13. Schematic diagram of RH probes inserted into concrete specimens [93].

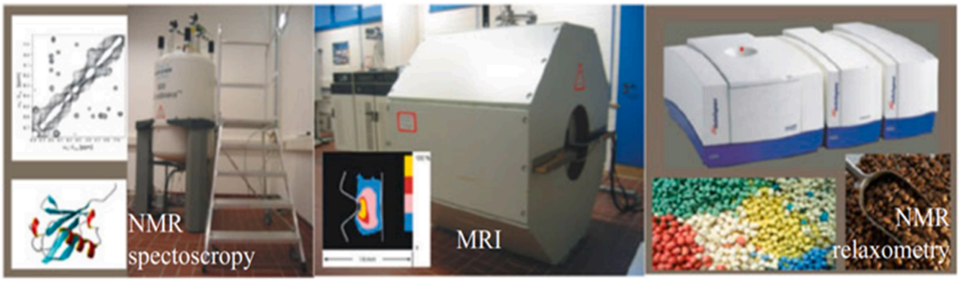

Fig. 14. NMR measurement instruments [83].

amplitude of the received waves and the time taken between waves can be used to understand moisture properties in concrete. This method is robust and can be made small enough so that a good spatial resolution can be obtained, or large enough, so that material inhomogeneities can be overlooked [83,100]. Wide Angle Reflection and Refraction WARR is a method where the wave velocity can be estimated using the direct wave. In this method, the first time of arrival of the wave is measured in relation to surface waves through which the wave's velocity and dielectric constant (which is influenced only by moisture volumetric content) is estimated. However, since an increase of conductivity can be obtained where there is high moisture presence, the amplitude of the waves can be more easily used and recorded than the velocity to determine moisture. An attenuation (amplitude) of about 5 dB for dry concretes and higher than 11 dB for saturated concretes were reported [101].

3.1.8. X-ray and gamma-ray

This method of determining moisture has been utilized when conducting testing under laboratory conditions [83,102], however, the technique of using x-rays is better utilized in understanding the crack detection and propagation within concrete, rather than for the detection of water, as it is related to the density of the specimen. The test specimen is placed in between an X-ray source and a detector and the loss of intensity as the beam passes through the specimen is identified (Fig. 15). The moisture content of the specimens can be measured by performing and comparing to a second measurement conducted on a dried specimen of the same dimensions and compositions. Carmeliet et al. [103] used X-ray tomography to monitor 3D cracks in concrete, where a crack segment map was used to construct a hydraulic network within the concrete. This was able to provide the pathways of moisture migration and could be used to identify the influence of moisture flow on spalling.

3.1.9. Neutron radiography (NR) and neutron tomography (NT)

Direct quantitative and qualitative time-dependent moisture migrations can be obtained using NR technique [83]. This very powerful tool consists mainly of source producing neutron beams through the collimator and a detector (Fig. 16). An image which shows the macroscopic structure of the specimen is produced on the detector system. As this technique is related to the neutrons scattering, it is more suited than the x-ray technique in understanding the moisture content and migration. It is highly sensitive and can identify two-directional moisture migration and the penetration to and vaporing from concrete materials. This method is valuable in understanding the deterioration processes of concrete due to moisture migration and has been used to study the moisture penetration through cracks [104,105]. NR uses the radiographic measurements of the weakened or loss in intensity after being transmitted through concretes. As different thicknesses and composition will result in different results, they can be used to understand the structure within the concrete. Moreover, neutron imaging can detect even small moisture migrations by providing a good contrast between compositions.

While NR measure the intensities in 2D, where object layers cannot be easily distinguished, the Neutron Tomography (NT) can take measurement in 3D. This is an innovative technique which allows to access the moisture distribution within concrete during heating. The principle of NT is similar to X-ray imaging, where both study the attenuation of incoming neutrons, in the former, and protons, in the latter, in relation to the local structure of concrete. While the x-ray radiation interacts with the outer electrons shell of the atoms it encounters, neutrons interact with the atoms' nuclei. Hydrogen absorbs an order of magnitude more than aluminum or titanium and the particularly high attenuation of hydrogen atoms is convenient to studying the moisture content, including the drying front, and particularity to quantify the moisture clog (which is a crucial condition to assess when understanding spalling) of concrete during elevated temperature exposure [83,106].

While NT enables a more comprehensive outlook on local distribution, a relatively long time may be taken to acquire one tomogram. This creates complications when being utilized in fast processes such as monitoring the drying front, which moves about

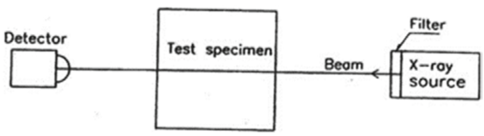

Fig. 15. Schematic view of testing system [102].

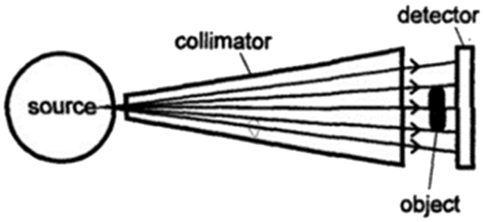

Fig. 16. Schematic diagram of a NR system [83].

6 mm in 10 min. Dauti et al. [107] presented the first results of fast neutron tomography at the Institute Laue Langevin (ILL) in Grenoble, France, where it was possible to acquire one tomogram per minute, which provided crucial information in understanding and modelling the underlying processes of concrete spalling. The authors stated that the complex mechanism of concrete spalling can be better understood when the movement of moisture within the concrete during temperature rise can be more closely followed. Dauti et al. [108] reported that a great deal of care must be taken when embedding thermocouples and pressure sensors to study the temperature and pressure of concrete during exposure to elevated temperatures, as air bubbles could be formed during insertion of such sensors, which could in turn directly affect the measurements. This drawback of using sensors led researchers in using NT techniques to detect moisture, as neutron imaging generally provides an ideal contrast between wet and dry regions, thus enabling 3D reconstruction of the moisture distribution pattern. A related study showed that a rapid NT technique revealed the evolution of the drying behaviours within test specimens, which can be considered as a direct proof of moisture accumulation/clogging ahead of the drying front [109].

