Fire Technology, 49, 509–529, 2013

DOI: 10.1007/s10694-011-0229-6

Assessment Methods of Fire Damages in Concrete Tunnel Linings

Roberto Felicetti, Department of Structural Engineering, Politecnico di Milano, Milan, Italy*

Received: 12 December 2010/**Accepted:** 30 April 2011

Abstract. The assessment of fire damage in concrete structures is a complex but intriguing task involving different areas of expertise, from Material Science to Structural Design, from Non-Destructive Testing to Fire Engineering. The problem grows to be even more challenging in the case of tunnels, as a consequence of the high fire severity and the operational difficulties implied by this type of infrastructure, but also because of the pressing time restrictions due to the high cost of traffic disruption during the assessment and repair works. A general overview on this subject is given in the paper, pointing out the different scales of observation, the relevant clues to be analysed at each scale and their appropriate inspection tools. These latter comprise a wide range of investigation techniques of different reliability and cost, but not many of them turn out to be viable and convenient to tackle the problem in question. In this perspective, some innovative assessment methods have been developed in recent years, having in common the ability to reveal the layered structure of fire damaged concrete, the relatively fast and easy implementation and the immediate availability of the results. A brief account on the features and the limitations of these methods is given also, as a tentative to trace some directions for future advances in this important and still open issue.

Keywords: Assessment, Concrete, Fire damage, Non-Destructive Testing (NDT), Residual properties

1. Introduction

Fire in tunnels is one of the main open issues concerning the safety of infrastructures, as testified by a number of recent events occurred in road, rail and metro tunnels [1]. Limiting the discussion to the structural point of view, one important aspect to be considered is the high severity of the fire scenarios that may develop in these underground traffic systems. The considerable fire load due to the tailed-back vehicles and the transported goods, the effective confinement of the released heat and the lack of active control measures are the main factors which may lead to remarkably high temperatures and long fire duration. In most cases the thermal impact is the highest at the top of the tunnel, due to the direct flame impingement, and becomes smaller at the benches.

One well-known example to be cited is the Mont Blanc Tunnel fire (1999), where the total duration was about 53 h, the temperatures reached and locally

* Correspondence should be addressed to: Roberto Felicetti, E-mail: roberto.felicetti@polimi.it

exceeded 800–1000°C and a stretch of over 900 m of the tunnel ceiling was considerably damaged [1, 2]. Less prolonged heating condition are depicted by different standardized temperature–time curves (Hydrocarbon, RWS, RABT) simulating the burnout of a petrol or chemical tanker and involving a fast heating to 1100–1350°C and a fire duration in the order of 2 h [1].

The effects on the concrete lining of such an intensive fire exposure strongly depend on the material quality, the moisture content and the loading conditions. Steep temperature gradients develop within the wall thickness, increasing the compressive stress and the pore pressure nearby the vault intrados. This translates into high probability of explosive spalling, especially in the case of high performance concrete.

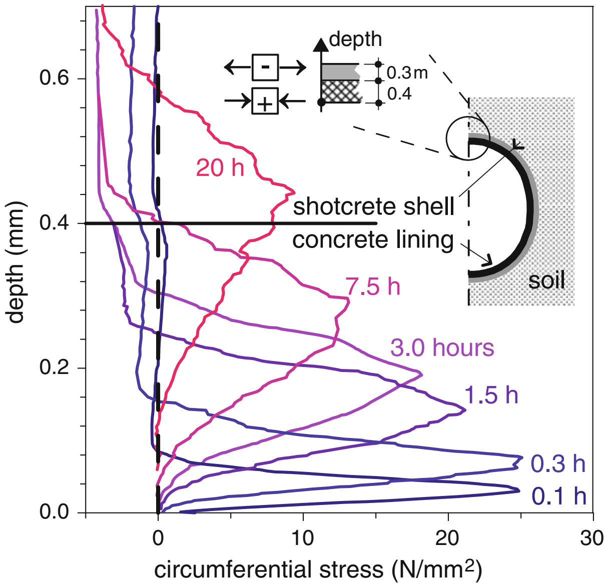
One paradigmatic example is provided by the precast lining segments of the Channel Tunnel (compressive strength = 80–100 N/mm^2) whose 0.45 m thickness was progressively reduced by 0.10–0.20 m and more, as a consequence of the 1996 fire (10 h, gas temperature up to 700°C) [3]. On the contrary, most of the low-grade and highly permeable concrete in the Mont Blanc Tunnel remained in place, despite the lack of reinforcement and the sizeable damage undergone by 20–40% of the 0.5 m wall thickness [4]. Nonetheless, explosive spalling was observed in about 40% of the underground traffic systems experiencing fires in the last 40 years [1] and specific measures for passive protection are currently adopted in the design of new tunnels (application of boards, cladding panels or sprayed-on materials, admixture of polypropylene fibres).

