Ground-Penetrating Radar Monitoring of Concrete at High Temperature

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Abstract: Water front in concrete exposed to rapid heating is the layer where water vaporization and the subsequent pore pressure rise take place. Pore pressure is one of the main triggering factors in heat-induced explosive spalling (relevant for structures such as tunnels exposed to fire), while moisture migration influences concrete radiation shielding capability (important in containment shells of nuclear power plants and radioactive waste repositories). Hence, the experimental monitoring of water front in concrete at high temperature is a very interesting – though challenging – task. In a recent experimental campaign carried out at Politecnico di Milano, promising results have been obtained by coupling pore pressure-temperature measurements and water front monitoring through Ground-Penetrating Radar. This technique was implemented in a fire test performed on a concrete slab heated at the bottom face and proved to be effective in detecting the position of the water front during heating. The combination with pressure measurement allowed to confirm that pressure peaks are achieved in correspondence of the water front.

Keywords: Concrete, drying, fire, Ground-Penetrating Radar, high temperature, pore pressure, spalling, vaporization, water.

1. Introduction

1.1 Effect of water in concrete at high temperature: fire spalling and shielding capability

Fire and, more generally, high temperature are extreme loads which need to be considered when strategic buildings and infrastructures are at issue, such as hospitals, tall buildings, nuclear power plants and tunnels. Even though concrete performs fairly well at high temperature, thanks to its low thermal conductivity and incombustibility, adequate fire resistance in structures can be achieved only if attention is paid to mix design, reinforcement arrangement and structural redundancy. In some cases, such as tunnels and nuclear power plants, not only the bearing capacity should be guaranteed, but also the performance regarding specific aspects such as fire- or heat-induced spalling and radiation shielding capability.

Heat-induced spalling is the violent breaking-off of concrete pieces from the exposed face, leading to sectional reduction and direct exposure of the reinforcing bars to the flames, both aspects being detrimental to the overall fire resistance.

Even though structural fire behaviour of tunnels is of concern just in extremely severe scenarios, avoiding spalling is a primary objective, since repair time and cost are critical issues together with the revenue loss because of traffic disruption.

A full understanding of spalling phenomenon, however, is no simple matter because of the presence of different factors such as heating rate, concrete thermo-physical properties degradation, initial moisture content and saturation level, pore pressure and stress (Kalifa et al., 2000; Khoury, 2000 and 2008; Fu and Li, 2010).

As sketched in Fig.1, the phenomenon can be ascribed to the mutual interaction between stress-induced cracking, ensuing from thermal gradients and external loads, and pore pressure rise, due to water vaporization and/or saturation (Khoury, 2000).

Thermal stress is caused by the significant temperature gradients typical of heated insulating materials.

In particular, compression arises in the exposed hot layers and tension in the cold core, followed by cracking parallel to the exposed face in the former case and orthogonal to the heated face in the latter one. Kinematic incompatibility between aggregate and cement paste, and release of absorbed- and chemically-bound water, as well as cement dehydration, also favour cracking (Fu and Li, 2010).

Pressure in the pores, on the other hand, is caused by water vaporization and vapour dilation. Pressure gradients cause moisture migration towards both the hot face and the inner core. In the latter case, moisture content can increase also due to vapour condensation, with possible saturation of the pores (Khoury, 2008). Especially in low-porosity concretes, such as High-Performance Concretes – HPC, water saturation in the pores can be attained, with the formation of a region characterized by very low permeability (the so-called moisture clog; Khoury, 2008). Consequently, very high values of pore vapour pressure can develop behind moisture clog (up to 5 MPa; Kalifa et al., 2000).

On the contrary in high-porosity concretes, such as Normal-Strength Concrete – NSC, vapour can more easily flow through cement matrix, this reducing the pressure. This is the reason why spalling is a big concern in HPC, together with its higher heat-sensitivity compared to NSC (Felicetti and Gambarova, 1998).

A well-established way to reduce spalling sensitivity is the addition of polypropylene fibre, whose beneficial effect comes from the further porosity induced by fibre melting at 160-170°C (Khoury, 2008), accompanied by microcracking in the cement matrix due to thermal dilation of melting fibre (Khoury, 2008) and to the stress intensification around the edges of the melting fibre (Pistol et al., 2014).

