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The drilling resistance test for the assessment of fire damaged concrete

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Abstract

In this paper, the evaluation of the drilling resistance is regarded as a method to ascertain the thermal damage undergone by concrete members after fire. Some preliminary tests on a good quality concrete were functional in defining the test procedure, the optimal bit diameter and the effect of the drilling thrust. A further study on uniformly damaged concrete cubes (ordinary and lightweight concretes – $R_{cm} = 50$ N/mm^2) allowed to ascertain the sensitivity of the method. The reliability of this technique for the assessment of the damage depth within structural members exposed to fire has then been checked by testing some concrete panels exposed to marked temperature gradients. Finally, the viability of the method for in situ applications has been confirmed by testing the members of a precast RC structure which survived a real fire.

Keywords: Assessment; Concrete; Damage; Fire; Fracture; Non-destructive testing (NDT); Residual properties

1. Introduction

Concrete is known to exhibit a good behaviour at high temperature, thanks to its incombustible nature and low thermal diffusivity [1], which guarantee a slow propagation of thermal transients within the structural members. As a consequence, very strong temperature gradients are experienced by the reinforcement cover during a fire and the material thermal damage rapidly decreases from a maximum to nil within a few centimetres depth [2]. For this reason, assessing the residual capacity of concrete structures exposed to fire is quite a difficult task, because the traditional destructive or non-destructive testing techniques are generally not suitable for the inspection of such a highly heterogeneous material.

The possible approaches to this problem (Table 1) generally involve the testing of the average response of the concrete cover [3,4], a point by point analysis of small samples taken at different depths [5,6] or some special techniques for the interpretation of the overall response of the concrete member [7,8]. However, the majority of these methods are generally not practical for in situ applications, being either fast but sketchy (e.g. the rebound hammer) or accurate but time consuming (e.g. the point by point analyses).

In order to overcome these limitations, an extensive research programme has been performed at Politecnico di Milano in the framework of UPTUN, an European Research Project focused on the innovative upgrading methods for fire safety in existing tunnels. The twofold objective was to check the viability of some well-established NDT techniques and to propose quick and easy methods for the assessment of the damage experienced by reinforced concrete structures in consequence of a fire [9].

To this latter purpose, the measurement of the drilling resistance seems to be a promising and fast technique, which allows to continuously "scan" the material response at increasing depth. Several examples of this kind of approach for the assessment of construction materials are available in the literature. A first application [10] was based on the measurement of the thrust to be exerted on the drill to drive the bit at a constant rate in the tested material (bit ∅ = 4–8 mm, max hole depth = 15–20 mm for concrete and mortar). Recently, this method has been proposed also as a means to validate the performance of the surface

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Table 1
Possible approaches to the non-destructive assessment of fire damaged concrete structures

Average response of the concrete cover	Point by point response of small samples	Special interpretation techniques
Schmidt rebound hammer	Small scale mechanical testing	UPV indirect method
Windsor probe	Differential thermal analysis (DTA)	Impact echo
Capo test	Thermo-gravimetric analysis (TGA)	Sonic tomography
BRE internal fracture	Dilatometry (TMA)	Modal analysis of surface waves (MASW)
Ultrasonic pulse velocity (UPV)	Thermoluminescence	Ground-penetrating radar
	Porosimetry	Electric resistivity
	Colorimetry	
	Micro-crack density analysis	
	Chemical analysis	

treatments for stone constructions [11,12] and is in the process of being standardized by CEN TC 246 (Natural Stones).

An alternative indicator of the material response is provided by the resistant torque at constant turning and feed rates, which is currently adopted for ascertaining the preservation of wooden structures [13]. It is worth noting that the resistant torque actually corresponds to the power spent to drive the bit, being the drill turning rate almost constant (power = torque · angular velocity).

In principle, the advantage of focusing on the drilling work is that a change on the exerted thrust concurrently affects the power consumption (J/s) and the advancing rate (mm/s). Therefore, their ratio, namely the specific work that has to be spent to drill a unit deep hole (J/mm), is expected to be marginally affected by the thrust. This assumption has been confirmed in a broad series of tests on the mortar joints of different brick masonry walls (bit $\varnothing = 4$–6 mm, max hole depth = 5–10 mm [14]). The method based on the drilling work has been recently standardized by Rilem TC 177-MDT (Masonry durability and on-site testing) for the assessment of hydraulic cement mortars [15]. It is clear that releasing the test method from an accurate control of either the thrust or the bit feed rate allows to considerably simplify the experimental apparatus. A relationship between the dissipated energy and the material fracture properties was also proposed in the cited study.

In actual fact, the specific drilling work is more or less influenced by a number of operational parameters (bit type, shape and size, rotational speed, exerted thrust, etc.) and it cannot be strictly regarded as a material constitutive property [16]. Contrary to the drilling process in ductile materials, which is governed by fracture propagation under tensile stress (continuous chipping), in the case of quasi-brittle materials (concrete, masonry, rocks) the shape of the bit is designed so that compressive stress prevails ahead of the tool [17]. Therefore, fine pulverization (plastic crushing) occurs in the vicinity of the bit head and a pattern of tensile cracks is initiated in the surrounding zone. These fractures may propagate as a consequence of the tool dragging, leading to the discontinuous separation of relatively larger fragments (brittle chipping) [18]. The former mechanism and the ensuing internal friction among the grains (milling) are certainly the main cause of energy dissipation, whereas the chipping mechanism is far less energy demanding [19].