The implications on the bearing capacity of the liner of both the material decay and the cross-section reduction depend on the type of structure. In circular and horseshoe tunnels the principal load condition is hoop compression. During fire a critical condition is reached within the thickness (Figure 1), where a stress peak arises as a result of the stress relaxation of the most exposed layer and the deformation constraint (hoop tension) exerted by the cold extrados [3, 5]. If the conditions for activating a collapse mechanism are not met, the contour of the tube section is little affected by the thermal strain and no significant change in the interaction with the surrounding soil is expected. One exception is represented by segmental linings, due to the possible local bending of the joints [6].

A different behaviour characterizes the box (rectangular) tunnels, where the moment action is more pronounced and sagging of the roof due to overheating of the steel reinforcement is a possible failure mechanism. This is generally prevented by the considerable thickness of the members and by the structural redundancy of the box section (negative moment in the corners). One exception are the false ceilings separating the ventilation ducts above the traffic space (Figure 1): a stretch of 230 m collapsed or showed severe damage in the Gotthard Tunnel fire in 2001 [7] and 350 m had to be replaced in the Tauern Tunnel after the 1999 fire [8]. In these latter elements some local collapse mechanisms may also develop, as a consequence of the indirect actions ensuing from the restrained thermal dilatation.

The above discussion draws attention to some challenging aspects to be tackled in the assessment of fire damage in concrete tunnels:

- A wide range of material conditions can be encountered, with the most severe heating above the heaviest burnt vehicles, maximum temperatures from a few



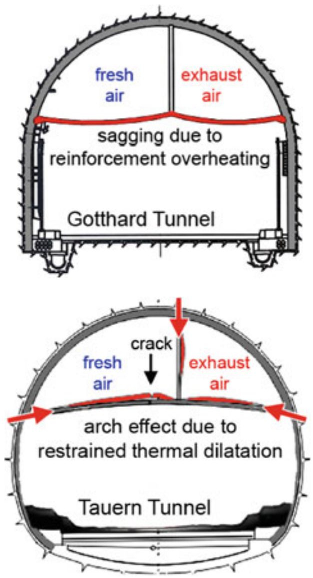


Figure 1. Hoop stress in the lining of a circular tunnel under fire [5] and collapse mechanisms in the false ceilings separating the ventilation ducts [7, 8].

hundreds degrees up to concrete melting (~1200°C) and a deterioration depth from a few centimetres to an important share of the lining thickness.

- The exposed surface may be considerably rough, because of either the original finish (shotcrete linings) or the incidence of explosive spalling. This makes the implementation of some Non-Destructive Testing (NDT) techniques quite difficult.
- The signs of any incipient collapse are seldom visible, due to the stiffness of the tunnel cross-section. Also the implementation of global static or dynamic load tests is hardly practicable.
- The most significant parts to be inspected are difficult to access, being generally located at the crown of the concrete vault. This entails some limitations on the choice of the investigation techniques and on the number of test points.
- There are stringent time limitations, due to the high cost of traffic disruption during the assessment and repair works.

In this context, the purpose of the present paper is to outline the general strategy and the most suitable investigation techniques for the assessment of the residual conditions of the tunnel lining after a fire. Some innovative and viable techniques are also discussed, which may represent a reasonable compromise between the required accuracy and the tight time restrictions.

2. General Approach to Fire Damage Assessment

The main objective of fire damage assessment in concrete structures is to provide the information required to evaluate the residual bearing capacity and durability of the structure and to design any strengthening or repair intervention.

An overview on the possible approach to this problem can be found in a couple of recognized technical publications on the assessment and repair of fire damaged structures [9, 10]. The aim of these documents is to define the repairability criteria and to outline suitable assessment procedures based on the collection of event data, the inspection of the structural members and the analysis and classification of the material damage.