Sleiman et al. [110] stated that due to the high hydrogen sensitivity of NT the evolution of the moisture field can be studied in a 4D plane. The authors presented novel 5D datasets of a cement paste and concrete sample when subjected to temperatures of up to 140 °C. This 5D data sets were obtained using 3D tomographies along time, including truly simultaneous x-ray and neutron rapid acquisitions. While NT was used to study the changes in moisture, x-ray tomography was used to understand crack initiation and propagation. In this study, it was found that hydraulic equilibrium was reached when 20% volumetric fraction of the capillary water was lost, and that crack-induced local drying was noticeable in areas having lower temperatures, lower drying areas with effects extending as far a 4 mm from crack tips. Fig. 17 shows the experimental setup used in the study.

3.2. Review of small–scale tests that showed moisture migration and water pooling during heat exposure

Farage et al. [111] stuided the evolution of the pore network of cement paste specimens exposed to elevated temperature levels between 80 °C and 300 °C, using mercury intrusion porosimetry (MIP), which is a commonly used setup to measure the mesopores and macropores in cementitious materials. It was found that the total mercury porosity changed between a temperature of up to 150 °C (indicating microstructural changes in the cement matrix), which could be due to the loss of interlayer water from the C-S-H gel. The elastic modulus and Poisson's ratio had been seen to slightly decreased with temperture (−17% at 300 °C).

Van der Heijden et al. [50] used cylindrical specimens to understand the influence of moisture and vapour transportation on spalling. It was found that superheated water (at 170 °C) within the concrete causes an increased pressure and the pressure was recorded to be the highest at the drying front. Furthermore, it was stated that the main factors influencing the movement of the drying front, which was predicted using a model, were the rate of heating rate, permeability and pore size.

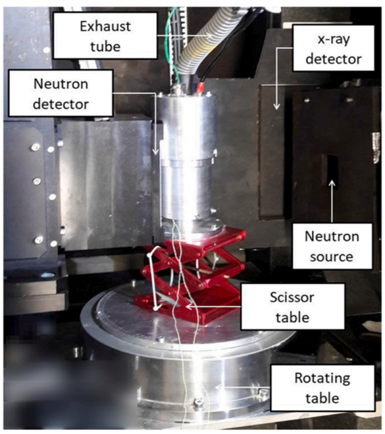

Fig. 17. Heating cell in beam-line (x-ray source yet to be moved): the cell is to be crossed by a neutron flux on a first axis and by an x-ray flux on a nearly-perpendicular second axis [110].

Gas retention, which is a phenomenon brought about by the moisture clog theory that blocks the porous network and prevents gas from moving through the concrete when heated, was used to understand the hydraulic behaviour. It was reported that gas retention due to the moisture clog does indeed affect spalling and that the clogging of the porous system can be by either the vapour of free water and/or dehydrated water. While gas retention is highly dependent on the heating rate, results further revealed that the permeability decreased after temperatures above 146 °C in dry samples but was obtained much lower temperature in the saturated samples. This was assumed to be attribute with the free water dilation and/or flow out [41].

Pel et al. [98] presented the first quantitative proof for the build-up of a moisture peak using a NMR test setup, where the moisture and temperature profiles were measured more accurately. Results revealed that the temperatures of the boiling front increased from approximately 160 °C to 195 °C, and compared to an atmospheric pressure of 0.1 MPa, the saturated vapour pressures corresponding to these temperatures were 0.7 and 1.4 MPa, respectively. This increased vapour pressure entertains the vapor released at the boiling front in moving both towards the heated surface and towards the back of the concrete specimen. This movement can also be verified through the observations made of the moisture content on the unexposed side of the boiling front, which significantly increased, thus, creating a fully saturated region. It was stated that due to the formation of this fully saturated region, as the boiling front progressed the moisture content, which corresponds to the porosity of concrete, did not increase above approximately 0.11 m^3/m^3. The increased moisture content on the back of the sample (unexposed surface) was assumed to be due to the vapour pressure of the boiling front being large enough to drive the moisture towards the unexposed surface.

A study was conducted to measure the moisture profiles experimentally using neutron imaging techniques where the results obtained were used to improve a numerical model [112]. During the experimental stages, it had been observed that the accumulation of moisture occurred behind the dehydration front, and this accumulated moisture migrated to the coder regions. The authors stated that neutron imaging is important in fine-tuning numerical models and for improving and understanding the process of dehydration and water retention curves when concrete is heated.

Testing conducted on small, heated rectangular specimens revealed that the moisture levels within the concrete significantly affected the strength. The compressive strength was reported to have decreased by about 40% when moisture was present in comparison to dry specimens. Additionally, it was stated that this high strength reduction is independent of the pore pressure and that the influence of moisture on the mechanical properties in the critical zone can be a governing factor for spalling [75].

Powierza et al. [66] studied the water migration in one sided heated concrete using cylindrical specimens. Specimens were encased in a glass-ceramic shell, impermeable to water vapour and then surrounded by a high-temperature aluminium silicate wool shell to obtain unilateral heating. X-ray CT scanning was conducted at 15 min intervals from 0 to 150 min where the density was tested using scans to identify moisture migration. Initial scans resulted in blurry images which was due to the fast-moving moisture front that later slowed down, thus producing clearer images. The density in the fire exposed surface showed a continuous decrease in density which provided evidence that the vaporised moisture migrated away from the heated surface and condensed in the pores located in the cooler regions within the concrete. Furthermore, the low pressures present in the inner pores/regions within the concrete accommodated the condensed steam as it migrated deeper. The study states that the analysis on thermally induced moisture migration can be used to understand the thermo-hydral processes and that the X-ray CT scanning technique can be further developed to investigate the spalling behaviour of concrete through moisture movement. Obviously, such an attempt can reveal limited information relating to the basic physio-chemical processes pertaining to the movement of moisture within the concrete specimen when it is exposed heat/fire.