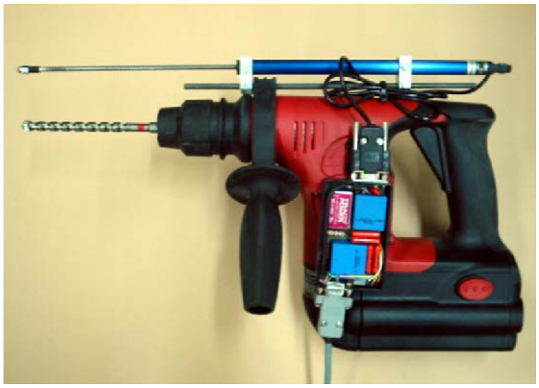
For this reason, drilling hard and homogeneous brittle materials is expected to yield more propagated fractures, a limited crushed layer and a coarser particle size distribution, and it may require less specific work compared to heterogeneous soft materials. Exerting an increased thrust on a bit head fitted with a few larger indenters also enhances the favourable effect of the material brittleness, improving the efficiency of the drilling process [17].

Concerning the application to fire damaged concrete structures, the thickness to be inspected usually extends to several centimetres and a hammer drill is generally recommended in order to foster the brittle chipping penetration mechanism, preventing an excessive bit wearing and overheating. In this case, the sensitivity to the force exerted by the operator is partly masked by the hammering action [10] and the dissipated work appears again to be the most promising indicator of the material soundness.

Once a steady drill performance is guaranteed via the percussive-rotatory combination, the most interesting feature of the drilling technique is that the deep pristine material is inspected in the final stage of the drilling process. Hence, a reference drilling resistance is available for each test and no special calibration curves should be needed to detect the thickness of the damaged concrete.

2. Experimental setup

The drilling resistance has been measured by modifying a Hilti TE 6-A battery hammer-drill in order to monitor the electrical power consumption, the bit rotation and the hole depth (Fig. 1). Thanks to the significant motor power (350 W) and the effective percussive action (impact energy = 1.5 J) this tool allows to drill small diameter holes in good quality concrete at quite a fast rate (about 5–10 mm/s for $\varnothing = 6$–10 mm). The electro-pneumatic hammer mechanism is based on a driving piston (moved by a crankshaft), an intermediate air cushion and a striker (the flying piston) running within the same cylinder. A quick succession of vacuum and compression is then exerted on the flying striker on its rebounds against the drill bit shank, leading to resonance. This effect considerably boosts the



measured parameters		
chuck rotation	θ (rad)	- photodiode
current	I (A)	- Hall effect transd.
DC tension	V (V)	- Hall effect transd.
hole depth	d (mm)	- potentiometer
worked out parameters		
angular velocity	ω	$= d\theta / dt$
total electric power	P_{tot}	$= V \cdot I$
idle resistant torque	T_i	$= A + B\omega + C\, d\omega/dt$
idle power	P_i	$= T_i \cdot \omega$
net drilling work	W_{net}	$= \int (P_{tot} - P_i)\, dt$
drilling resistance	DR	$= \Delta W_{net} / \Delta d$

Fig. 1. The battery hammer drill fitted with the electronic circuits and the displacement transducer; list of the parameters directly measured or worked out during the test.

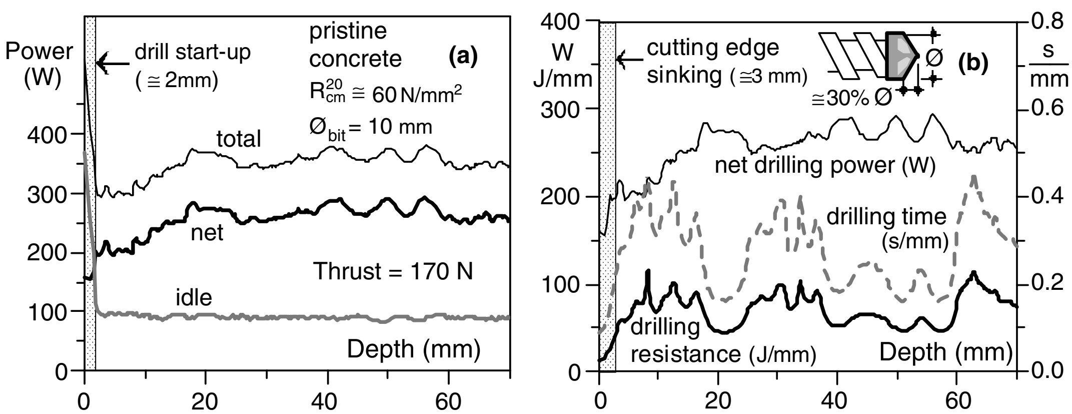


Fig. 2. (a) Total and net drilling power and (b) alternative definition of the drilling resistance (J/mm) as the product of the net drilling power (W = J/s) by the drilling time (s/mm).

impact energy, provided that the workpiece is sufficiently stiff and effectively restrained, in order to prevent a significant damping of the striker speed.