In spalling-sensitive structures like tunnels, the quantification of shard detachment via coupled hygro-thermo-mechanical or hygro-thermal numerical models can be useful in the design phase. Such analyses can be performed by means of available numerical codes able to simulate heat and (fluids) mass transfer in concrete at high temperature (Gray and Schrefler, 2001; Ichikawa and England, 2004; Tenchev and Purnell, 2005; Davie et al., 2006; Gray and Schrefler, 2007; Gawin et al., 2011a and 2011b).

The main problem for such models is the definition of concrete properties (first of all, porosity and permeability), that can be hardly measured at high temperature. In this case, inverse analysis based on experimental fire tests is the most reliable means for preliminary calibration. Within this context, water front monitoring in lab tests may be very helpful.

Water plays an important role also in the containment shells of nuclear power plants and radioactive waste repositories, thanks to its shielding property against α, β and neutron radiation. Consequently, knowing how water front migrates at high temperature is instrumental in assessing the time required by a containment shell to fully dry, as complete drying reduces its shielding capability (Ichikawa and England, 2004; USNRC, 2013).

1.2 Ground-Penetrating Radar for water front monitoring

Water front monitoring in concrete at high temperature is a challenging task, since the few techniques able to perform such measurement, as for example Neutron Radiography Imaging – NRI (Weber et al., 2013; Toropovs et al., 2015) and Nuclear Magnetic Resonance – NMR (van der Heijden et al., 2007; Erich et al., 2008; van der Heijden et al., 2011; van der Heijden et al., 2012) are very costly and strongly limit specimen geometry (100×100×25 mm for NRI in Toropovs et al., 2015; DxH = 80x100 mm for NMR in van der Heijden et al., 2012).

Another technique able to monitor water content and saturation in concrete is based on Ground-Penetrating Radar – GPR (Laurens et al., 2005; Sbartai et al., 2012; Rodriguez-Abad et al., 2014; Bagnoli et al. 2015).

GPR is a well-known and established non-destructive geophysical technique (Jol, 2008) commonly used in the field of structure inspections and building diagnosis (Lualdi and Lombardi, 2014a; Lualdi and Lombardi, 2014b; Benedetto and Pajewski, 2015), in addition to a number of other high resolution subsurface imaging applications. It employs electromagnetic fields for the detection of buried objects and subsurface structures, and for material property characterization (Muller et a., 2016; Daniels, 2004). GPR relies on the principle that electromagnetic waves are reflected and scattered to some extent at boundaries separating different regions in the subsurface (Maierhofer, 2003; Yehia et al., 2014). Reflected and scattered waves are then collected by the receiver.

Among all the parameters determining the overall electrical properties, water content is the most significant factor (Sbartai et al., 2006a; Lai et al., 2009). Water content variations produce amplitude changes of GPR data (Laurens et al., 2002; Sbartai et al., 2006b; Klys and Balayssac, 2007), and significant travel time shifts once the changes involve a large portion of the imaged subsurface.

The amplitude of the reflections depends on the magnitude of the contrast between two contiguous regions, while the time shifts are caused by water slowing down the electromagnetic wave velocity. As reported in Laurens et al. (2005), the dielectric constant ε_r can be increased by more than two times going from dry ($\varepsilon_{r,dry} \approx 4$) to saturated concrete ($\varepsilon_{r,sat} \geq 8$). An even higher range is reported in IAEA (2002): $\varepsilon_{r,dry} - \varepsilon_{r,sat} \approx 4.5 - 15$.

As demonstrated by Laurens et al. (2005), Sbartai et al. (2012), Rodriguez-Abad et al. (2014) and Xiao et al. (2016), the above-mentioned mechanisms make GPR an effective method to characterize water content and transfer in concrete. GPR has also been used for assessing thermal damage in concrete after a fire, as shown in Abraham and Dérobert (2003).

In the present study, the primary objective is to detect the water front position in concrete at high temperature, rather than to directly measure the water content. GPR technique has been implemented within a research project at Politecnico di Milano (Lo Monte and Felicetti, 2017). Concrete slabs heated at the bottom face have been tested both in unloaded conditions and under biaxial membrane loading, as discussed in the following sections.

2. Experimental set-up and mix design

2.1 Fire test on concrete slabs

A test setup has been designed and built at Politecnico di Milano for assessing concrete spalling sensitivity in fire conditions (Lo Monte and Felicetti, 2017). The specimen is a square concrete slab with an 800 mm-side and 100 mm-thickness (Fig.2a), subjected to heating at the bottom face according to the Standard temperature-time curve defined by EC1 (EN 1991-1-2:2004). During heating, a biaxial membrane load can be applied thanks to 8 hydraulic jacks restrained by a welded steel frame (Fig.2b). The fire load is applied by means of a horizontal furnace provided with a propane burner controlled by an active control system.