To this purpose, different disciplines of Civil Engineering should be involved in a coordinated way, namely Structural Design, Fire Engineering and Non-Destructive Testing (NDT). As an example, the evaluation of the maximum temperature reached in a few significant points may allow to validate a numerical model of the gas temperature in the compartment [11] and then to extend the results to other parts not directly investigated. Some expertise in Structural Engineering is of help in assigning threshold values to the allowable residual deformation, crack opening and residual stiffness of the damaged members.

It turns out that the structure should be observed at different scales, from the whole fire scenario to the identification of the residual material properties at a point.

2.1. Fire Scenario and Global Structural Effects

The course of the fire, the nature and quantity of the fire load, the ventilation conditions and the steps of the extinguishing and rescue work can be generally retrieved from the fire service operational reports and the shipping orders of the carried goods. This allows some comparisons with the published data concerning real scale tests or similar accidents [1, 11].

Further information on the fire severity can be gained by examining the conditions of the remaining debris before their removal [9]. Melting and charring of any plastic remains (cables, ducts, lighting device, etc.), softening and melting of metals (aluminium lamp reflectors and fan components, copper wires, etc.), softening and flowing of lamp bulbs are some clues to substantiate an estimate of the maximum temperature experienced during the fire (Table 1).

At the structural level the global effects of fire are usually surveyed in order to detect any incipient collapse. Any irreversible deformation of the lining can be revealed by comparing the geometry of the concrete vault with the regular shape of the tunnel cross-section in undamaged stretches. This can be easily achieved with modern systems for topographic survey (laser theodolite or scanner). On the contrary, assessing the residual static or dynamic response of the structure is generally feasible only for secondary members like false ceilings and cladding panels.

These kinds of investigation are of interest for defining the global diagnosis strategy and for a first classification of the parts which are unquestionably damaged, the ones which are worthy of a deeper analysis and the ones not significantly affected by the fire.

Table 1 Effect of temperature on selected materials (adapted from [9])

Substance	Typical examples	Conditions	Approx temperat. (°C)
Polyamide (Nylon)	Plastic anchors, automotive and electronic components	Softens	180
		Melts	260
Polymethyl methacrylate	Glazing, automotive lights	Softens	130–200
	Motorcycle helmet visors	Bubbles	250
Polycarbonate	Automotive and signal lights	Softens	140
		Melts	270
PVC	Cables, pipes, ducts	Degrades	100
		Fumes	150
		Browns	200
		Chars	400–500
Glass reinf. polyester	Junction boxes, electrical ducts, lighting devices	Softens	190–230
		Chars	350–480
Solder	Electric and electronic components	Melts	180–190
Aluminium and alloys	Lighting devices, casings, brackets, small mechanical parts	Softens	400
		Melts	600
		Drop formation	650
Glass	Glazing, incandescent lamps	Softens, sharp edges rounded	500–600
		Flowing easily, viscous	800
Borosilicate glass	Outer bulb of gas discharge lamps (mercury, sodium)	Softens	800
Brass	Taps, fasteners	Melts (particul. at edges)	900–1000
		Drop formation	950–1050
Copper	Wiring, cables	Melts	1000–1100
Cast iron	Pipes, manhole covers, drainage gratings	Melts	1100–1200
		Drop formation	1150–1250
Bronze	Bearings, fittings	Edges rounded	900
		Drop formation	900–1000
Paints		Deteriorates	100
		Destroyed	250

2.2. Local Conditions of the Damaged Lining

At the scale of the lining cross section the effects of the thermal gradients and the interaction between concrete and reinforcement can be observed (cracking, spalling, rebar buckling).

Diffuse micro-cracks are one inherent effect of concrete heating due to the diverging thermal strains of cement matrix and aggregate [9]. Nonetheless, a map of distinct cracks may appear on the surface after cooling (pattern cracking—Figure 2), as a result of the irreversible plastic contraction (transient creep) due to the restrained thermal dilatation in the hot phase. The geometry of this pattern can be mapped by means of digital image processing techniques and some tentative correlations have been found between the area of the irregular cells enclosed by the cracks and the severity of fire damage [12].