After proper transformation and analog filtering, the electrical signals are acquired by a PCMCIA A/D card (National Instruments – DAQ Card 6036E) and processed by a dedicated software, allowing to work out different test parameters such as the motor rate and acceleration, the instantaneous total power consumption and the net drilling work per unit depth (J/mm), which will be regarded as the "drilling resistance" hereafter (Fig. 2).

3. Test procedure

Several preliminary tests on both a pristine and a thermally-damaged good quality concrete have been performed ($R_{cm} \cong 60$ N/mm^2 – max aggregate size = 16 mm – $T = 20$ °C and 600 °C), aimed at defining a simple test procedure able to guarantee repeatable results. In the final arrangement, the bit is firstly pointed against the sample to be tested and the drill is pushed to preload the hammering mechanism. Then the drill is activated at the maximum power, in order to ensure a constant performance during the whole process. In this way, only the first 2–3 mm are expected to be somehow influenced by the drill start-up and by the initial sinking of the bit cutting edge.

Concerning the thrust to exert on the drill, all these tests have been performed downwards in the vertical direction, putting different weights on top of the drill. It has been found that the maximum total thrust should not exceed the value of 200 N, so as to limit the bit wearing and overheating. On the opposite side, a thrust of at least 50 N is needed to guarantee the effectiveness of the electro-pneumatic hammering mechanism. Within this range, the thrust does not significantly affect the drilling resistance of pristine concrete, whereas the sensitivity to thermal damage improves approaching the upper limit (Fig. 3). The same conclusion is valid for the drilling time (i.e. the inverse of the feed rate), confirming the regularizing effect of the hammering action. Therefore, all the succeeding laboratory tests have been performed by adding a 100 N dead weight to the self weight of the drill (about 70 N). In any case, the recommendation of keeping the thrust nearly constant during the test should guarantee consistent results in the case of in situ applications.

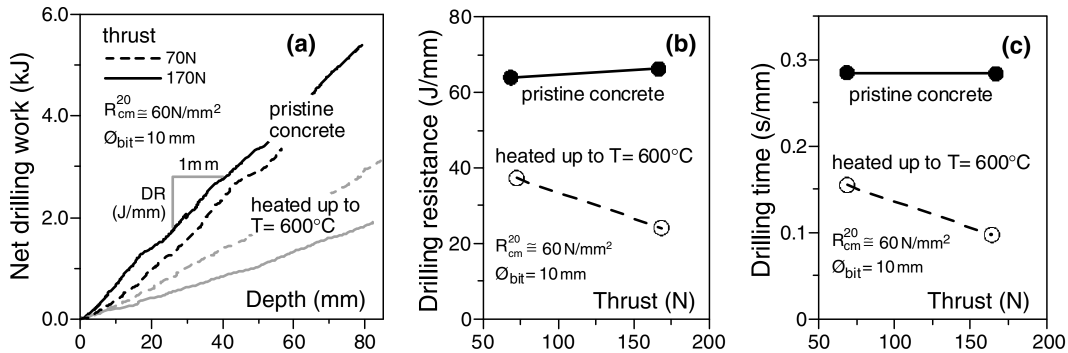


Fig. 3. Effect of the exerted thrust on (a) the net drilling work, (b) the specific net drilling work (drilling resistance – J/mm) and (c) the drilling time of both a pristine and a thermally damaged concrete.

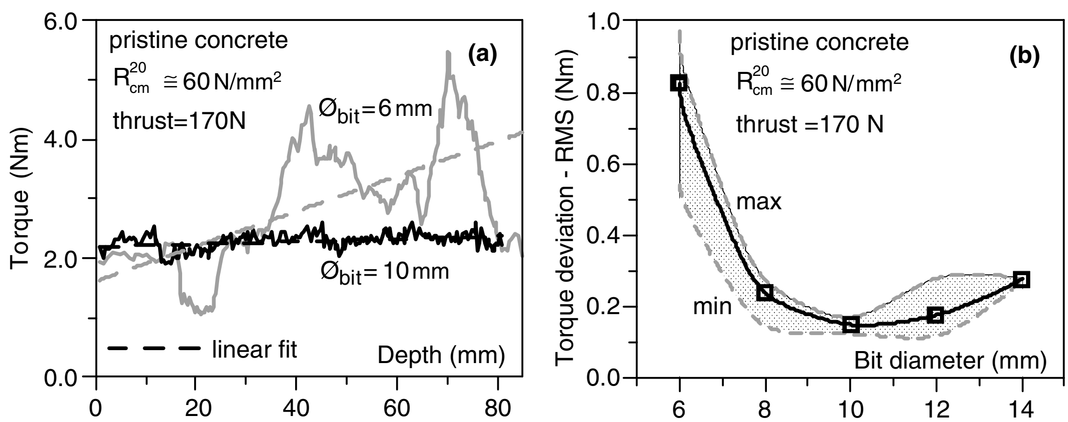


Fig. 4. (a) Variation of the net torque at the chuck due to the inherent material heterogeneity and (b) torque deviation from linearity with different drill bit diameters.