In situ NT was used by Dauti et al. [106] to provide the first 3D analysis of the distribution of moisture within cylindrical concrete specimens subjected to single face heating up to 300 °C. The fast dehydration process was monitored using one 3D scan per minute. The experimental set up of the cell and the beamline setup is given in Figs. 18 and 19, respectively. The observations made on the attenuation coefficients of the cement paste were used to investigate the changes in the water content. The attenuation coefficient (arbitrarily assigned) is directly linked to the water content, were a high value would mean a high water content, and vice versa.

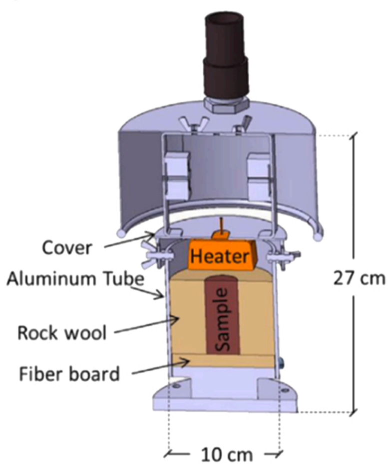

Fig. 18. AutoCAD drawing of the experimental setup of the cell [106].

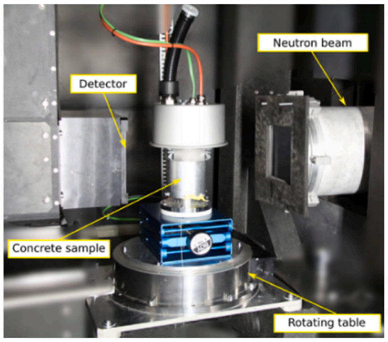

Fig. 19. Set up in beamline [106].

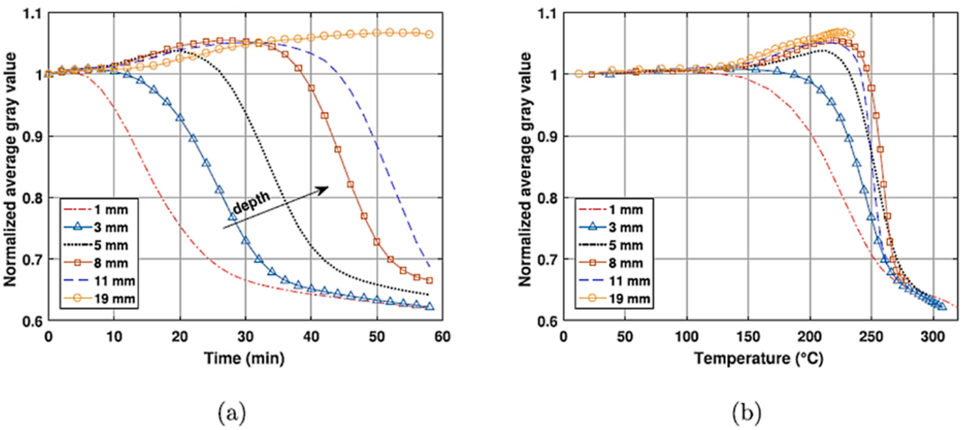

Fig. 20. Moisture profile evolution at different depths evaluated through the normalized attenuation coefficient to which they are directly proportional. (a) Water content evolution against time and (b) water content evolution against temperature (interpolated from the thermocouples) [106].

Results of the normalized average values against both time and temperature are given in Fig. 20. Results showed a peak increase in the normalized average values (which relates to an increase in the water content) between 200 and 250 °C at depths of 5, 8, 11 and 19 mm. The maximum gray value was witness at a depth of 19 mm which was a clear indication of the accumulation of water as known as a moisture clog. The author stated that NT experimentation provides critical information to understand and model the underlying processes, however, improved boundary conditions are required for more conclusive proof.

A study conducted by Stelzner [113] explored the transport and reconfiguration of moisture due to unilateral heating, achieved by the use of a special insulation casing (Fig. 21), up to 300 °C and 500 °C. NMR results revealed that the moisture distribution before heating was almost homogenous throughout the cylinders; however, after heating, the moisture on the heated surface decreased. In addition to this, the moisture distribution analysis had showed that the position of the drying front accommodated explosive spalling. The formation of the drying zone was visible from the X-ray CT measurements and results showed that the accumulation of moisture took place in deeper areas of the cylinders in the macro-pores as the heating surface propagated into the concrete. Fig. 22 shows the

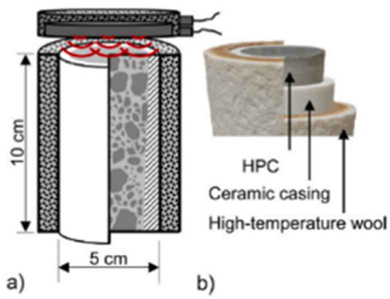

Fig. 21. HPC specimen with ceramic casing and insulation shell made of high-temperature wool [113].