In order to protect the hydraulic jacks from high temperature, only the central portion of the slab is heated (600x600 mm). As shown in Fig.2a, 16 slits have been cut in the peripheral region of the specimen in order to break the mechanical continuity of the external cold rim so as to minimize the confining effect.

During the test, pressure and temperature can be monitored through the thickness via special embedded sensors (see also Felicetti et al., 2017) placed at 10, 20, 30, 40, 50 and 60 mm from the exposed face (Figs.2c,d).

2.2 Ground-Penetrating Radar – GPR

In one of the slabs tested so far, GPR technique has been implemented at the cold face (Fig.2a), aimed at monitoring the water front position during fire exposure. The measurements have been performed by exploiting the reflection of the electromagnetic waves propagating through a continuum, when a sudden change in electric properties occurs (see Fig.3a).

In the present case, the discontinuity is represented by the water front, namely the sharp gradient in water content separating dried and moist concrete (Fig.3a), while no or negligible influence is expected to be introduced by any possible fracturing process. Since, as abovementioned, concrete dielectric constant can increase by more than two times between dry and saturated concrete, the aim of the present experimental study is to verify if the reflection due to such variation of electric properties allows to detect and monitor water front migration with sufficient accuracy.

The equipment is an IDS georadar antenna with a central frequency of 3GHz (Fig.3b). The two dipoles are 60 mm-spaced and are oriented orthogonally to the acquisition direction.

A series of profiles have been acquired at the cold face of the slab over the same scan line (Fig.2a and Fig.3b) during heating, with an almost constant time separation between subsequent scans. Profiles characteristics are reported in Table 1, while the processing steps (Yilmaz, 2001) applied on the datasets are described in Table 2.

The location of the GPR has been studied in order to avoid boundary effects linked to thermal, electromagnetic or stress fields. Temperature and stress distributions have been previously analysed via thermo-mechanical numerical models performed via the finite element code Abaqus, while no disturbance in GPR measurements has been observed during the experimental test due to the presence of the hydraulic jacks (thanks to the distance between the antenna and the actuators, which was larger than 20 cm).

Preliminarily, the wave velocity has been accurately computed by placing a metallic plate at the bottom face of the slab to plainly detect wave reflection. Time to depth conversion resulted in a velocity of 13.5 cm/ns, corresponding to a relative dielectric constant of approximately 5 and a vertical radar resolution $\lambda/4$ of about 1 cm.

2.3 Concrete mix design and applied load

The tested slab was made of HPC with 400 kg/m^3 of CEM I, 200 kg/m^3 of Ground Granulated Blast Furnace Slag, 1559 kg/m^3 of silico-calcareous aggregates (maximum aggregate size 16 mm) and water-to-cement ratio equal to 0.36.

Monofilament polypropylene fibre was added (content = 2 kg/m^3, L = 12 mm; $Ø_{eq}$ = 20 μm; extruded straight fibre treated with a surfactant agent). Membrane load was designed to induce a constant mean compressive stress of 10 MPa, sufficient to avoid any tensile stress throughout the test. To authors' knowledge, this is the first fire test in which water front, temperature and pore pressure are simultaneously monitored under loading in fire conditions.

3. Results and discussion

Results from GPR scans are shown in Fig.4 for different values of fire duration. In each frame the geometrical limits of the slab (top and bottom faces) are indicated (solid triangles), as well as the rising water front position (black dots). The comparison among the accurate repeated GPR surveys reveals travel time shifts and amplitude variations among corresponding reflection events. Beside each frame of Fig.4, the spatial average trace is provided to facilitate the identification of the recorded events. In this way, for each time step, the information is synthesized by a single wave, in which the effects of concrete heterogeneity are minimized.

While the amplitude at the top of the slab remains constant throughout the test, a significant blurring appears in the lower part after approximately 20 min of heating. This is a clear evidence of the presence of a highly absorbing thin layer of water moving from the heated surface towards the cold core of the slab. This effect ensues from the high absorption capability of water that reduces the amount of energy transmitted through the remaining portion of the slab and then collected at the receiver.