As for the bit diameter (Hilti TE-CX – ∅ = 6–14 mm), it has been found that a small bit (6 mm) exhibits a higher sensitivity to the material inherent heterogeneity (Fig. 4(a)), whereas a large bit (14 mm) is prone to overheating problems and is too demanding for the drill motor. Moreover, looking at the torque at the chuck, it has been observed that the most regular response at increasing hole depth is obtained in the case of a 10 mm bit (Fig. 4(b)), which has been adopted for all the succeeding tests.

4. Sensitivity to thermal damage

Once the optimal bit diameter and drilling thrust have been defined, a series of tests on 150 mm concrete cubes has been performed in order to ascertain the sensitivity of this method to different levels of uniform thermal damage. An ordinary concrete and a structural lightweight concrete (average cubic strength $R_{cm} = 50\ N/mm^2$ – max aggregate size = 16 mm) have been tested as they were or after a slow thermal cycle up to T_{max} = 200, 400, 600 and 800 °C (heating rate = 0.5 °C/min, 1 h spell at T_{max}, cooling rate = 0.2 °C/min). These concretes exhibited very similar compressive strength decays (Fig. 5), with a more pronounced loss beyond 400 °C, in accordance with Eurocode 2 (Part 1.2: General rules – Structural fire design, draft October 2002).

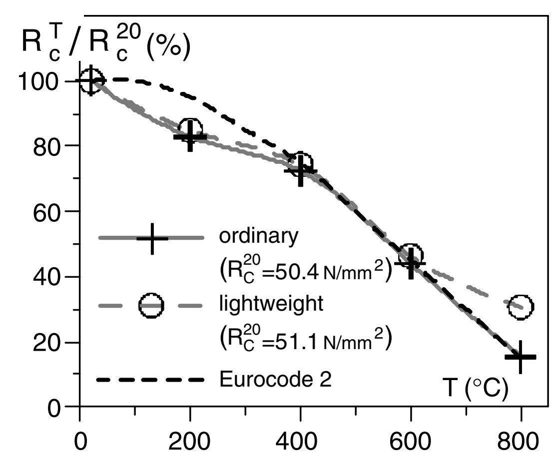


Fig. 5. Residual cubic strength of the thermally damaged concretes investigated in the laboratory tests (average of three samples for each temperature).

On the contrary, the drilling resistance is an almost constant or even increasing function of temperature up to about 400 °C (Fig. 6), probably because at the onset of

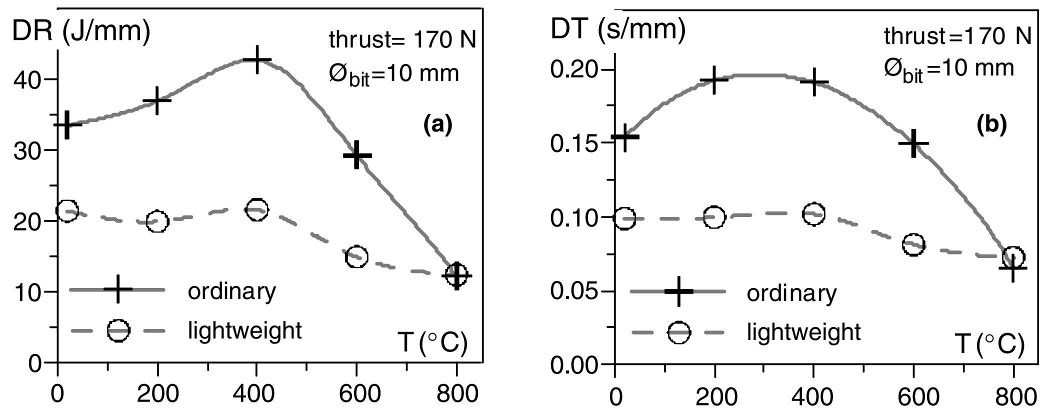


Fig. 6. Effect of the thermal damage on (a) the drilling resistance DR and (b) the drilling time DT (average of 10 tests on two cubes for each temperature).

thermal damage the chipping effect occurring in good-grade brittle concrete gives way to more energy demanding penetration mechanisms (plastic crushing and milling), as a result of the increased material deformability and nearly constant fracture energy [20]. Nevertheless, a marked drilling resistance decrease takes place at higher temperatures, as soon as the severe strength decay offsets the improved material ductility ($R_c^T < 0.5$–$0.7\,R_c^{20\,^\circ C}$). Due to the softer aggregate, the lightweight concrete is definitely easier to be drilled, but the temperature effect is still recognizable in relative terms (Fig. 7). In this latter case the drilling resistance decay starts taking place at a lower temperature, possibly because the initial counteracting effect of the ductility enhancement is less pronounced in an originally softer concrete mix (the penetration mechanisms keep their shares).

