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New NDT techniques for the assessment of fire-damaged concrete structures

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Abstract

An extensive research programme has been performed at Politecnico di Milano in order to identify quick and easy methods for the assessment of the thermal damage undergone by reinforced concrete structures in consequence of a fire. As a result, three new investigation techniques have been proposed, which allow to assess the whole thermal damage profile in one single test: a simplified interpretation technique for the indirect Ultrasonic Pulse Velocity (UPV) method (based on the refraction of longitudinal waves), an affordable approach to concrete colorimetry and the real-time monitoring of the drilling resistance. In this paper, the pros and cons of the proposed techniques are pointed out, as revealed by laboratory tests. The actual in situ viability of each method is then discussed, after the investigations conducted on two full-scale structures: a precast R/C industrial building surviving a real fire and a concrete tunnel submitted to a series of hydrocarbon-pool fire tests.

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

1. Introduction

Concrete is known to exhibit a good behaviour at high temperature, thanks to its incombustible nature and low thermal diffusivity, which guarantee a slow propagation of thermal transients within the structural members. As a consequence, very strong thermal gradients take place in the reinforcement cover during a fire and the material thermal damage rapidly decreases from a maximum to nil within a few centimetres depth. Only in the cases of quite long fire duration and relatively thin cross-sections, the exposure to high temperature is expected to sizeably impair the bearing capacity of the structural members [1]. One important exception is the occurrence of explosive spalling, i.e. the sudden expulsion of concrete chips prompted by the vapour pressure build-up, which has the effect of exposing deeper layers of concrete to the maximum fire temperature, thereby increasing the rate of transmission of the heat. This phenomenon usually takes place at relatively low temperature (<400 °C) and, underneath the visible erosion of the member surface, the remaining material might have not undergone a significantly high temperature (as in the case of the Channel Tunnel fire).

The outcome of heating is a series of chemo-physical transformations occurring in concrete at increasing temperature [2]: the physically combined water is released above 100 °C; the silicate hydrates decompose above 300 °C and the portlandite will be dehydrated above 500 °C; some aggregates begin to convert or to decompose at higher temperatures (α–β SiO_2 conversion, decomposition of limestone). The mechanical response of the material is weakened concurrently and the compressive strength is expected to be reduced, slightly up to 400 °C and then more noticeably. This irreversible decay can significantly depend on the mix design, the heating and cooling conditions and the structural effects of thermal gradients (self-stress and cracking). Then, no fixed relationship can be found between the maximum experienced temperature and the residual concrete strength. Nevertheless, concrete structures frequently survive a fire with no major member collapse and the problem of assessing their residual

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capacity becomes of prime interest for designing possible strengthening and repair interventions.

Concerning the other mechanical parameters, a more marked decrease of the Young's modulus is usually observed, whereas the tensile strength exhibits the most temperature-sensitive behaviour [3]. Other physical properties are more or less affected by the exposure to high temperature, such as density, porosity (total volume and average size of pores), concentration of microcracks, colour, electrical conductivity, etc. This extensive series of transformations provides the basis for the non-destructive material assessment, although the traditional testing techniques are generally not suitable for the inspection of such a highly heterogeneous layered and fractured material.

The possible approaches to this problem (Table 1) involve either the inspection of the average response of the concrete cover [4,5], a point-by-point analysis of small samples taken at different depths [6–8] or some special techniques for the interpretation of the overall response of the concrete member [8–10]. However, the majority of these methods are usually not very 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).

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 (Technical Task 4.3—*Innovative damage assessment, repair, recovery and retrofitting*).

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 fire-damaged concrete structures [11]. To this latter goal, three new investigation techniques have been proposed which allow the assessment of the whole thermal damage profile in one single test, even being based on inexpensive devices and not requiring demanding laboratory analyses. The main features of the proposed test methods and the outline of the experimental programme performed for their calibration and verification are illustrated in the following. Then, their in situ practicability is discussed, after the investigations conducted on two RC structures surviving a real fire.

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

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

2. Laboratory benchmarks for fire damage assessment

The main aspect to be considered in any experimental investigation on the response of thermally damaged concrete is the temperature field reached during the heating phase, that is a function of both the heating rate and the period of exposure to the hot environment. The maximum temperature undergone by the material at each point is usually of prime interest, as the chemo-physical transformations are almost totally irreversible while less affected by the cooling process. Nonetheless, the heating and cooling rates also play a significant role, by governing the thermal stress, the pore pressure and the possible formation of cracks.

To ascertain the effectiveness of the proposed techniques in the whole range, from the material characterisation under homogeneous damage conditions to the strong gradients ensuing from real fires, a set of three testing conditions has been considered in the preliminary part of this research programme.

2.1. Uniformly damaged concrete cubes for calibration tests

A series of concrete cubes (side = 150 mm, max aggregate size = 16 mm, average cubic strength $R_{cm} \cong 50\,\mathrm{N/mm^2}$) has been prepared by using two different concrete mixes: an ordinary concrete (NC, siliceous aggregate) and a structural lightweight concrete (LWC, expanded clay coarse aggregate + siliceous sand). The samples have been moist-cured for 1 month, kept in the laboratory environment for 2 months and then submitted to a slow thermal cycle up to $T_{max} = 200$, 400, 600 and 800 °C (heating rate = 0.5 °C/min, 2-h spell at T_{max}, cooling rate = 0.2 °C/min). Finally, they have been tested in compression, revealing very similar strength decays (Fig. 1), with a significant loss at temperatures higher than 400 °C in accordance with Eurocode 2 for siliceous concrete (EN 1992 Part 1.2–2004: General rules—Structural fire design, f_c^T/f_c^{20} = relative "hot" strength of cylinders).