Larger isolated cracks may also develop through the lining, as a consequence of either the thermal gradients or any local failure. Not emerging radial fractures, as those ascribable to the hoop tension at the extrados of circular tunnels (see Figure 1), can be hardly revealed by the common ND techniques for concrete structures. Conversely, the depth of surface-opening cracks can be assessed via the established ultrasonic pulse diffraction method [13, 14] or more advanced wave propagation analyses [15].

Delamination cracks running parallel to the exposed surface are another possible defect resulting from fire exposure. They can be generally detected by tapping the structure with a hammer and checking the acoustic response by ear. This approach takes roots in the low frequency flexural vibrations governing the impact response of the detached concrete for a sufficiently low thickness/extent ratio (Figure 3).

In fact, the method can be made more objective and rigorous by recording and properly processing the sound of the hit surface, leading to the impact acoustics technique [16, 17].

In case of relatively small and deep defects a different vibration mechanism in the ultrasonic range is exploited. This is based on the propagation of short pulses

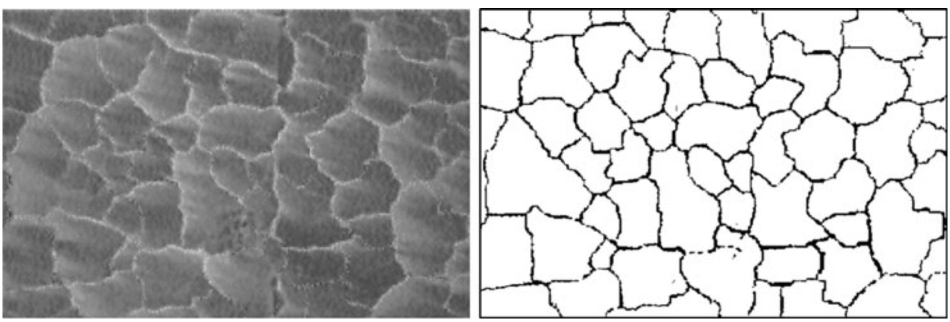


Figure 2. Crack pattern over 1 m^2 lining in the Mont Blanc tunnel and shape of the irregular cells highlighted via digital image processing (skeletonization and filtering) [12].

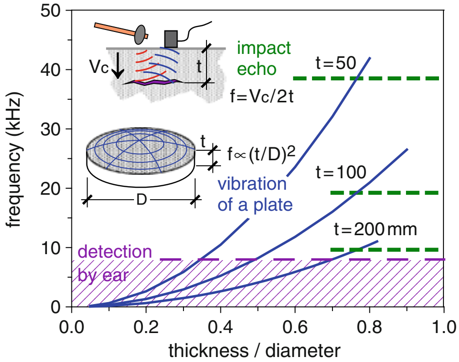


Figure 3. Mechanisms governing the acoustic response of a delaminated layer.

(20–100 μs) which are partly back-reflected by any sizeable discontinuity in the material and then detected in the form of delayed echoes via a sensor applied on the hit surface (impact- and pulse-echo techniques) [18]. The latter approach allows also to assess the local thickness of the concrete lining and to check the effective grouting of the outer annulus in segmental tunnels. The same echo principle is applied to electromagnetic pulses in the Ground Penetrating Radar technique, which is remarkably faster to implement but rather sketchy and can be profitably used just for a first classification of the damaged zones [2].

It has to be remarked that the preliminary detection of delamination and through cracks is of interest not only for their impact on the structural integrity, but also for their influence on the results of most Non-Destructive investigation techniques.

2.3. Residual Properties of the Material

At the smallest scale of observation, the object are the residual material properties at a point. Due to the low thermal diffusivity of concrete and to the consequent steep thermal gradients that develop during a fire, the lining has to be regarded as a strongly layered element. This applies both to the mechanical response (compressive and tensile strength, Young's modulus, hardness) and to a number of chemo-physical properties that are markedly affected by the exposure to high temperature (velocity and attenuation of elastic waves, density of micro-cracks, porosity, humidity, chemical composition, colour, etc.) [19, 20].

Such an extensive series of transformations casts the base for the indirect material assessment via the Non-Destructive Testing techniques. Unfortunately, most of the commonly used ND test methods for reinforced concrete structures are intended to smooth the inherent material heterogeneity due to the coarse aggregate. Hence, they are not very effective in detecting the sharp variations of the physical properties taking place in the concrete cover of fire damaged members. On the other hand, the apparent damage that generally characterizes the exposed surface makes partially-destructive methods acceptable, extending the range of the available options.