The same trends can be observed for the drilling time, although this parameter proved to be less sensitive to the thermal damage, especially in the case of lightweight concrete. For this reason, only the drilling resistance will be considered in the following analyses.

The results concerning the uniformly damaged cubes also showed that different concretes having almost the same compressive strength may exhibit a markedly different drilling resistance. Then, no simple relationship can be established between these two parameters and other features should be probably taken into account to this purpose (e.g. the aggregate hardness, as in the Windsor probe test [21]). However, the definition of this kind of relationship is beyond the scopes of this study and the material analysis will be focused on the drilling resistance profiles themselves, keeping the drilling response of the pristine material as a reference.

5. Assessment of damage gradients

The same two concretes adopted for calibration tests were used to prepare as many small panels (275 × 550 × 80 mm) which have been exposed to a marked thermal gradient (>5 °C/mm) by heating them on the one side ($T_{max} = 750$ °C) while keeping cold the opposite side with a fan (Fig. 8). These specimens are intended as a first, well controlled benchmark for checking the reliability of the proposed test method in the assessment of the damage gradient within a concrete member.

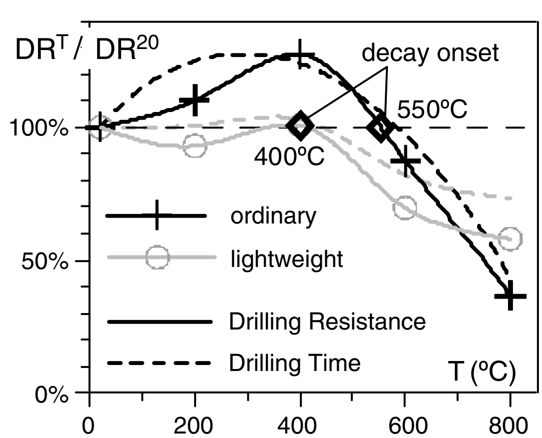


Fig. 7. Relative decay of the drilling parameters.

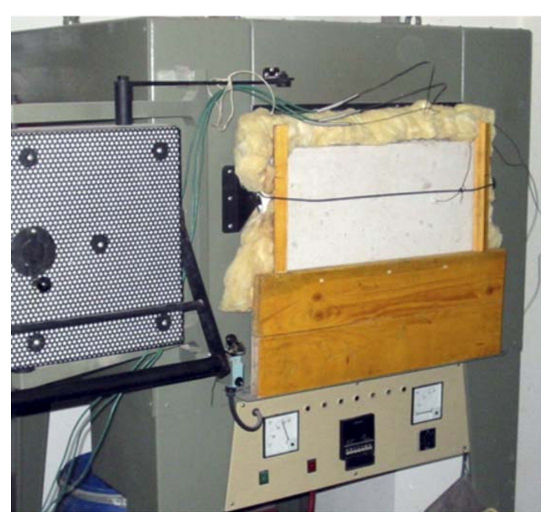


Fig. 8. Concrete panel positioned as a replacement for the furnace door and exposed to a thermal gradient.

In this case, the maximum temperature experienced by the material is of prime interest, being the mechanical decay almost totally irreversible and very little affected by the slow cooling process. The maximum temperature profile within the panels has then been determined by means of three embedded thermocouples, allowing to recognize the isotherms corresponding to the onset of the drilling resistance decay (Fig. 10(a) – about 550 °C and 400 °C for ordinary and lightweight concrete respectively – see Fig. 7). From the temperature at each point and after the plots of the strength decay (Fig. 5) the profiles of the relative residual strength R_c^T/R_c^{20} have been also worked out, in order to better illustrate the expected mechanical response through the specimen thickness (dashed plots in Fig. 10(a)).

The drilling tests clearly reveal the effect of the thermal gradient (Fig. 9), albeit the result is partially masked by the inherent material heterogeneity ascribable to the aggregate. However, owing to the random nature of this disturbance, it can be easily cleaned out by averaging the results of a few repeated tests. Due to the small thickness and the residual thermal warping of these panels, it has not been possible to provide an effective restraint to withstand the hammering action of the tool, yielding a reduced drill efficiency and a sizeably higher specific drilling work than in the calibration tests. Nonetheless, the plots of the relative drilling resistance (i.e. referred to the innermost material response) still allow to recognize the external damaged layer, regardless of the absolute value of this parameter (Fig. 10(b)).