The same cubes have been used to calibrate the response of a series of different NDT methods, in order to ascertain their intrinsic sensitivity to the thermally induced strength loss (Fig. 1). The results concerning some well-established techniques (Schmidt's rebound hammer and Ultrasonic Pulse Velocity, UPV) showed a remarkable dispersion,

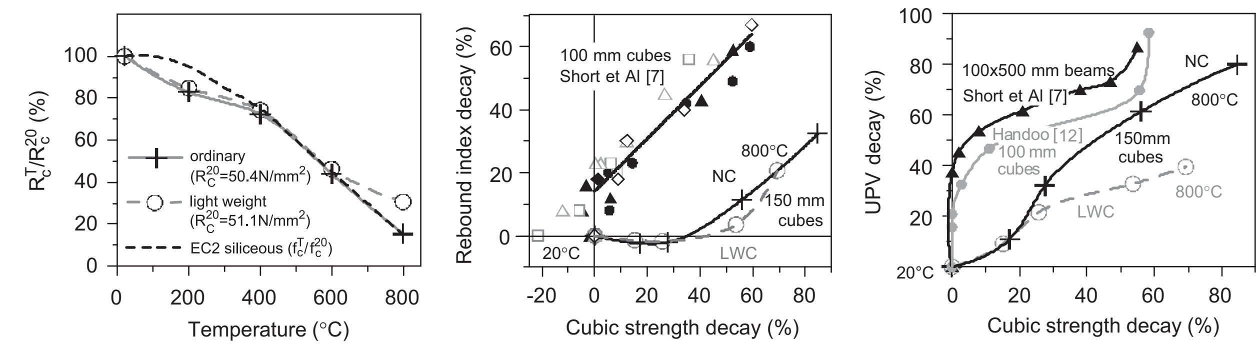

Fig. 1. Residual strength decay of the uniformly damaged concrete cubes and concurrent relative decay of the Schmidt's rebound index and of the Ultrasonic Pulse Velocity.

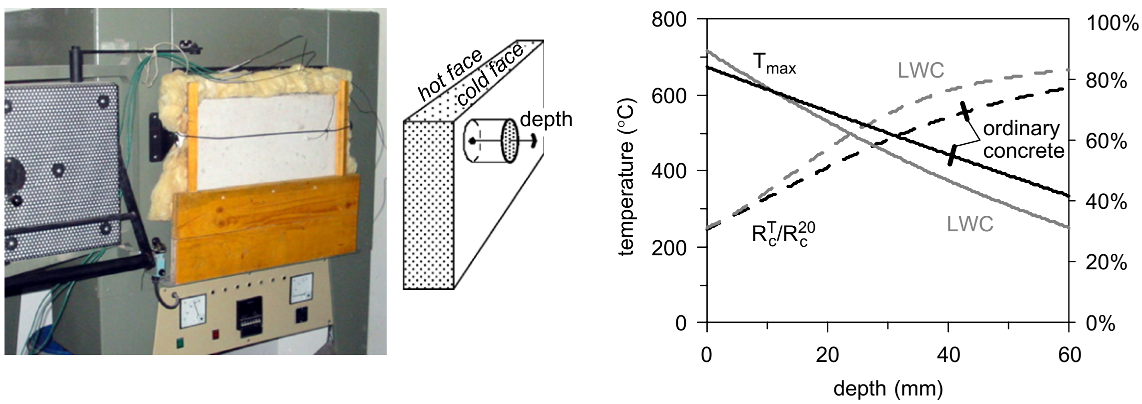

Fig. 2. Concrete panel positioned as a replacement for the furnace door and exposed to a thermal gradient; ensuing maximum temperature and residual strength profiles through the panels thickness.

compared to like results available in the literature [7,12]. This evidence is probably ascribable to a number of differences in the operational parameters (specimens' size, experimental procedure, material porosity and initial moisture content), bringing to light the need for standardised calibration procedures.

2.2. Concrete panels under a constant temperature gradient

The two concretes adopted for calibration tests were used also to prepare as many small panels ($275 \times 550 \times 80$ mm) which have been exposed to a marked thermal gradient ($>5\,^{\circ}$C/mm) by heating them on the one side ($T_{furnace} = 750\,^{\circ}$C) while keeping the opposite side cool with a fan (Fig. 2). These specimens are intended as a first, well-controlled benchmark for checking the reliability of the proposed test methods in the assessment of the damage gradient within a concrete member. Then, the maximum temperature profile within the panels has been determined by means of three embedded thermocouples. From the temperature at each point and after the plots of the cubic strength decay (see Fig. 1) 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.

2.3. Concrete wall submitted to an ISO 834 standard fire

A more realistic benchmark for the effects of thermal gradients has been 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. 3). The test was run in a vertical furnace, after closing the specimen in a low-grade reinforced concrete box (average cubic strength $R_{cm} \cong 30\,\mathrm{N/mm^2}$). 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 non-uniform damage pattern resulting from a severe fire. A first evidence of this aspect is provided by the plot of the average rebound index at different heights on the back wall (Fig. 3).

In view of the following studies, the temperature of the most exposed portion (lines A–C) has then been monitored on both faces and at half thickness and the experimental temperature field has been modelled and fitted numerically, allowing the envelope profile of the maximum temperature experienced by this concrete member to be plotted, including the cooling phase. It has to be remarked that in the case of a strong thermal transient, which is the rule in

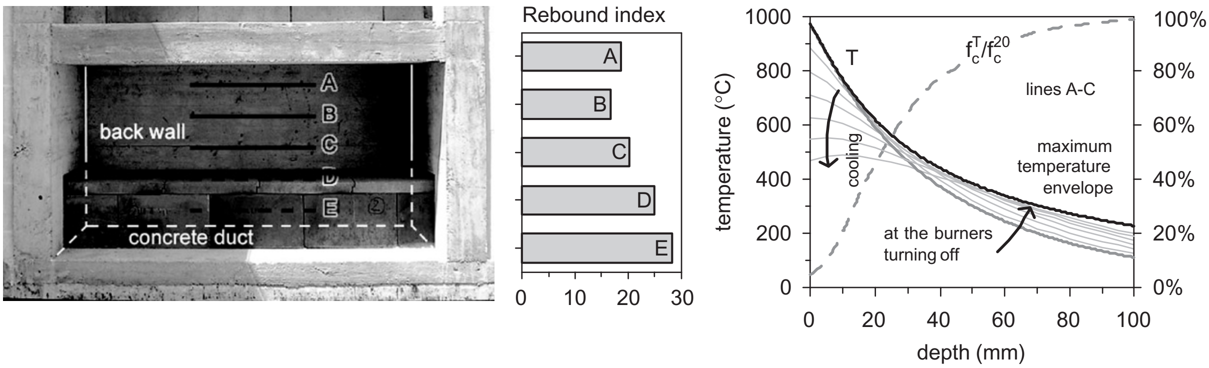

Fig. 3. Fire test set-up including the concrete duct to be tested and the back wall which has been the object of ND testing; rebound hammer response of the wall after testing and maximum temperature envelope in the exposed part of the wall.