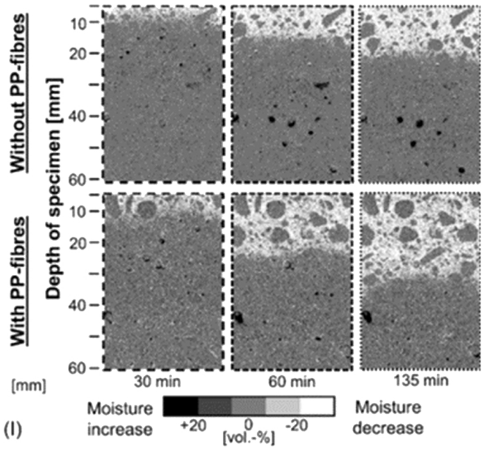

Fig. 22. Quantified moisture changes inside heated HPC (T_{max} = 300 °C) [113].

movement of the drying front (moisture movement) at different depths during 30, 60 and 135 min. The authors state that this method of testing is suitable in investigating the thermally induced moisture transport to understand spalling at a deeper level. However, it must be noted that experimentation to follow the migration of moisture in concrete during heat exposure using X-ray alone is insufficient, and in reference to the work of [114], neutron imaging is a more prominent tool in detecting this moisture, due to the advanced sensitivity of a neutron beam to hydrogen molecules. Here it is also pertinent to note that the NMR and GPR techniques, as they stand, are limited value as compared with the scattering method, and hence these methods should be further explored for their

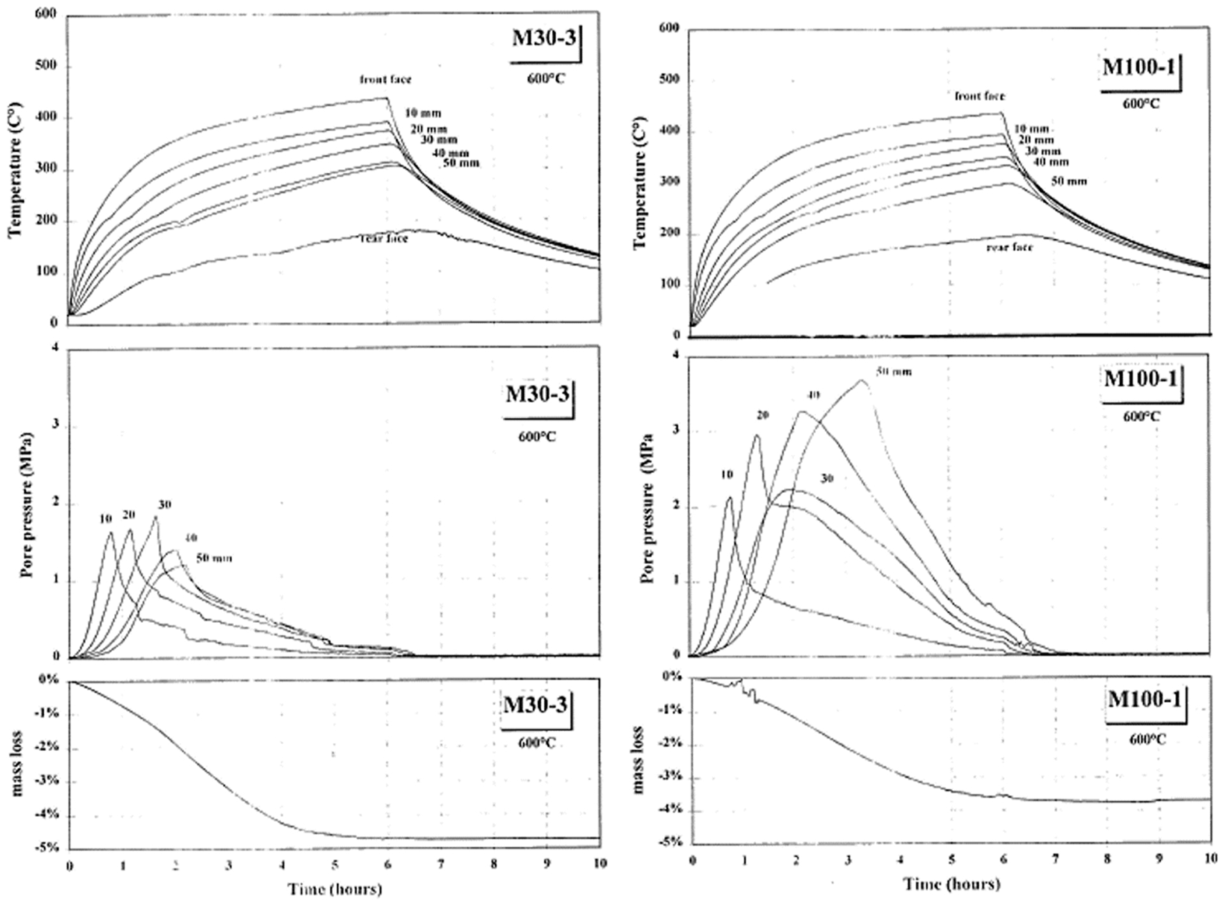

Fig. 23. Mass loss, pressure and temperature fields vs. time of NSC (left) and HSC (right) [26].

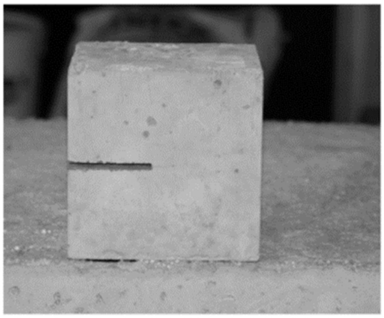

Fig. 24. Test specimen with a 70 mm notch used to slip cubes after exposure [68].

wider utility.

3.3. Review of medium–scale tests that showed moisture migration and water pooling during heat exposure

Choe et al. [46] tested the level of influence moisture migration had on spalling at two different heating rates: 1°Cmin^{-1} and 18°Cmin^{-1}. It was reported that during the slow heating temperature distribution was rather even and the moisture clog effect had not occurred. However, during the fast heating rate the temperature was unevenly distributed forming a moisture clog hence, a super-saturated region. This had, in turn, increased the vapour pressure which eventually caused popping of concrete (spalling).