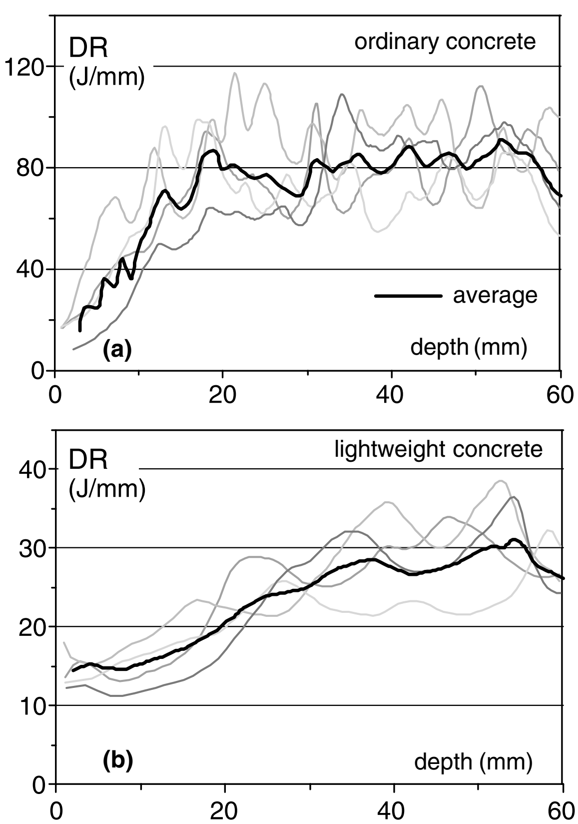


Fig. 9. Drilling resistance profiles through (a) the ordinary and (b) the lightweight concrete panels after heating from the left side.

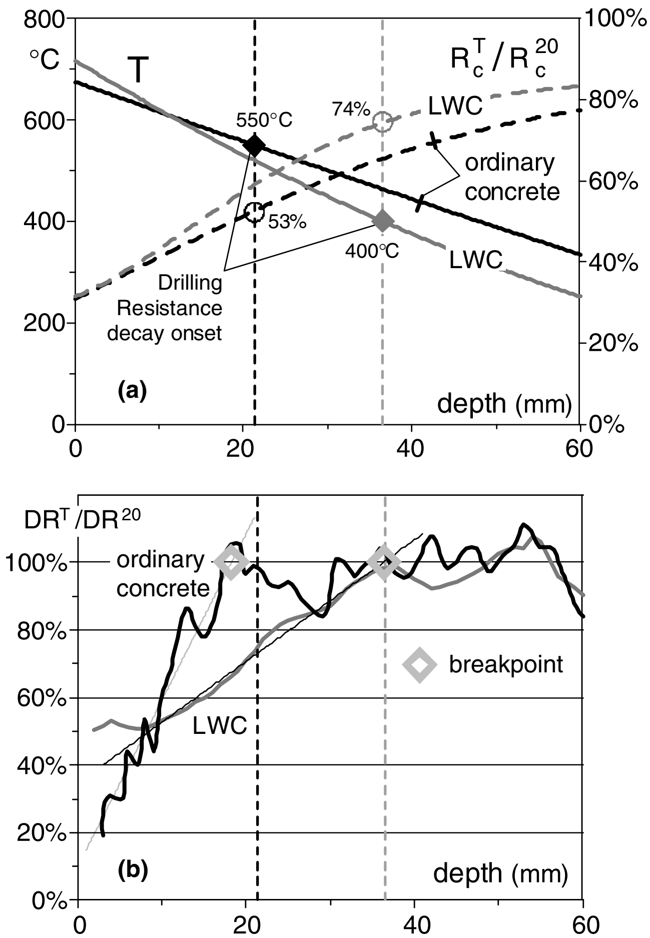


Fig. 10. (a) Profiles of the maximum temperature and of the residual strength through the heated panels and their connections to the average profiles of the relative drilling resistance (b).

It can be observed that the breakpoints defined by the rising branch and the final plateau of the drilling resistance profiles are in good agreement with the isotherms corresponding to the onset of the drilling resistance decay. Hence, the thickness of the damaged concrete layer can be reliably detected within the sensitivity limits of this method. The final result is the outcome of the different thermal conductivity (which limits the temperature rise in the lightweight concrete panel) and the different sensitivity of the drilling test for soft and hard concretes. Then a thicker damaged layer was detected in the lightweight panel, but it corresponds to a lower damage threshold.

6. Tests on a wall submitted to a standard fire

The opportunity for a further check on this damage assessment technique was provided by a standard fire test on a concrete duct for electric cabling protection in railway tunnels (ISO 834 fire curve, 90 min duration – Fig. 11). The test was run in a vertical furnace, after closing the specimen in a low-grade reinforced-concrete box ($R_{cm} \cong 30$ N/mm^2).

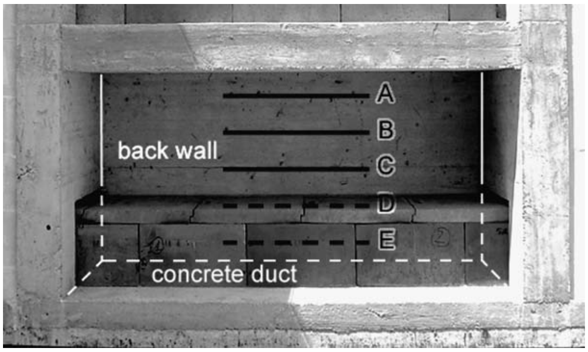


Fig. 11. Fire test setup including the concrete duct to be tested and the back wall which was subsequently examined via the drilling resistance technique.