One first approach simply consists in the evaluation of the average response of the lining surface via well established techniques (Table 2, column A). As an example, the Schmidt's rebound hammer is an easy tool to sound the elastic and inelastic deformability of the first 20–30 mm layer [13]. It allows a quick mapping of the damage severity, even being sensitive just to a heavy material decay (Figure 4) and not applicable to spalled or delaminated concrete [20]. Also the removal of fragments by chiselling is a way to ascertain the soundness and increasing depth and to make visible the possible discoloration due to the exposure to high temperature [9]. In closer connection to the residual compressive strength of the surface layer is the pull-out strength of undercut anchors (CAPO test [13, 14, 20]), at the cost of a slower execution (about half an hour per test).

Another more rigorous approach is based on the point-by-point analyses of concrete cores (Table 2—column B). Taking advantage of a number of chemo-physical properties that can be measured on very small samples or thin slices, a profile of the material deterioration and increasing depth can be worked out. A first set of this kind of methods (ultrasonic pulse velocity, dynamic Young's modulus, thermal analyses, X-ray diffraction) is presented in a up-to-date report [12], including a systematic description of the principle of each test, the experimental devices and procedures, the interpretation and reliability of the results. Other proposals can be found in distinct papers, involving mechanical testing at a small scale (splitting [21] and punching of disks [22]), colour measurement and water

Table 2
Possible approaches to the assessment of the local lining conditions

(A) Average response of the concrete cover	(B) Point by point response of small samples	(C) Special interpretation techniques
Hammer tapping	Small scale mechanical testing	Sonic refraction
Hammer and chisel	While drilling tests	Impact-/pulse-echo
Schmidt rebound hammer	Dynamic Young's modulus	Impulse response
Windsor probe	Ultrasonic Pulse Velocity	Analysis of Surface Waves
Cut and Pull Out test	Porosimetry	Velocity and transmission
BRE internal fracture	Micro-crack density analysis	Spectral Analysis (SASW)
Ultrasonic Pulse Velocity (UPV)	Air permeability	Modal Analysis (MASW)
	Water absorption	Ground Penetr. Radar (GPR):
	Colorimetry	Wide Angle Reflection Refraction (WARR)
	Petrographic examination	Common Middle Point (CMP)
	Differential Thermal An. (DTA)	Electric resistivity and capacity
	Thermo-Gravimetric An. (TGA)	Quantitative impulse-thermography
	Dilatometry (TMA)	
	X ray diffraction (XRD)	
	Laser Induced Breakdown Spectroscopy (LIBS)	
	Thermoluminescence	
	Chemical analysis	

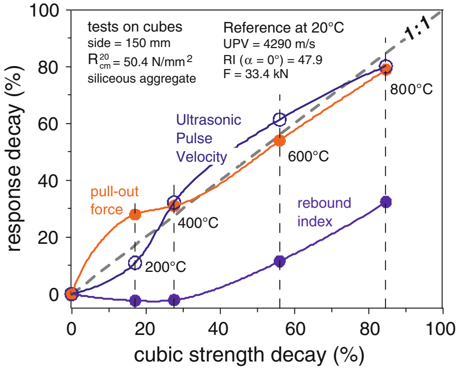


Figure 4. Sensitivity to thermal damage of some conventional techniques for the surface assessment of the lining.

absorption [23, 24], micro cracks density [25] and gas permeability [26]. The multifarious information gained from microscopical observation of polished thin-section specimens are grouped in the petrographic examination techniques [27, 28].

The general remark on this thorough approach is that repeating a laboratory analysis several times on each concrete core is quite a demanding task, and that no immediate feedback is provided for guiding further tests on the inspected structure. One exception are the so called "while drilling" techniques, in which the operation of cutting a core or drilling a hole is regarded in itself as a way to continuously scan the material soundness at increasing depth [29, 30].