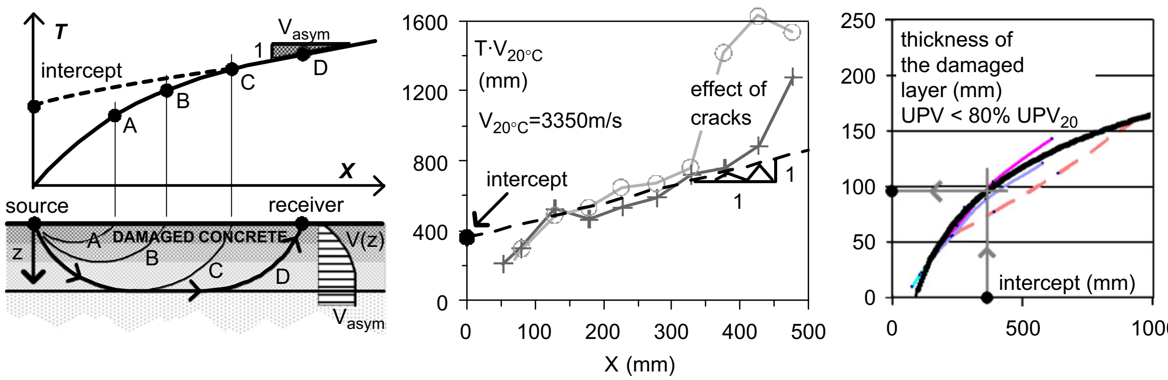

Fig. 4. Minimum travel-time path and shape parameters of the X–T curve; experimental X–$TV_{20\,^\circ C}$ curves obtained from the concrete wall of Fig. 3 (lines B and C) and assessment of the damage thickness (≅100 mm) via the intercept of the final asymptote (≅360 mm).

real fires, the temperature of the inner material of a structural member keeps rising during the early part of the cooling phase. This is due to the heat stored in the external hot layer, which is conducted towards the colder part of the member regardless of the stage of the fire load. As in the previous case, the profiles of the expected strength have been also worked out, based on the standard decay curve of the cylindrical strength f_c^T/f_c^{20} for siliceous concrete (EC2 plot in Fig. 1).

3. New non-destructive investigation techniques

As already stated, the main objective of the present research programme is to identify quick and easy methods which could allow the whole thermal damage profile to be assessed. The outcome consists of three proposals, which are herein briefly illustrated.

3.1. Simplified interpretation of the indirect UPV test results

As is generally recognised, the velocity of sound in concrete is strongly affected by the thermal damage, due to the drying of pores and to the pronounced temperature sensitivity of the Young's modulus (Fig. 1). However, detecting the residual velocity profile within a member submitted to strong temperature gradients is quite a difficult task. Useful information on the damage depth and severity can be provided via the indirect UPV technique, which is based on the refraction of longitudinal ultrasonic waves [13]. In this method, the measurement of the pulse arrival time is performed by applying both the emitting and the receiving probes on the same face of the investigated element (Fig. 4). Under the assumption that the pulse velocity rises at increasing depth (which is the rule after a fire), the path of sound waves corresponding to the minimum travel time is the best compromise between reducing the covered distance via a shallow path and exploiting the faster deep layers. Then, the maximum depth of the material involved in this pulse propagation is a function of the distance X between the probes. As a consequence, a series of repeated measurements of the pulse arrival time T at increasing distance X allows deeper and deeper material layers to be investigated. The outcome is a plot on the X–T axes whose interpretation has been the object of different numerical methods proposed in the literature [9,10].

One important property of this experimental diagram is that the reciprocal of the final slope corresponds to the asymptotic velocity V_{asym} of the deep concrete layers, which is normally equal to the velocity $V_{20\,^\circ C}$ in the pristine material (for thick members and relatively short fire duration). After multiplying the ordinate by the asymptotic velocity ($T \to TV_{\text{asym}}$), the final slope is normalised to a unit value and the shape of the plot is controlled only by the profile of the relative velocity $V(z)/V_{\text{asym}}$.

Among the geometric features of this normalised plot, the intercept of the final asymptote at $X = 0$ is of particular interest, because it is a measure of the time delay accumulated in the slow shallow layers and it is strongly related to the thickness of the sizeably damaged concrete (a 20% velocity decay threshold has been adopted in this study, Fig. 4). A series of numerical simulations of different thermal transients involving a broad range of concrete mixes revealed little influence on this relationship of either the heating conditions or the inherent material sensitivity to high temperature [11]. Then, no preliminary information on the member under investigation is needed for the application of this method. Other correlation curves are available for detecting the depth of different damage thresholds and for assessing the maximum material decay on the surface of the member.

The reliability and viability of this procedure have been tested by analysing the concrete wall exposed to a 90 min ISO 834 fire (Fig. 4). The results highlight the good sensitivity of the method, which allows a relatively small mechanical decay to be detected (see the profiles of the maximum temperature and expected residual strength in Fig. 3). Nonetheless, it has to be noted that the recording of each X–T plot is generally a demanding task, especially in the presence of cracks, which could more or less noticeably delay the pulse arrival time and undo the convexity of the experimental curve. Moreover, this technique requires a flat surface and is therefore not appropriate for shotcrete or if spalling has occurred.

3.2. Digital camera colorimetry

The colour of concrete is expected to change at increasing temperature, generally from normal to pink or red (300–600 °C), whitish grey (600–900 °C) and buff (900–1000 °C). The pink–red discolouration ensues from the possible presence of iron compounds in the fine or coarse aggregate, which dehydrate or oxidise in the indicated temperature range [14]. The strength of this colour change depends on the aggregate type and it is more pronounced for siliceous aggregates and less so for calcareous and igneous aggregates. Detecting this first colour alteration [8,14] is of great interest because its appearance usually coincides with the onset of a significant loss of concrete strength as a result of heating.

In this research programme, a simplified approach to colorimetry has been formulated, based on the analysis of a photograph of a section through the concrete, taken with a commonly available low-cost digital camera [15]. The starting point of this method is that digital pictures are usually not very accurate from the colorimetric point of view, but they still allow slight colour variations to be recognised among different points on the same sample. Moreover, the considerable amount of data available in a single digital image (many thousands of pixels) allows to separately analyse the cement mortar and the aggregate and to outline some statistical trends ascribable to the inherent heterogeneity of the material.