Cylindrical specimens were used to compare experimental results and theoretical predictions. It was reported that the migration of moisture away from the heat exposed surface was initiated by the pore pressure, similar to what was reported by Chapman and England [44]. Moreover, moisture was recorded to migrate in the positive direction of the concentration gradient. The study concluded by stating that factors which affect moisture migration needed to be isolated and the response level of these factors under specified test conditions were needed to be determined moving forward [115].

Chapman and England [44] reported that moisture migrated away from the heat exposed surface which causes reduction in water content and pore pressure which created a drying front. The permeability of the wet regions reduced, with the coefficient of permeability (k) being about 100 times less than in the drying front. Additionally, moisture migration caused a shrinkage and

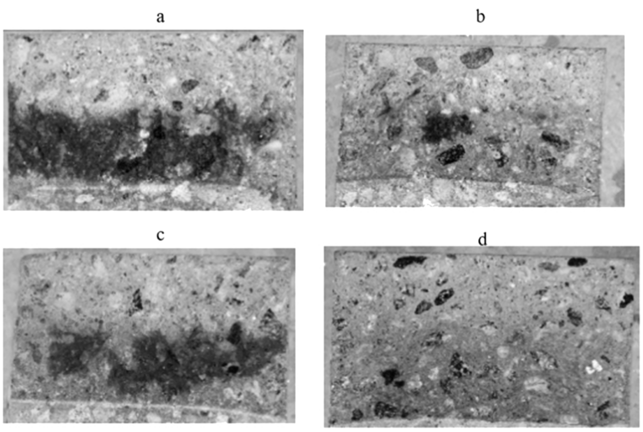

Fig. 25. Saturation after 15 min fire exposure [68]. a. No PP fibres unloaded b. 1 kg/m^3 PP fibres unloaded. c. No PP fibres loaded at 2 MPa d. 1 kg/m^3 PP fibres loaded at 2 MPa.

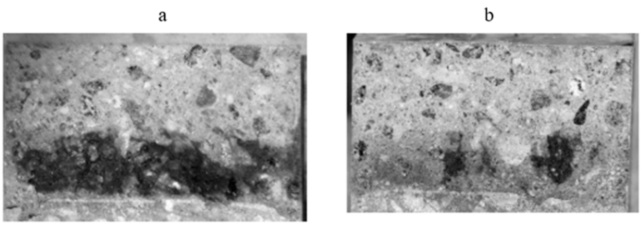

Fig. 26. Saturation after 20 min fire exposure unloaded[68]. a. No PP fibres b. 1 kg/m^3 PP fibres.

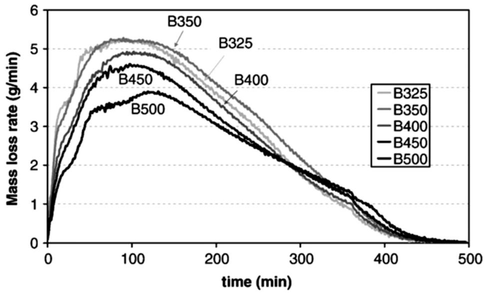

Fig. 27. Mass loss rate for the tested concrete mixtures [117].

contraction in dry areas with the mass loss being about 50% within the first 100 days with a total period 500 days. hydrated products were seen to break up and reduce in size on the Scanning Electron Microscope (SEM) photographs causing cracking or flaking of the dry areas. Additionally, the rate of movement of the drying front was reported to have been influenced by the pressure gradients where considerable amounts of moisture had been seen to migrate due to the pore pressure. Swelling was witnessed in areas where moisture migrated to, and once this swelling was restricted, internal stresses had increases.

Kalifa et al. [26] designed a device to simultaneously measure the temperature and the pressure profiles within concrete specimens exposed to heating on one of the faces, while being continuously monitored for the mass loss. NSC and HSC specimens were tested, and results showed that the pore pressure build up within the HSC were much higher compared to the NS concretes, where up to 38 bars was measured in HSC and 18 bars in NSC. It was stated that the movement of moisture towards the inner sections of the concrete contributed significantly to the accumulation of gas pressure, and that the correlation between the pressure and temperature profiles confirmed the presence of a quasi-saturated layer after the drying front, which showed evidence of the moisture clog theory. Fig. 23 shows the mass loss, pressure and temperature fields vs. time for the two types of concretes.

Jansson and Boström [68] investigated the development of the moisture clog by monitoring the location and movement of the saturation layer as the temperature increased. A 70 mm notch was sawn on the unexposed side of the cubes (Fig. 24) and the cubes were exposed to fire. Immediately after exposure, the cubes were split in to two halves to visually identify the location of moisture. The study was successfully able to clearly identify the movement of the saturation layer within the concrete and monitor the moisture clog, and this provided the first ever visual confirmation of the presence and movement of a saturated layer. Figs. 25 and 26 shows the saturation after 15 and 20 min respectively in different concretes.

Noguchi et al. [116] conducted an experimental study on rectangular specimens having two different w/c contents of 25% and 55%, to clarify the moisture migration process and the change in internal pressure. Moisture measuring electrodes made of SUS 403 materials, which have excellent resistance to corrosion and heat, were embedded into the specimens to measure moisture. It was found that specimens having 55% w/c content displayed higher moisture migration rates compared to the 25% specimens. This could be due to the higher pore structure which provided pathways for moisture migration. Moreover, along with the rapid increase in temperature, the vapour pressure was seen to rapidly increase to the critical temperature. A proper understanding of the behaviour of moisture in the critical region where the internal temperature exceeded 600 °C could have explained this occurrence.