A promising alternative to the local material inspection is a series of advanced techniques for the interpretation of the overall response of the concrete lining under different kinds of input (mechanical pulses, electromagnetic waves, electric fields, etc.—column C in Table 2). They can be actually regarded as the application at a smaller scale of the methods that are commonly used in geophysics to reveal the layered structure of soils. Among them, the study of the dispersive waves (Rayleigh and Lamb waves) is of great interest for the potential to provide a tomography of the elastic properties and shear wave velocity within the wall thickness [31]. A specific application to the post-fire assessment of the Mont Blanc tunnel [4] showed the effectiveness of this approach, though a number of sensors had to be repeatedly mounted on the tested areas and a burdensome interpretation procedure had to be followed. By this point of view, an improvement will probably derive from the option of sweeping the surface with a contactless sensor moved by an automatic positioning system [32], which is presently a general trend in advanced ultrasonic testing of large infrastructures.

From the above discussion, it transpires that a wide assortment of tools for the assessment of fire damaged tunnel linings is available, ranging from well established and relatively simple techniques to the latest and rather sophisticated test methods. However, the majority of them are not always suited to the challenging operational conditions and the stringent time limitations which characterize the problem at issue. Keeping the in situ viability in mind, some innovative techniques for the material assessment at the local scale have been proposed by the author in recent years. A brief summary of their pros and cons is given in the following sections.

3. While-drilling Techniques

The wide assortment of material analyses based on the extraction of a core inspires the idea to consider the operation of drilling the tunnel lining as a further way to scan the concrete soundness at increasing depth. This is a common practice in geophysical prospection, but not many systematic studies have been published as concerns the assessment of construction materials.

The application of the core-drilling resistance to the inspection of fire damaged concrete has been investigated in a recent paper [33]. To this purpose, a common core-drill has been fitted with a set of sensors for measuring the main functioning parameters (rotational speed, longitudinal stroke, exerted thrust and electric power consumption). One meaningful result that can be worked out for ascertaining the quality of the material is the time taken for a unit advance of the tool (s/mm). Though very simple to determine, this value is markedly influenced by the exerted thrust and the peripheral speed of the cutting tool. As an alternative, the net work spent per unit notched volume (J/mm^3) can be calculated (work = power × time). This quantity is less affected by the working variables, because any variation of the exerted thrust or the peripheral speed has opposite effects on the power input and the drilling time.

Both parameters proved to be fairly sensitive to thermal damage (Figure 5) and not much influenced by the inherent heterogeneity of the material. The only limitation of the method regards its viability for the extensive testing of a tunnel ceiling, due the relatively heavy drill and to the need for water and AC power supply.

Another option is to monitor the destructive drilling of holes (i.e. not intended to provide any intact sample of the tested material). Several examples of this kind

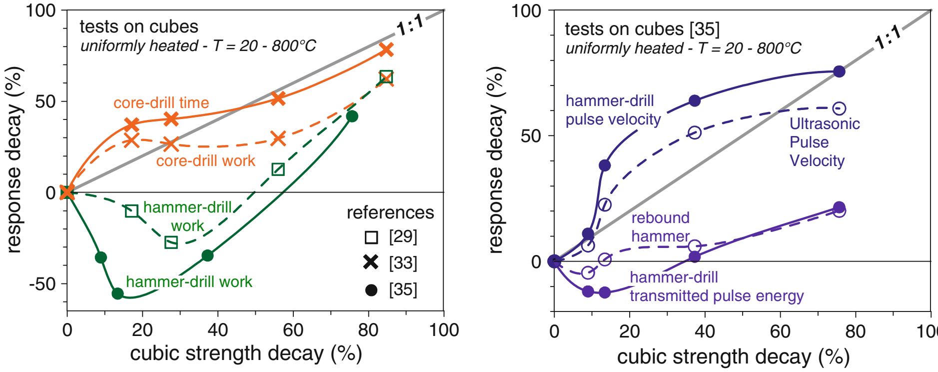


Figure 5. Sensitivity to thermal damage of different drilling resistance indicators.

of approach can be found in the literature, dealing with the assessment of metals, timber, mortar and stones. A specific implementation to fire damaged concrete was performed in the Mont Blanc tunnel by means of an instrumented rig for micropile and tieback drilling [4]. The large size and the coarse accuracy of this kind of equipment look proportionate just for rather thick and deeply damaged linings, as was the case of the structure in question.