One remarkable difficulty dealing with the numeric representation of colours is that they are usually expressed in a 3-D space, according to the three different stimuli perceived by as many types of receptors in the human retina (e.g. the $X\ Y\ Z$ colour space established by the Commission Internationale de l'Éclairage and the standard Red–Green–Blue system—sRGB—of most digital imaging devices). Three simultaneously varying parameters are then involved in the analysis of concrete at increasing temperature, although only the proportion among the coordinates can be considered [i.e. the chromaticity coordinates $x = X/(X+Y+Z)$ and $y = Y/(X+Y+Z)$] being the colour lightness of minor interest in this case.

The preliminary examination of the cores taken from the uniformly heated concrete cubes allow the main features of the colour variation in the CIE 1931 xy chromaticity diagram to be recognised (Fig. 5) and a well-suited scalar measure of the colour variation for the problem at issue to be defined (namely the difference $x-y$).

Concerning the assessment of damage gradients, four concrete cores have been taken from each of the concrete panels described in Section 2.2. The colour variation profiles clearly reveal up to which depth the material has been significantly affected by high temperature. For both the concretes herein investigated, the onset of chromatic alteration corresponds to a 470 °C maximum temperature and a 35% decay of the residual strength. These thresholds are slightly higher compared to the UPV technique, but they seem still adequate for the purpose of the structural assessment after a fire. The only limitation of this method is that a core has to be cut from the member, precluding the systematic analysis of thin structural elements.

3.3. Drilling resistance

The measurement of the drilling resistance appears to be a promising and fast technique to continuously "scan" any strongly layered materials at increasing depth. Some examples of this kind of approach are available in the literature, mainly based on the measurement of either the thrust to be exerted to drill the material at a constant feed rate [16] or the work dissipated to drill a unit deep hole (J/mm) [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 to prevent excessive bit wear and overheating. In this case, the sensitivity to the exerted thrust is largely masked by the hammering action and the specific dissipated work (the "drilling resistance") appears to be the most promising indicator of the material soundness. Once a constant drill bit performance is guaranteed via the hammering action, the most interesting feature of this technique is that the deep virgin material is

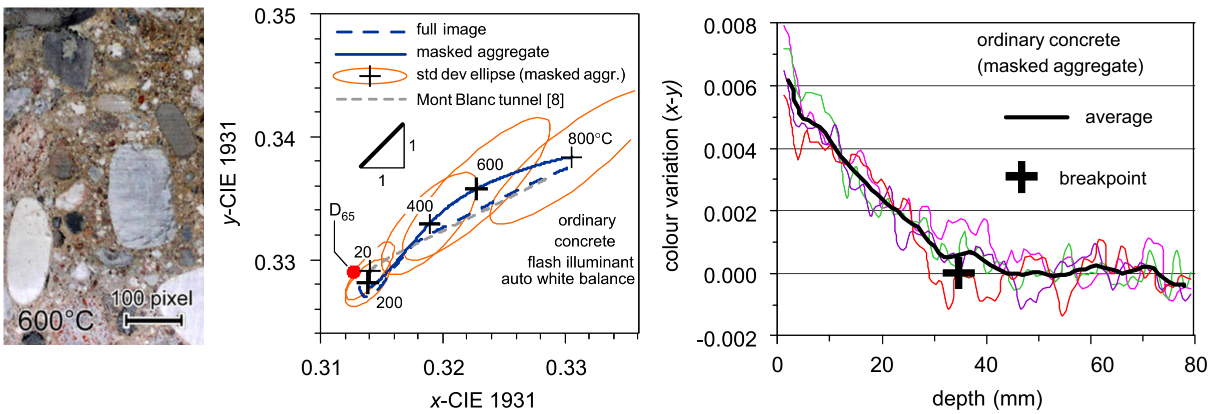

Fig. 5. Digital image of a uniformly heated concrete core and effect of high temperature on the chromaticity of ordinary concrete; colour variation profiles within one small panel submitted to a constant thermal gradient (see Fig. 2).

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 for the evaluation of the thickness of damaged concrete.

In this research programme, the drilling resistance has been measured by modifying a common battery hammer drill (Hilti TE 6-A fitted with 10 mm bits) in order to monitor the electrical power consumption, the bit rotation and the hole depth (Fig. 6, [18]). After proper transformation and analog filtering, the electrical signals are acquired by a laptop computer and processed by a dedicated software, which allows the test results to be displayed in real time.

The sensitivity of this method to the thermal damage has been preliminarily ascertained by testing the uniformly damaged concrete cubes. Due to the counteracting effect of the increasing material deformability and nearly constant fracture energy (which initially foster more dissipative penetration mechanisms), only significant thermal damage can be detected via the drilling resistance technique ($T \geqslant 400$–$550\,^{\circ}\mathrm{C}$, $R_c^{\mathrm{T}} \leqslant 0.5-0.7 R_c^{20\,^{\circ}\mathrm{C}}$). 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 (temperature threshold = 500 °C).

As regards the assessment of thermal gradients, the drilling tests clearly reveal their effect on the mechanical response of a member (Fig. 6), 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 smoothed out by averaging the results of a few repeated tests. In the case of the concrete wall submitted to an ISO 834 fire, the average diagrams pertaining to different areas clearly indicates which part of the structure went through a severe thermal exposure (lines A–C) and which one was only marginally impaired during the fire test (lines D and E). It is worth noting that only about 5 min were needed in this latter case to perform the whole series of tests and the results were immediately available for interpretation thereafter. These are definitely the main benefits of this kind of NDT technique.

4. Real fire in a precast RC structure

The first occasion to check the viability of the cited NDT techniques for a real fire has been provided by the thorough analysis of an industrial building which survived a 4-h fire. The original grade of this concrete is typical of precast RC structures ($R_{\mathrm{cm}} \cong 55\,\mathrm{N/mm^2}$). Although the actual thermal load experienced by each member is unknown, this case allowed a number of investigation techniques to be compared in terms of sensitivity to the thermal damage, time required for implementation, and in situ practicability (Table 2).

Among them, the well-known rebound hammer technique [13] is confirmed to be of value for a first, quick monitoring of the severity of the effect of fire on each structural element. In the case of a severely damaged column (0.45×0.45 m; Fig. 7), the simple inspection of the rebound index itself allowed the most impaired parts of the member to be identified, with no need for specific correlations with the residual strength. 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 performing three repeated tests on each face. The results clearly show that different damage depths actually correspond to the same surface hardness.