As a consequence, the 0.2 m thick concrete wall on the back of the duct was partly exposed to the burners and partly protected by the tested specimen itself.

Even not being the object of the fire test, this wall is an interesting example of the possible not uniform damage pattern resulting from a severe fire. Therefore, the temperature of the exposed portion has been monitored on both faces and at half thickness and the experimental temperature field has been modelled and fitted numerically, allowing to continuously plot the maximum temperature profile experienced by this concrete member (including the cooling phase – Fig. 12(a)). It has to be remarked that in the case of a strong thermal transient, which is the rule in real fires, the temperature of the inner material of a structural member keeps raising during the early cooling phase. This is due to the heat stored in the external hot layer, which flows towards the colder part of the member regardless of the stage of the fire load.

After cooling, the wall has been examined by drilling a series of holes along five rows (from A to E – three holes for each row). The average diagrams pertaining to each row (Fig. 12(b)) clearly reveal which part of the structure went through a severe thermal exposure (rows from A to C) and which one was only marginally impaired during the fire test (rows D and E). In this case, the temperature corresponding to the onset of the drilling resistance decay ($T \cong 460$ °C) lies below the limit determined in the calibration tests for the ordinary concrete. As in the case of lightweight concrete, this is probably ascribable to the less pronounced ductility enhancement which is expected to take place in a low-grade concrete mix at increasing temperature.

It is worth to note that only about 5 min were needed to perform the whole series of tests and the results were immediately available for the interpretation thereafter. This is definitely the main benefit of this kind of NDT technique. Other analyses via the indirect ultrasonic pulse velocity method revealed the presence of several cracks in the concrete cover [9]. This is a common structural effect of strong thermal gradients, which makes the ultrasonic inspection difficult to be performed but has no practical consequences

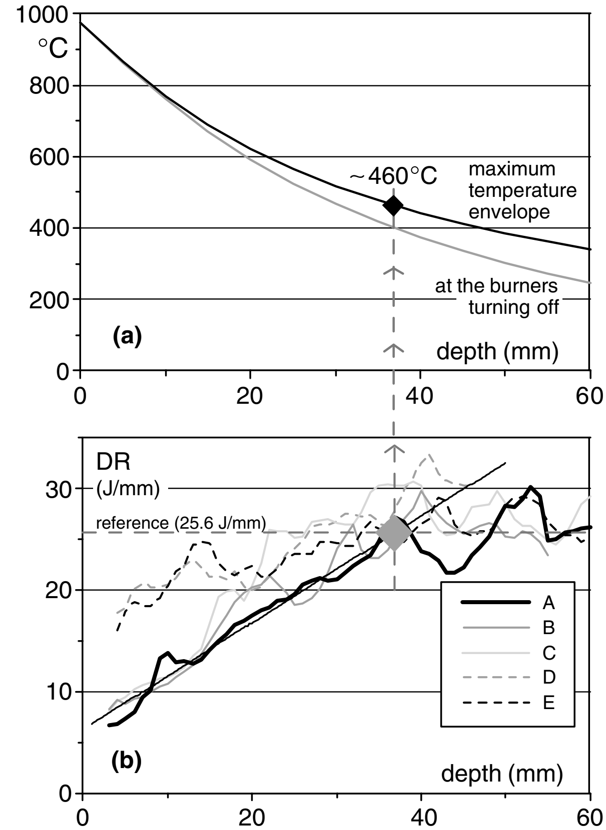


Fig. 12. (a) Maximum temperature envelope in the exposed part of the back wall (lines A–B) and (b) average drilling resistance profiles along the five equally spaced lines.

on either the implementation and the results of the drilling test.

7. In situ application

The in situ viability of this NDT technique has been finally confirmed in the thorough analysis of an industrial building surviving a 4 h real fire. The original grade of this concrete is typical of precast RC structures ($R_{cm} \cong 55$ N/mm^2). Despite the actual thermal load experienced by each member is unknown, this case made possible to compare a number of investigation techniques in terms of sensitivity to the thermal damage, time needs for the implementation and in situ practicability.

Among them, the well-known rebound hammer technique [21] confirmed to be of valuable help for a first, quick monitoring of the severity of the effect of fire on a concrete structure [6,9]. In the case of a severely damaged column (0.45×0.45 m – Fig. 13(a)), the simple inspection of the rebound index itself allowed to recognise the most impaired parts of the member, with no need for specific correlations with the residual strength (Fig. 13(b)). However, this parameter provides just an estimate of the surface hardness, but no information on the damage depth.