At a smaller scale, the same principle has been applied to an instrumented battery hammer-drill [29] fitted with an ordinary masonry bit (diameter ~10 mm). Thanks to the strong hammering action of the drill (pulse amplitude ~10 kN), here the results are not influenced by the thrust exerted by the operator. On the other hand, the local disturbances due to the hard aggregate pebbles require to average some tests in order to recognize a clear trend in the material response. The remarkable advantage of this technique is the very fast and easy implementation, even in the case of spalled concrete or roughly finished shotcrete, as was proved in the assessment of a motorway tunnel following a series of hydrocarbon-pool fire tests [34]. The main drawback is the initial opposite trend of the material response, since a higher work is required to drill slightly damaged concrete and a sizeable decrease can be recognized just for a decay of the compressive strength exceeding 50% (Figure 5).

Further studies have been recently carried out, aimed to go beyond this limitation by monitoring other working parameters of the hammer-drill [35]. One direction is focused on the propagation along the bit body of the compression pulses induced by the hammering mechanism. The stress-wave generated by each impact propagates towards the tip of the drill bit, where it is partly reflected in the form of a tensile stress-wave (Figure 6). This phenomenon can be effectively captured by means of strain gages glued on the bit shank and connected to a wide band signal conditioner via a slip-ring.

In case of a severe fire damage, the considerable mismatch between the elastic properties of the steel bit and the drilled material (namely their acoustic impedance) translates into a high reflection of the incident wave. Hence, an indicator of the residual material integrity can be associated to the transmitted share of the pulse energy and then defined as $(A_i - A_r)/A_i$, where A_i and A_r are the areas enveloped by the time plots of the incident and the reflected waves. In principle, the device can be regarded as a scanning rebound hammer, which repeatedly senses the local hardness of concrete at increasing depth. Unfortunately, as in the original rebound hammer, the sensitivity to thermal damage is rather poor (Figure 5), also in consideration of the dispersion of the results (coefficient of variation = 0.15 in homogeneous concrete).

Another, more promising parameter to consider is the velocity of propagation of the pulses transmitted in the inspected material. By applying an ultrasonic sensor on the lining surface, while drilling a hole through its thickness, the pulse time of flight from the tip of the drill bit is continuously measured. This allows to work out the profile of the wave velocity within the concrete wall, which is known to be an effective indicator of the fire damage.

The results obtained on uniformly heated concrete cubes confirm the high sensitivity of this parameter (Figure 5). Other tests, concerning the direct pulse