The migration of the water front, together with the significant temperature rise in the hot layers of the slab, produces a variation in the electrical properties distribution. This appears as a change in the location of the bottom face as shown in the last frame of Fig.4 and highlighted in Fig.5. Considering the initial conditions of the slab, this modification induces an average increase in the velocity of about 10%, corresponding to a decrease of the average relative dielectric constant from 5 to 4. On the other hand, the thermal effect on the location of the water front is expected to be not significant. This depends on the fact that the region of the slab comprised between the cold face (where GPR is implemented) and the water front, experiences limited temperatures (≤ 330°C, see Fig.8). For this thermal range, electric properties should be negligibly influenced by temperature, as demonstrated by the absence of any shift in the location of the bottom face of the slab in the first 50 min of heating.

In order to clearly identify the migration of the water front during the test, the spatial average traces of Fig.4 have been arranged in the *synthetic radargram* shown in Fig.6a.

The horizontal gradient has been then computed by subtracting to each spatial average trace the initial one (corresponding to concrete in virgin conditions), and the result is reported in Fig.6b. The subtraction of repeated GPR surveys produces an image in which the differences among time steps are enhanced, in order to more easily detect hygrally active regions.

In Fig.6 the rise of a high reflective front is clearly detectable, as well as the bottom reflection. The result in terms of water front position as a function of time is finally reported in Fig.7. Once the water front position is known for any given fire duration, it is possible to evaluate the time at which the water front crosses the points where temperature and pressure have been measured, as shown in Fig.8.

The measurements of temperature and pressure as a function of time for the 6 measuring points within the slab thickness are reported in Figs.8a,c, respectively. The coloured dots in the same plots represent the time at which the water front crosses those points. Temperature and pressure profiles in the depth for different values of fire duration are reported in Figs.8b,d, respectively. Also in these plots, coloured dots are used to show the position of the water front at the time step corresponding to each pressure and temperature profile.

In Figs.8a,b it can be observed that the water front starts rising at 10 min, when temperature exceeds 200°C. After 20 min of heating, the temperature at the water front goes up to 322°C. Afterward, water front continuously rises, while the corresponding temperature decreases down to about 200°C after 110 min. In Figs.8c,d it is clear that the peak pore pressure (both in time and space domains) is reached in correspondence of the water front.

Such result is reasonable, since the highest vapour pressure is expected to develop where evaporation takes place, reaching its maximum value when almost all water is vaporized.

The reason why temperature at the water front decreases with time can be found in Fig.9a, where the pressure at the measuring points is plotted as a function of temperature, together with the dots representing the time at which the water front crosses such points. At increasing depths, in fact, pore pressure-temperature rate increases, since the path that vapour has to travel to escape is higher and moisture migration is slower, as schematically described in Fig.9b (adapted from Mindeguia, 2009). Hence, moving towards the core of the slab, pressure development with temperature becomes closer to the vapour pressure saturation curve, which represents the pressure at which water vaporizes at a given temperature when no vapour leakage is allowed. This explains why higher pressure can be reached at lower temperature, for increasing values of water front distance from the heated face.

4. Concluding remarks

The use of Ground-Penetrating Radar (GPR) for monitoring water front migration in concrete during heating is discussed in the present paper. GPR has been implemented in a fire test based on one-side heated concrete slab, together with the continuous measurement of temperature and pressure along the thickness of the specimen.

GPR proves to be able of detecting the water front position during heating with an accuracy comparable to other methods such as Neutron Radiography Imaging and Nuclear Magnetic Resonance. The big advantage of GPR is the possibility to be easily implemented in any concrete member heated on one side, which is the common configuration of fire tests for tunnel lining segments and concrete slabs.

The combination of GPR and pressure measurement allows to better characterize the hygro-thermal behaviour of concrete, this being instrumental in investigating spalling mechanisms and radiation shielding capability in case of fire.

The experimental results highlight that water front cannot be directly related to a particular temperature, while it is evident that pore pressure peaks in both time and space domains are reached in correspondence of water front position. This is probably the first experimental evidence of such behaviour.

Finally, it is worth noting that the most effective approach for the evaluation of fire spalling evolution in concrete is based on the combination between experimental testing and numerical analyses involving the hygro-thermo-mechanical behaviour. For such numerical models, fire tests in which temperature, pressure and water front are monitored represent detailed benchmarks instrumental for the calibration phase. This can be of big help when the design of strategic reinforced-concrete structures and infrastructures is at issue.

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