Similar conclusions have been drawn by means of the indirect UPV method, though at the price of a more demanding test procedure and under the possible influence of cracks within the concrete cover, which may lead to an over-estimation of the damage depth (the first branch of the X–T curve in Fig. 7 is not convex and the intercept value appears too large). This is a common structural effect of strong thermal gradients, which makes the ultrasonic

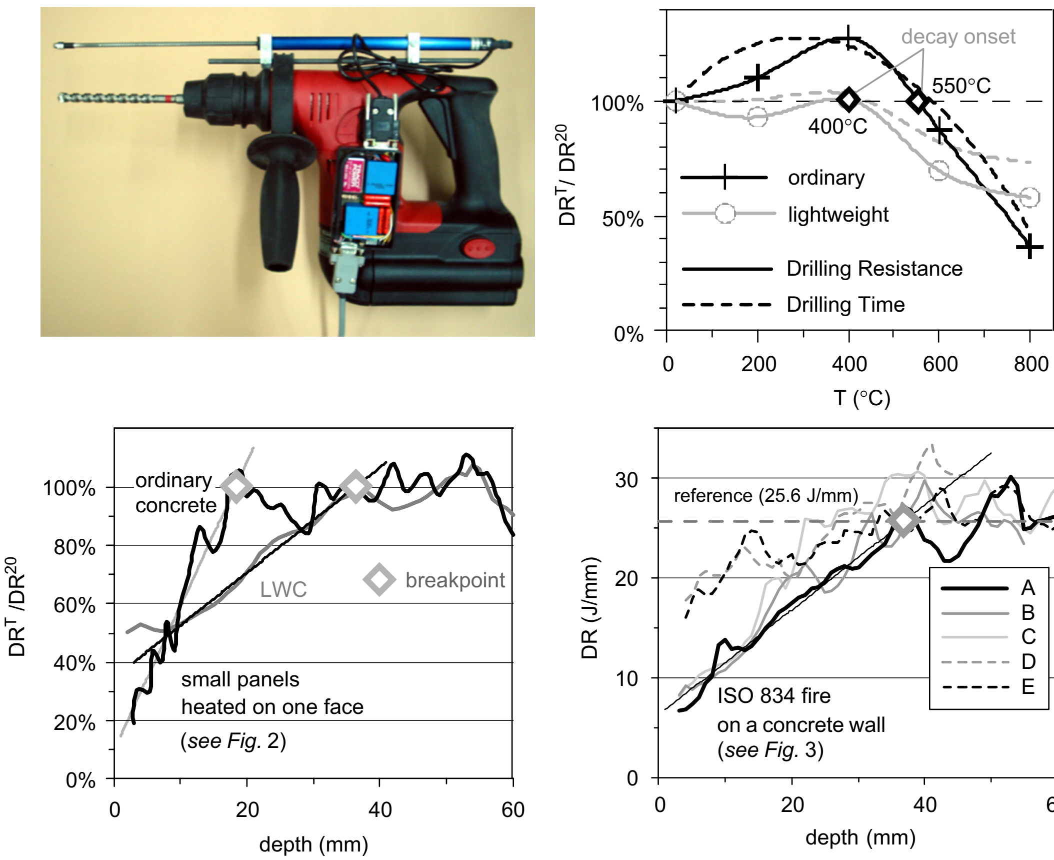

Fig. 6. The battery hammer drill fitted with the electronic circuits and the displacement transducer; sensitivity to high temperature of the drilling parameters and average profiles of the drilling resistance through the concrete panels submitted to strong thermal gradients.

Table 2
Summary of the techniques utilised for the assessment of the precast RC structure

Structural element	Parameter	Method
Main beams of the roof	Residual deflection	Laser theodolite
	First mode frequency (torsional)	Accelerometer
	Shrinkage cracks opening	Microscope
	Rebound index	Schmidt's hammer
	Ultrasonic Pulse Velocity	Indirect UPV
	Drilling resistance	Modified drill
Thin webbed roof elements	Residual deflection	Digital image analysis
	Rebound index	Schmidt's hammer
Columns	Rebound index	Schmidt's hammer
	Ultrasonic Pulse Velocity	Indirect UPV
	Drilling resistance	Modified drill

inspection difficult to perform but has no practical consequences on the implementation and the results of the drilling test.

No colorimetric analyses have been performed in this case, in order to prevent the further damage of cutting the cores from the slender precast members.

5. Hydrocarbon fire tests in a motorway tunnel

The second verification case considered in this programme is connected again to the tasks of the UPTUN Project (Workpackage 6—*Fire effects and tunnel performance: system response*). Taking advantage of the lining renovation works in progress in the north channel of the Virgolo tunnel (Bolzano, Italy—Fig. 8), the Brennero Motorway management decided to run a series of real-scale tests on different active and passive fire protection systems and to compare the performance of six different shotcrete mixes for lining repair (shotcretes A to F, Table 3, [19]). The fire load was provided by diesel oil in a series of stainless steel trays arranged next to the side wall of the tunnel (three tests—10 to 30 MW pool fires). Both the environment temperature (28 points) and the concrete lining temperature (92 points at 5, 25 and 50 mm depth) were accurately monitored during the tests. A further small-scale test has been also conducted in a concrete box (the "mini-tunnel"), where a series of protective lining materials laid on concrete supports have been exposed to a very severe fire (panels 1–4, Table 4). The available data on