Mindeguia et al. [117] studied the temperature, pore pressure and mass loss of five concrete samples. The samples were labelled as B325, B350, B400, B450, B500, having 28-days compressive strengths of 35, 36, 53, 62 and 76 MPa, respectively. Table 5 gives information on the total water content, which is the free water plus the bonded water, given as a ratio of the mass of water used during casting and total mass of all ingredients (water, cement, aggregate and SP). The table also shows the lost water as the concrete heats up as a percentage, and it can be noted that the water loss is about two-thirds the initial water during temperature rise, which peaks at around 100 °C due to the loss of free water. Fig. 27 shows the rate of mass loss of the concrete specimens.

Testing on prismatic specimens for the determination of temperature and pore gas pressure was conducted using the ISO 831, moderate and rapid heating, curve [118]. The heating rates of both moderate and rapid heating curves are lower than the standard temperature-time curve heating rate. Results revealed that on samples exposed to rapid heating, a greater crack network on the

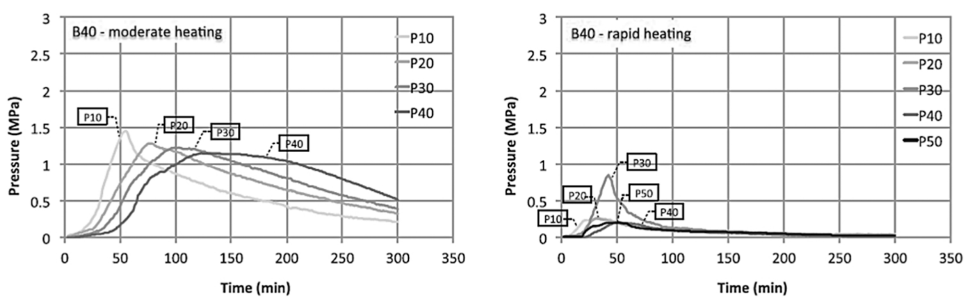

Fig. 28. Temporal evolution of pore gas pressure of concrete specimens exposed to moderate and rapid curves [118].

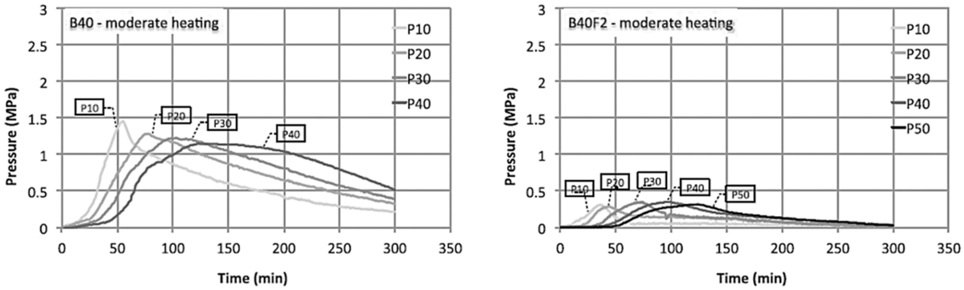

Fig. 29. Temporal evolution of pore gas pressure of concrete specimens with and without the addition of PP fibres [118].

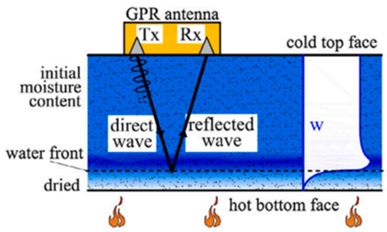

Fig. 30. Principle of electromagnetic wave reflection at the waterfront [100].

exposed surface and around 1 mm large crack propagation on the sides were visible. Samples exposed to moderate heating had no similar cracks observed. It was concluded that a higher heating rate, induce higher thermal damage. Fig. 28 shows the difference in recorded pressures in samples exposed to moderate and rapid heating rates. The addition of 2 kg/m^3 PP fibres were also reported to have an effect on the gas pore pressure with all probes recording a pressure of less than 0.5 MPa compared to specimens without PP fibres, which recorded values between 1 and 1.5 MPa. Fig. 29 shows the temporal evolution of pore gas pressure with and without the incorporation of PP fibre, exposed to moderate heating rate [118].

Ground-Penetrating Radar (GPR) was used by Lo Monte et al. [100] to monitor the movement of the waterfront with increasing temperatures and changing pressures. The GPR sends electromagnetic waves at a constant velocity which is reflected when they strike the waterfront (boundaries of the regions having different saturation levels). Fig. 30 gives a schematic diagram of the principle of the GPR. The time between sent and received wave is recorded and the distance of the waterfront is calculated using velocity and time equations. Temperature and pressure measurement were taken at depths of 10 mm, 20 mm, 30 mm, 40 mm, 50 mm and 60 mm and the specimens were heated from the bottom. It was found that at 10 min (200 °C) the waterfront starts rising, at 20 min (322 °C) the waterfront continues rising and at 110 min (200 °C) the waterfront is about 70 mm. The maximum pressure was recorded at the 400 mm measuring point between 60 and 80 min. The authors stated that a combination of experimental testing and numerical analyses are required. For such numerical models, fire tests in which temperature, pressure and waterfront are monitored represent detailed benchmarks instrumental for the calibration phase.

Felicetti et al. [119] developed a novel test method to understand the influence of pore pressure and heating rates on the fracture behaviour of concrete cube specimens. NSC were used with and without the addition of 2 kg/m^3 PP fibres. Specimens were exposed to heat at 4 different heating rates of 1, 2, 10 and 120 °C/min on two opposite surfaces, and insulated on the remaining surfaces. Once the maximum pressure was reached (measured using probes) the insulation was removed and the specimens were subjected to the indirect split test. It was found that during the fast heating, cracking was induced by thermal stress and slow heating prolonged vapour flow, hence, the highest values of pore pressures are obtained for a heating rate of 10 °C/min. At 1 °C/min material decay is negligible up to 220 °C - 230 °C, however, at the fastest heating rate of 120 °C/min, a loss of 30% in apparent tensile strength had been observed. Moreover, the addition of PP fibre resulted in the reduction of the pressure peaks, and pore pressure is stated to have a damaging influence on the mechanical response of ordinary concrete.

