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# Ground-Penetrating Radar monitoring of concrete at high temperature

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## HIGHLIGHTS

- Water front migration has an important role in hygro-thermal behaviour of concrete.
- GPR proves to be able of detecting water front position in concrete during heating.
- GPR and pressure measurement combination is very effective in spalling investigation.
- Pore pressure peaks are reached in correspondence of the water front.

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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.



## 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. In this context, it is worth noting that, even though concrete performs fairly well at high temperature thanks to its low thermal conductivity and incombustibility, adequate fire resistance in R/C structures can be achieved only if attention is paid to mix design, reinforcement arrangement and structural redundancy. Furthermore, 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. In the particular case of tunnels, even though structural behaviour is of concern just in extremely severe fire 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 [1–4]. As sketched in Fig. 1, the phenomenon can be ascribed

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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 [2].

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 [4].

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 [3]. 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 [3]). Consequently, very high values of pore vapour pressure can develop behind moisture clog (up to 5 MPa [1]). 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 [5].

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 [3], accompanied by microcracking in the cement matrix due to thermal dilation of melting fibre [3] and to the stress intensification around their edges [6].

In the design phase of R/C structures, spalling assessment via coupled hygro-thermo-mechanical or hygro-thermal numerical models can be very useful. Such analyses can be performed by means of available numerical codes able to simulate heat and mass transfer in concrete at high temperature [7–13]. The main issue in these models is the definition of concrete properties (first of all,

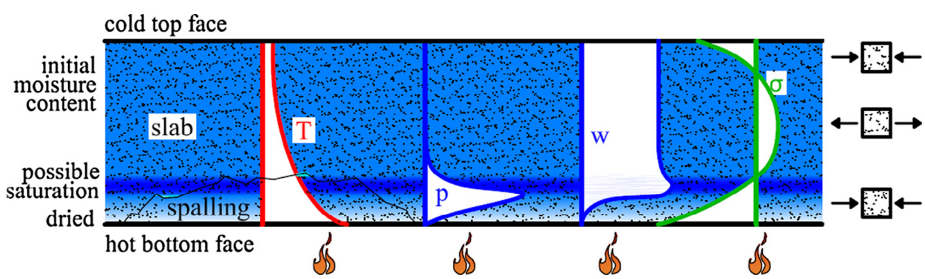


**Fig. 1.** Unloaded concrete slab heated at the bottom: plots of temperature *T*, pore pressure *p*, water content *w* and thermal stress *σ*, at a given fire duration.

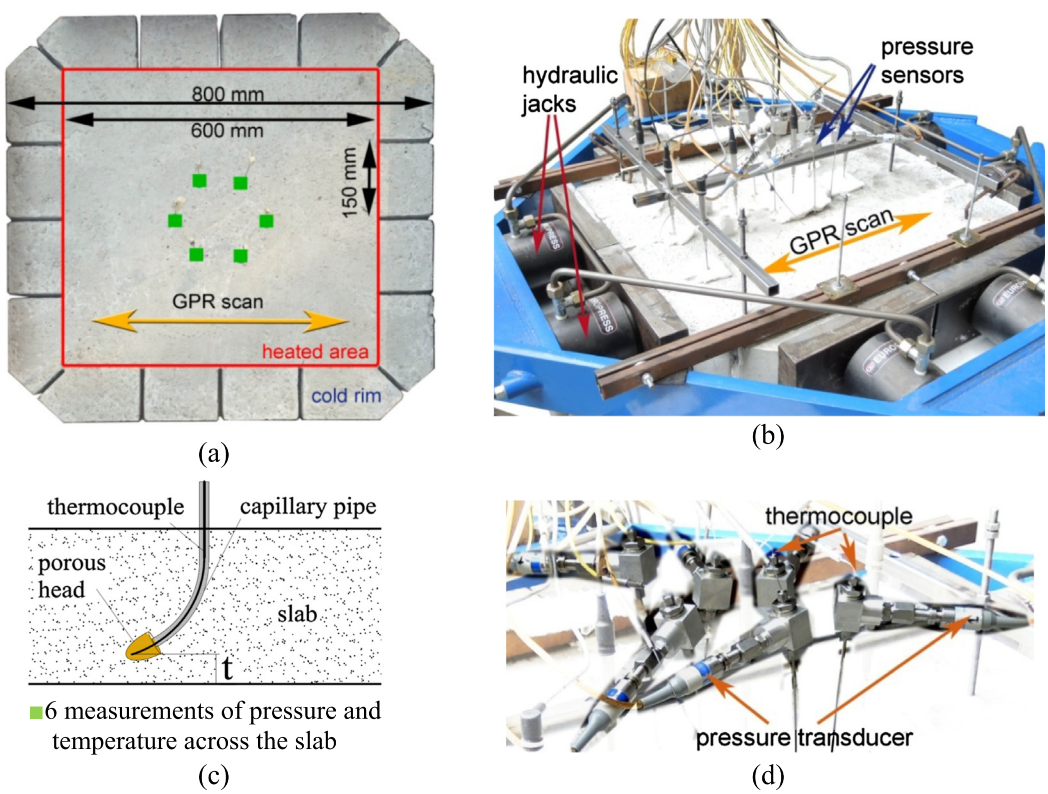


**Fig. 2.** Spalling test on concrete slabs subjected to heating at the bottom and to biaxial membrane load: (a) slab and measuring points, (b) instrumented slab on the horizontal furnace before testing, and (c, d) details of pressure-temperature sensors.