Hence, the drilling resistance profile has been evaluated on the two most severely exposed sides of the column, by

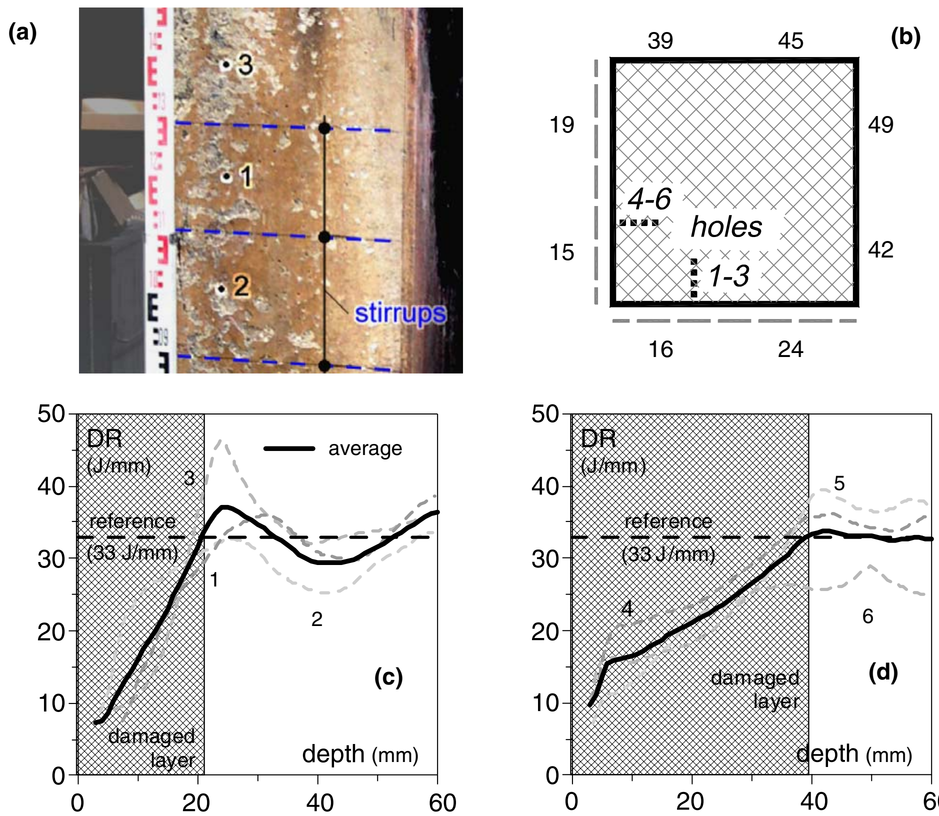


Fig. 13. (a) Severely fire damaged concrete column, (b) rebound index along its perimeter and (c, d) drilling resistance profiles at the most impaired sides.

performing three repeated tests on each face. The results clearly show that noticeably different damage depths actually correspond to the same response at the member surface (Fig. 13(c) and (d)). Similar conclusions have been drawn by means of the indirect ultrasonic pulse velocity method, though at the price of a more demanding test procedure.

8. Conclusions

In its different forms, the drilling resistance test is an accepted non-destructive testing technique for the assessment of some building materials such as wood, masonry and stone. The viability of the method in the case of reinforced concrete structures and its potential for the assessment of the thermal damage undergone during a fire have been checked in this study, allowing to formulate the following set of conclusions:

- A hammer drill is recommended in order to quickly inspect the concrete cover preventing an excessive bit wearing and overheating. In this case, the sensitivity to the exerted thrust is markedly reduced and no special control of either the drilling force or the feed rate is needed. A medium size drill bit ($\varnothing = 10$ mm) exhibits a regular response despite of the inherent material heterogeneity.
- The dissipated work per unit hole depth (J/mm) proved to be the most sensitive indicator of the material soundness. A correlation between this parameter and the material compressive strength cannot be easily worked out, because of the strong influence of other properties like the fracture energy and the aggregate hardness. However, the drilling resistance keeps its significance in relative terms and the comparison with the inner pristine material provides meaningful information on the thickness of the outer fire-damaged concrete. Moreover, the relative drilling resistance allows to release the results from the repeatability of the testing conditions (bit wearing, stiffness and mass of the tested member, average thrust).
- Due to the counteracting effect of the increasing material deformability, which fosters more dissipative penetration mechanisms, only a sizeable thermal damage can be detected via the drilling resistance technique ($R_c^T \leqslant 0.5$–$0.7\,R_c^{20\,^\circ\mathrm{C}}$). However, similar damage levels are considered in the popular "reduced cross-section method" for the design of concrete structures under thermal loads and for the evaluation of the residual capacity after a fire (critical temperature = 500 °C). For the same reason, the sensitivity of this technique is expected to improve in the case of originally softer materials (low-grade and lightweight concretes), compared to brittle high-performance concrete.
- The drilling resistance test proved to be a fast and viable method also in the case of in situ application and realistic fire conditions. The immediate availability of the

results is of valuable guidance in the assessment of concrete structures surviving complicated fire scenarios.

- Being based on the point by point mechanical response of the material under investigation, this technique is likely to provide useful results also in the case of different construction materials (stones, brickwork, etc.), regardless of their more or less pronounced sensitivity to high temperature. Other tests, not reported in this paper, confirmed the viability of this technique also for detecting voids, coarse defects and layers of distinct materials.

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