3.4. Review of large–scale tests that showed moisture migration and water pooling during heat exposure

Šelih et al. [120] used a thermal analysis to research the moisture and pressure distributions in 0.2 m thick concrete walls having high levels of moisture contents when exposed to fire. The walls were exposed to two fire curves: the standard curve (ASTM E-119) and the more realistic curve (Elligwood). Using two simplified models, measurements were taken at 0.05 m, 0.1 m, 0.15 m and at the unexposed surface. It was reported that in the free water areas, the saturation gradients are low but increased considerably in zones between the free water regions and the hygroscopic regions. Additionally, because the Ellingwood fire curve leads to higher temperature gradients, increased thermal stresses was recorded which could have been the reason behind an early collapse. The authors reported that the heat energy, which is partly absorbed by the moisture in the pores, causes evaporation and when this rate of evaporation exceeds the rate of migration, pore pressures could be formed. When this pore pressure exceeds the tensile strength of the concrete, spalling will occur.

Pont et al. [121] used hollow, cylindrical specimens to understand the evolution of intrinsic permeability, which provides an understanding of the gas/liquid penetration through a porous material, through an experimental as well as numerical modelling procedures. Cylinders were heated from the inside which created a tensile stress state on the external border creating expansions, hence the specimens were caged (encircled) in a steel layer of 1 cm thickness. The authors proposed a simple law for the description of the intrinsic permeability evolution of concrete in hot conditions. Temperature greatly affects the total damage occurring in concrete, where cement matrix degradation/dehydration, weakens the microstructure and influences the mass transport phenomena.

Jansson and Boström [122] investiagted the pressure and spalling behaviour of self-settling concrete (SSC) and tunnel concrete with and without the incorportion of PP fibres. The results showed that the highest pressure readings were recorded from the specimens which did not exhibit fire spalling, made with the inclusion of 1 kg/m^3 PP fibres. This study concluded by stating that the mechanical properties are advantageously affected by the PP fibres, which are assumed to reduce the moisture content in the critical zone close to the surface. Moreover, PP fibres were also assumed to relieve thermal stress by amplifying moisture movement. Table 7 Gives informartion of the pressure and spalling results.

Kang et al. [69] reported that thicker wall specimens (250 mm) recorded the highest temperatures close to the fire-exposed surface (30 mm) compared to thinner specimens (150 mm) exposed to same conditions measured at the same location. This could be due to the moisture clog, formed within the thicker specimens which prevents heat transferring and causing a considerable thermal gradient within the concrete. In thinner specimens, the moisture, moving through the specimens, can easily escape from the unexposed surface (creating water pooling) without creating a moisture clog region within the concrete.

In a research conducted by Guerrieri and Fragomeni [123], large-scale concrete wall specimens were exposed to hydrocarbon fire. It was reported that the in situ pore pressure profiles demonstrates the moisture clog theory. A peak water pressure had been clearly identified between the heat exposed surface and the unexposed surface in all specimens which shows the fully saturated areas where a moisture clog had formed. It was believed that when the pore pressure, which was increasing in the moisture clog region due to rising temperature, exceeds the tensile strength, spalling occurs, similar to the reports by [44,45,54,55,67,120]. Furthermore, water pooling had been witnessed on all tested specimens which was stated as either being due to the high saturation condition present towards the unexposed surface (as a result of the moisture clog) or due to moisture migration through the cracks within the concrete formed by the flexural forces, or both.

4. Conclusions

The demand for concrete within the construction industry has been seen to rapidly rise over time, owing to its superior properties in strength and durability. However, the knowledge in the fire behaviour of concrete is still an area having gaps, and the extent of concrete spalling is not fully understood, due to the complex transformations occurring simultaneously within the concrete. This is an extremely hazardous condition as it can compromise stability and cause collapse of entire structures. The current understanding on the causes of spalling in concrete is still far from clear, and while several theories have been put forth to try and close the gaps in knowledge of how and why concrete spalls, this task has been proven to be a complicated and difficult one. The numerous experimentations which have been and are being conducted on various types of concretes are sheading new light on the level of influence moisture has on the harmful behaviour of concrete at high temperature levels. However, although the migration of moisture and the pooling of water is thought of being a governing factor for spalling, the fact that this area of study requires investigation on a much deeper level is evident. This article presents a review on some of the spalling theories identified and techniques available to monitor the migration of moisture and its influence on the performance of concrete during heat exposure. Moreover, various test methods and findings on small-, medium- and large-scale specimens to evaluate the spalling behaviour of concrete as a result of moisture migration and water pooling, is also presented.

There are numerous physical and chemical changes occurring in concrete during increasing temperatures, which can be classified as thermo-mechanical (changes due to stress) and thermo-hydral (changes due to moisture). Spalling is considered to being a result of a combination of both thermo-mechanical and thermo-hydral changes which trigger the formation of cracks and cause sections of concrete to break away. Moreover, past literature shows evidence that in the presence of a higher moisture content, the risk of spalling is high, with the main factors influencing the movement of the water front were narrowed down as rate of heating rate, permeability and pore size. Additionally, the compressive strength is reported to decrease by about 40% in the presence of moisture as opposed to dry specimens.