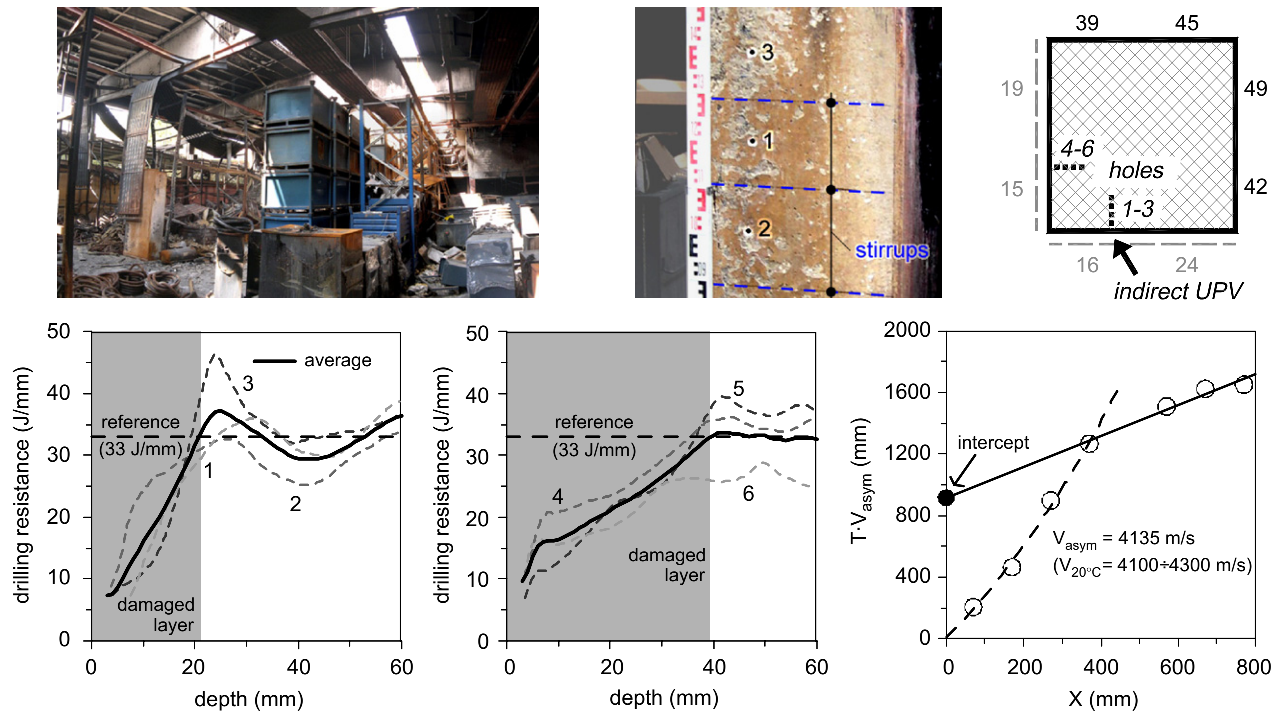

Fig. 7. View of the precast RC structure after the fire; detail of a significantly damaged column and rebound index around its cross-section; results of the drilling resistance and indirect UPV tests (final asymptote intercept ≅900 mm).

Table 3
Material properties of the six shotcrete mixes for tunnel lining renewal (f_c: cyl. compr. strength, f_{tcb}: bending strength, E_c: Young's modulus)

Id	f_c (MPa)	f_{ctb} (MPa)	E_c (GPa)	Rebound index	S.D.
A	34.8	4.7	18.4	35	3.7
B	49.0	4.3	28.3	19	5.0
C	13.5	1.1	6.9	20	1.8
D	85.5	3.0	35.5	31	3.6
E	37.0	7.6	22.6	33	2.7
F	3.7	1.1	2.5	13	0.83

Table 4
Geometry and initial Ultrasonic Pulse Velocity of the lining materials tested in the mini-tunnel (1.0 × 1.0 m panels)

Panel no.	Thickness (mm)	Base panel thickness (mm)	UPV (m/s)
1	45	50	2840
2	50	100	4530
3	40	50	1580
4	40	50	1620

the mechanical properties and the results of some preliminary non-destructive tests highlight the wide assortment of the materials at issue, ranging from lightweight insulating mixes (C, F, 3 and 4) to a high performance micro-concrete (D and 2).

Besides the intriguing figures of this experimental programme, a stringent verification of the in situ viability of different NDT techniques has been possible, involving the problems associated with a number of operational difficulties (roughly finished shotcrete surfaces, relatively inaccessible test points, the presence of other research teams and the short time available to carry out the tests). Regarding the results of the main tunnel test, it can be observed that the gas temperature in the upper part of the tunnel section reached the value of 250–300 °C for about 15 min, leading to a temperature in the range 50–200 °C at a depth of 5 mm in the shotcrete samples, depending on the distance from the oil trays and on the ventilation conditions (Fig. 9). Due to the surface roughness, it was not feasible to perform the UPV tests and the rebound index itself has been measured only after smoothing some spots on the lining. Moreover, the time limitations and the difficulty in accessing the vault prevented the recovery of any core samples from the lining, and thus the analysis of the colour alterations in the concrete.

On the other hand, the drilling resistance tests were easy and fast to perform and about 40 holes were drilled in less than 10 min at a height of 3 m, using only a ladder for access. The average drilling resistance profiles pertaining to the six shotcrete samples can be summarised in terms of a few damage parameters (the damage depth and the minimum drilling resistance at the surface), by simply normalising the whole profile on the final, almost constant reference value (Fig. 10).

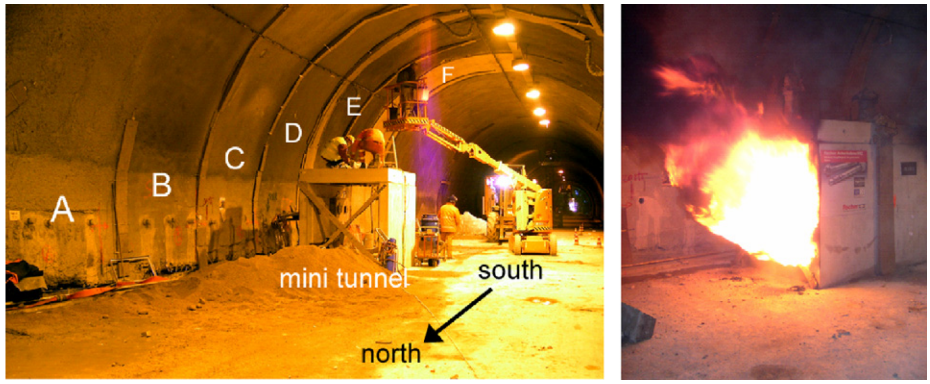

Fig. 8. The north channel of the Virgolo tunnel covered with six different lining systems and the “mini-tunnel” containing four concrete panels during the hydrocarbon-pool fire test.

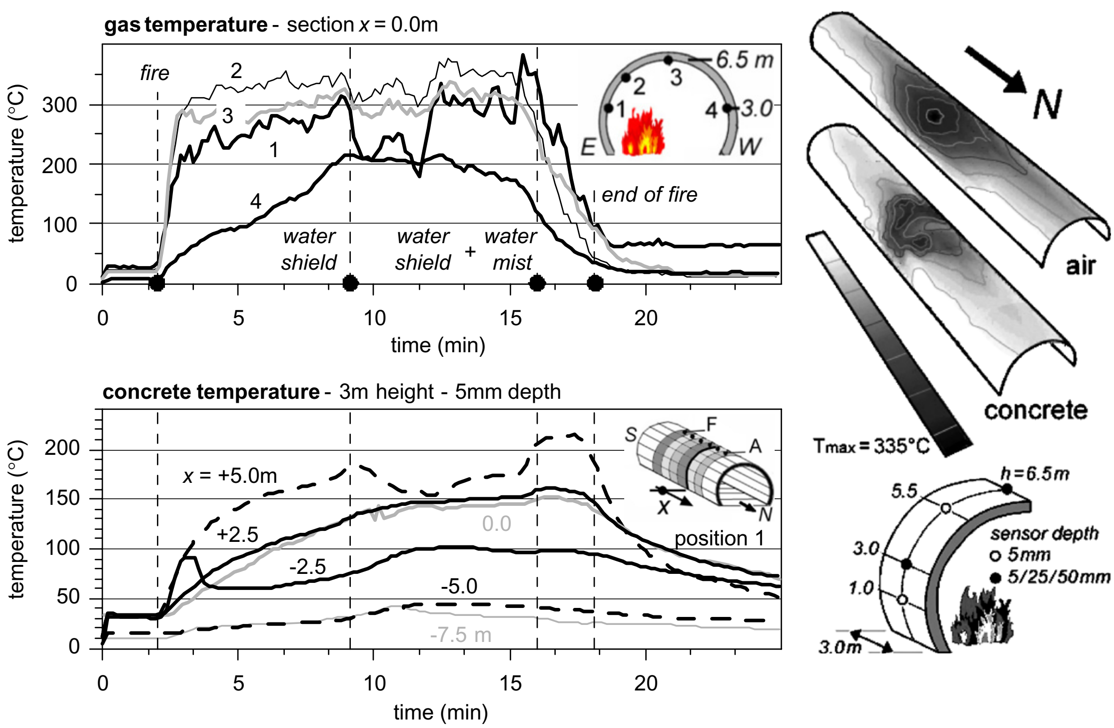

Fig. 9. Gas and concrete temperature during the 30-MW fire test in the Virgolo tunnel [19].

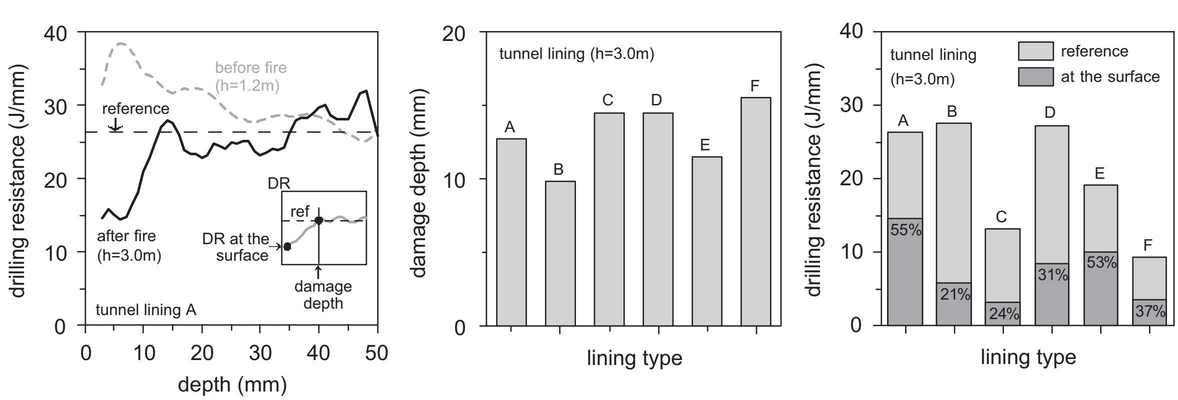

Fig. 10. Drilling resistance profile in the first shotcrete sample and histograms of the damage depth and maximum damage at the surface for the six samples.

It has to be noted that significant damage was detected in the first 10–15 mm via the drilling technique, despite the relatively low temperatures recorded within the lining. This result is consistent with the visual observation of the vault after the fire, highlighting the extensive delamination and buckling of sample B and the microcracking of sample D, and it can be probably explained as the outcome of the self-stress ensuing from the strong thermal gradients.

More severe heating conditions have been recorded in the mini-tunnel test, although the short fire duration considerably smoothed the effects at depths exceeding 10 mm (Fig. 11). The results also draw attention to the strong effect of thermal diffusivity, which can halve the maximum temperature reached by concrete in the case of insulating lightweight mixes (panel #1).

Concerning the assessment of the damaged materials, much better operational conditions have been managed in this case and the smooth face of the tested panels allowed the indirect UPV tests to be performed. However, the presence of a stiff base panel and the possible effect of the lining delamination took the lion's share in determining the final asymptote of X–T curve, especially for soft insulating materials. Just in the case of the high-performance concrete (panel #2), the effect of fire exposure can be clearly detected, with a 15% decay of the asymptotic velocity (as a possible effect of drying) and a 150-mm intercept (Fig. 12), corresponding to a 35-mm depth of the 20% decay threshold (see Fig. 4). This result shows again that the mechanical weakening seems to exceed the simple chemo-physical effects of heating, probably because of the strong thermal gradients induced by the severe fire in this stiff and brittle concrete.

The colour variation profiles have been assessed as well, taking advantage of the holes remaining after cutting some small diameter cores. In the case of sample #2, the discolouration onset is determined at about 5 mm depth, which seems to be in good agreement with the temperature recorded during the test and in consideration of the sensitivity of the method. It has to be noted that the inception of this colour alteration was hardly noticeable with the naked eye.

Finally, the drilling resistance method confirmed its good reliability and viability, allowing to detect the damage depth, the maximum damage at the surface and the interface between the protective lining material and the harder concrete support (Fig. 13). The results show once more that the material deterioration goes slightly beyond what might have been expected from the temperature plots, after considering the sensitivity of the drillling test method.