The first record of moisture migrating towards and being expelled from the unexposed surface is given by Woolson, where after two hours of fire exposure, about $0.5 - 0.75$ in. of water had visibly accumulated on a concrete floor specimens. While the reason behind water pooling was not presented at that time, various theories have been deduced to explain this occurrence and its effects on spalling. Of the theories relating to water pooling presented in this review, one theory is that as heat increases and causes evaporation of the moisture within the pores, the rate of this evaporation would at some point exceed the rate of migration, thus, forming pore pressures. When this pore pressure exceeds the tensile strength, concrete will spall. Another very interesting theory explaining the movement of moisture and its effects on spalling, which has been over time proven, is the moisture clog theory. This theory states that, as the concrete heats up, a percentage of the moisture moves into the concrete, creating a fully saturated region and acting as a water-vapour barrier (a moisture clog), which can significantly increase the vapour pressure. It must be noted that the development of a fully saturated region can significantly disrupt the mechanical properties within the concrete, where an unstable crack growth can form, and literature shows that the formation of this moisture clog (supersaturated region) is prominent seen when the heating rate is about

$18^{\circ}Cmin^{-1}$ due to uneven distribution.

Literature precedents show that the evaporation of free water and dehydration of chemically bound water during heating is an important physical process, which causes the development of pore pressures and effects temperature propagation through concrete. Reports also show that the pressure is recorded to be the highest at the drying front of the saturated region. Numerous investigations to measuring the pore pressure changes of concrete during heating have been conducted in literature to understand indirectly the underlying process of the formation and migration of moisture. However, due to concrete heterogeneity, pressure sensing technologies and varied heating rates, measured values discrepant over a wide range. Literature shows that at higher heating rates, the thermal damage experience by concrete is high (an apparent tensile strength loss of approx. 30%), and larger network of crack and breakages form. Large crack networks on the heat-exposed surface and sides were seen at high heating rates. However, the gas pressure during high heating hates will reduce as more pathways (crack networks) form to release the internal pressure. Reports of thermal imagining to identify the cracks through which water pools out from the unexposed surface has also been conducted, and is found to being a used tool in identifying the crack network.

When considering researching methods of understanding the amount and behaviour of moisture within concrete, a straightforward method of moisture loss determination is through the drying process, where the weight of specimens before and after heat exposure can be measured (using a balance or TGA techniques), and this can be related to the amount of moisture lost. While this a quick and convenient method to measure the loss of moisture, the progression of the water front in relation to temperature and time, is a more prominent parameter to investigate in order to understand its effects on spalling. A simple experimental procedure was present by Jansson to identify the movement of the saturated layers, where concrete cubes were split immediately after heat exposure to visually observe the different locations of moisture layer. This is a very convenient method of observing the saturated layers which can be developed to not only see the saturated layers but also the pathways through which moisture migrates.

Two main methods widely used for the determination of local moisture distribution are NMR and neutron imaging; however, due to the longer time taken to obtain one tomogram (as it is reconstructed using a number of projections), fast process occurring within concrete during heating is difficult to monitor. Processes such as dehydration is difficult to monitor as it is a relatively fast moving process, and data obtain between two tomograms will not provide a comprehensive view. Researchers have identified this matter and developed *fast neutron tomography* which has the ability to capture one tomogram per minute, hence, providing a more detailed view of the changes in moisture distribution. Additionally, literature reports that, in a larger specimens, neutron experiments reveal that water release occurs suddenly, at higher temperature levels when compared with TGA results. Testing conducted using an NMR test setup revealed that the saturated vapour pressures of 1.4 MPa compared to an atmospheric pressure of 0.1 MPa, which proved the formation of an obstructive layer restricting the release of pressure. The composition of this layer was proved as being a moisture-clogged layer, through moisture distribution studies which showed a significantly high moisture content (approx. 0.11 m^3/m^3) on the non-heat exposed face of the boiling front. Researchers have now taken neutron imaging studies one step ahead to obtain novel 5D data sets using 3D tomographies along time, plus truly simultaneous x-ray and neutron rapid acquisitions. This setup facilitate the study of the changes in moisture using neutron tomography and crack initiation and propagation using x-ray tomography. The Ground-Penetration Radar (GPR), which uses information gathered between transmitted and received EM waves to determine the movement of the water front, is an innovative and robust method to monitor moisture migration. The beginning of movement of the water front (at about 200 °C) and the continued movement can easily be monitored using GPR. These methods can be used to not only better understand the underlying processes, but also to develop a more accurate model to predict spalling.

In summary, the review of existing literature proved that while numerous studies are in fact available on spalling of concrete, there are still several aspects of fire behaviour, in terms of the waterfront movement, concrete permeability and porosity, and water pooling which need further investigation. Through which, we can understand at a deeper level the basic mechanisms responsible for explosive spalling and develop a more accurate model to predict the level of spalling in different concretes. While large-scale testing using concrete slab and wall sections provides a detailed understanding of water pooling, the accumulated moisture needs to be comprehensively studied and analysed at a molecular level using experimentation like Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), which can identify the composition of elements in pooled water, thus providing an idea of the source and evolutions in moisture within concrete. The ICP-OES technique is a standardized, multi-element technique which involves the fundamental principles of non-radiative excitation of atoms or ions, followed by the emission of a photon that is collected by a detection system [124]. While this technique is generally used for geochemical analysis [125], studies show the use of this technique to investigate the chloride content in cementitious samples [126]. Moreover, [127] presented an easy and reliable method to quantify iron, calcium, sodium, aluminum, and several other elements in cement pore solutions with high accuracy using the ICP-OES. Advance testing such as particle accelerator studies which can dive deep and identify the micro-channels/pathways within the concrete which entertain the movement of moisture during elevated temperatures need to be investigated. The end goal of such an experimental and numerical model should be to narrow down an optimum technique (s) to, not only reduce, but to completely eliminate, if possible, the occurrence of explosive spalling in practice.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships, which have, or could be perceived to have, influenced the work reported in this review article.

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