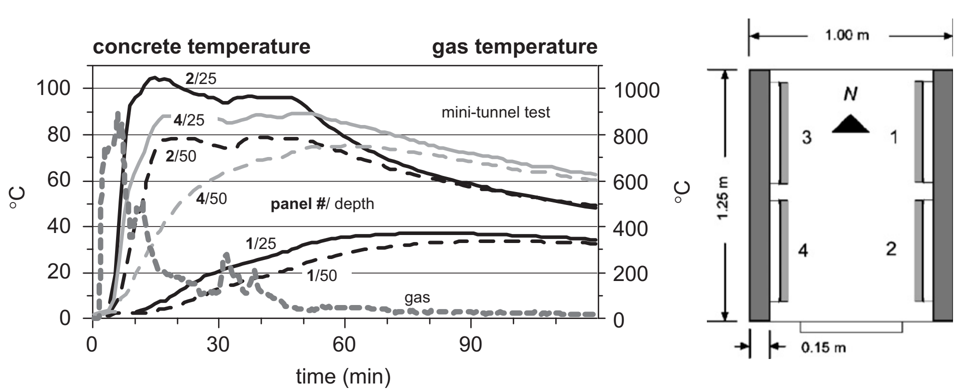

Fig. 11. Temperature of gas and concrete (25–50 mm depth) in the mini-tunnel fire test [19].

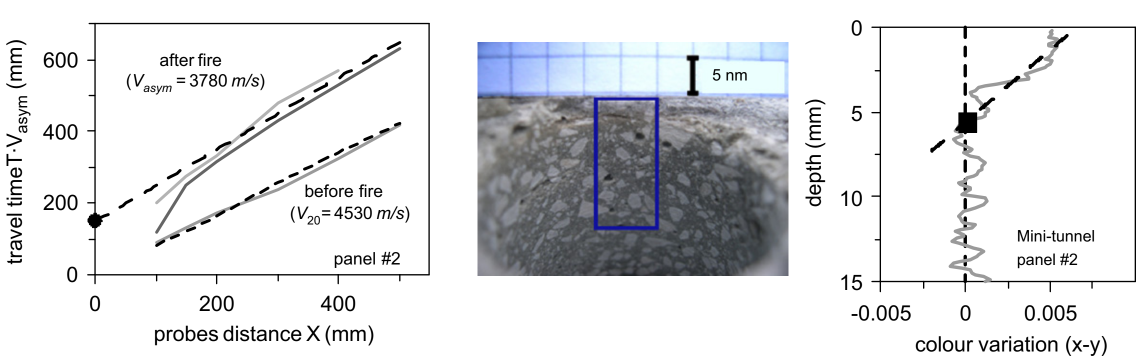

Fig. 12. Indirect UPV X–T curves measured on the mini-tunnel panel #2 and assessment of the colour variation profile on the face of a micro-core hole via the digital image analysis.

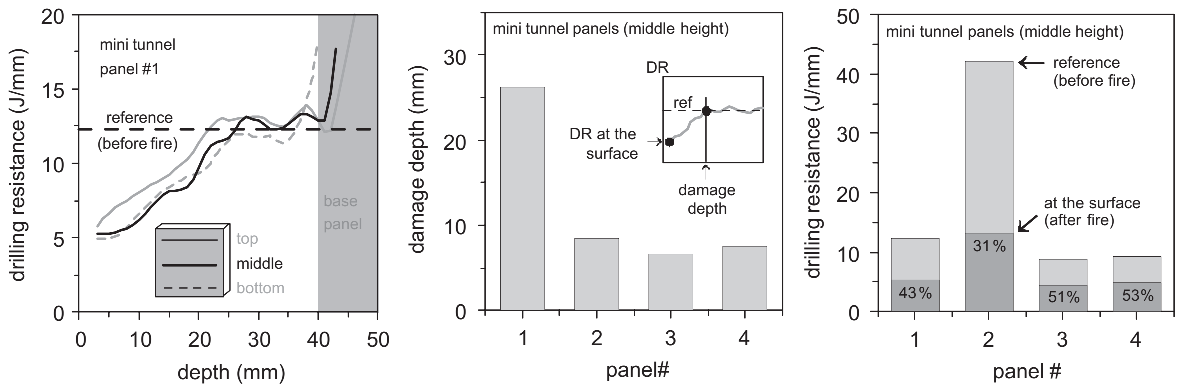

Fig. 13. Drilling resistance profile within the mini-tunnel panel #1 and histograms of the damage depth and maximum damage at the surface for the samples at issue.

6. Conclusions

In this paper, three innovative NDT methods for the assessment of fire damaged concrete structures have been presented, following the promising results of some preliminary laboratory tests. The viability of these methods in case of real fires and actual in situ operational conditions has then been checked with reference to a precast RC structure and a motorway tunnel, allowing the following set of conclusions to be formulated.

The indirect UPV method proved to be quite sensitive, thanks to the prompt effect of heating on both the dynamic Young's modulus and the moisture content of concrete. The application of this technique is rather time consuming ($\cong$15 min/test) and requires an almost flat surface, which makes it generally not appropriate for shotcrete or if there has been spalling. The proposed procedure allows rapid interpretation of the results with no need for a preliminary calibration for the specific material properties. However, the possible influence of cracks, delaminations and presence of distinct layers could markedly affect the results and a careful check on both their repeatability and consistency is recommended, regardless of the interpretation procedure.

The proposed simplified approach to colorimetry proved to be a powerful tool for evaluating the well-known colour changes of heated concrete without the need for an expert's judgement. Compared to a common colorimeter, the considerable amount of data available in a single digital image (many thousands of pixels) allows to separately analyse the cement mortar and the aggregate and to outline some statistical trends ascribable to the inherent heterogeneity of the material. Moreover, a scalar measure of the colour variation has been expressly defined in to order to simplify the assessment of the material. The in situ application to the real fire cases confirmed the viability of this method, with the only limitation of the permanent damage produced by cutting the concrete cores to be analysed.

The continuous monitoring of the energy expended by a common hammer drill was confirmed to be a reliable method for assessing the severe damage gradients occurring in concrete structures during a fire. In the case of in situ applications, this technique proved to be very fast and easily implemented, with no interference from cracking, surface roughness or spalling. The evaluation of the material response relative to the inner undamaged layer means that the results do not have to be compared with specific calibration curves and that the repeatability of the testing conditions (e.g. the condition of the drill bit, stiffness and mass of the tested member, and the average thrust) is not an issue. The immediate availability of the results has been shown to be of value in the assessment of concrete structures surviving complicated fire scenarios.

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