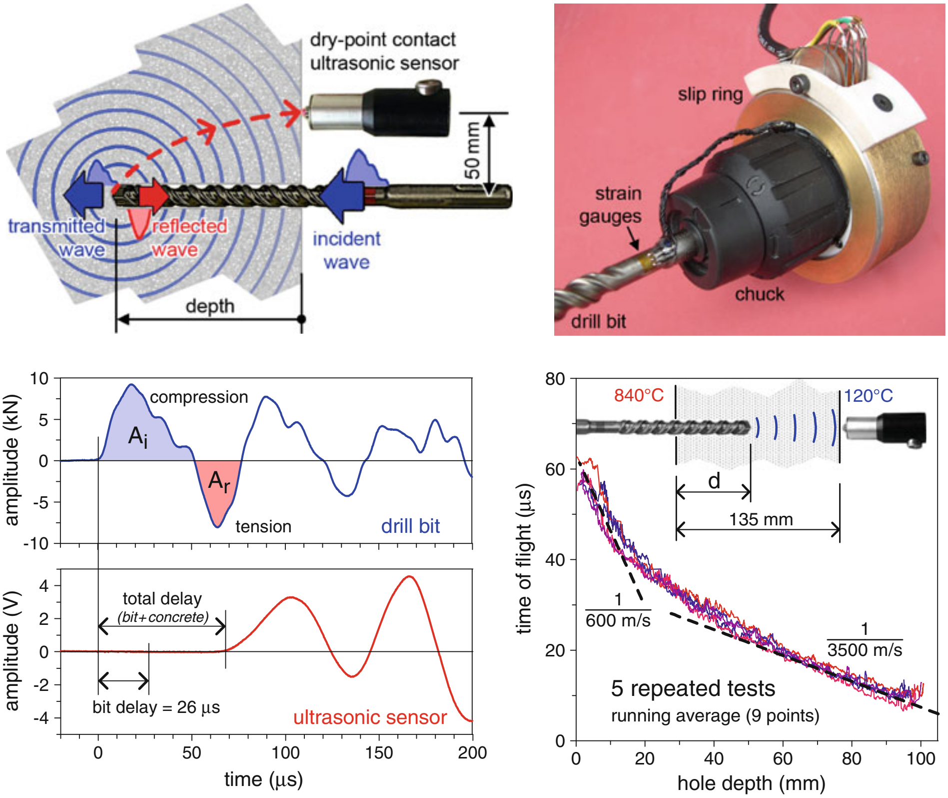


Figure 6. Working principle of the Hammer-Drill Pulse Propagation method; modified chuck for strain signal transmission and pulse time-of-flight through a thermally damaged concrete panel.

transmission through the thickness of a thermally damaged concrete panel, bring to light the high potential and the remarkable repeatability of this technique (Figure 6). The panel (thickness = 135 mm) was submitted to a thermal gradient by exposing one face to the radiant heating flux of an electric furnace (T = 840–120°C). The wide range of temperatures translates into a considerable change in the local pulse velocity and then in the slope of the time of flight versus bit-probe distance diagram (see also Figure 10).

Further studies are in progress, aimed at a more accurate interpretation of the results in the case of indirect transmission (drill and sensor on the same side), which is definitely more relevant to tunnels.

Summing up, different parameters can be monitored while drilling a core or a simple hole in the concrete lining (time, work, hardness, wave velocity). Besides their different sensitivity to thermal damage, they are also a function of the equipment and the operational details, to the point that the obtained values can be hardly regarded as intrinsic material properties. Nonetheless, the interesting feature of this approach is the ability to continuously scan the concrete response at increasing depth, even in the presence of strong gradients of the mechanical properties. In the common case of shallow deterioration of relatively thick members, a steady reference value of the drilling resistance is reached in the end of the process, when the deep unheated material is inspected. This allows to consider the response profiles in relative terms, with no need for specific calibration curves to determine the damaged depth.

Other remarkable advantages to be considered are the immediate availability of the results and their possible combination with the analysis of the removed material or the remaining hole [33]. Also in the case of destructive drilling, not providing any intact material sample, the ensuing ground-concrete powder can be the object of additional investigations, as discussed in the next section.

4. Analysis of Drilling Powder Samples

A number of physicochemical analyses suitable for the point-by-point inspection of fire damaged concrete (see Table 2—column B) require a preliminary grinding of the material into a fine powder (X-ray diffraction, thermo-luminescence, Differential Thermal Analysis DTA, Thermo-Gravimetric Analysis TGA, etc.). Moreover, some tests that are normally performed on the intact samples, may be in principle carried out also on the material in pulverized form (carbonation depth, colour measurement, etc.). This evidence casts the base for merging the results of the hammer-drill perforation test and the following examination of the ensuing powder. Compared to the ordinary laboratory practice, the main limitation is the impracticality of controlling whether to include or not the coarse aggregate in the sample, leading to some uncertainties for small diameter holes.

In the problem at issue, characterized by steep variations of the investigated properties with the drilling depth, an important requirement is to preserve the order of extraction, so to trace the original location of the powder. A special device has been developed to this purpose, which allows the continuous collection of the ground-concrete streaming through the helical flutes of the drill bit (Carbontest®) [36]. Basically, it consists of a annular head with a circular brush, to be pierced with the drill bit (Figure 7). The head is fitted with a funnel which converges the powder down into a vertical test tube. This can be of transparent material, which will allow to control the regular flow of the powder during drilling and to perform a first visual inspection. A narrow longitudinal cut, thin enough to prevent the particles to pass, makes possible to infiltrate the sample with the liquid chemicals used in some material analyses (e.g. the phenolphthalein solution for the carbonation test).

One first application in the field of fire damage assessment concerns the detection of the pink-red discoloration taking place in heated concrete in the range 300–600°C [23, 24]. In a former study, the processing of the digital image of a core, taken with a consumer-level digital camera, has been regarded as a method for detecting this slight colour variation [34, 37]. The same type of analysis can be performed on the drilling powder collected in the transparent test tube. After having determined the appropriate scale factor between the length of the powder sample and the actual

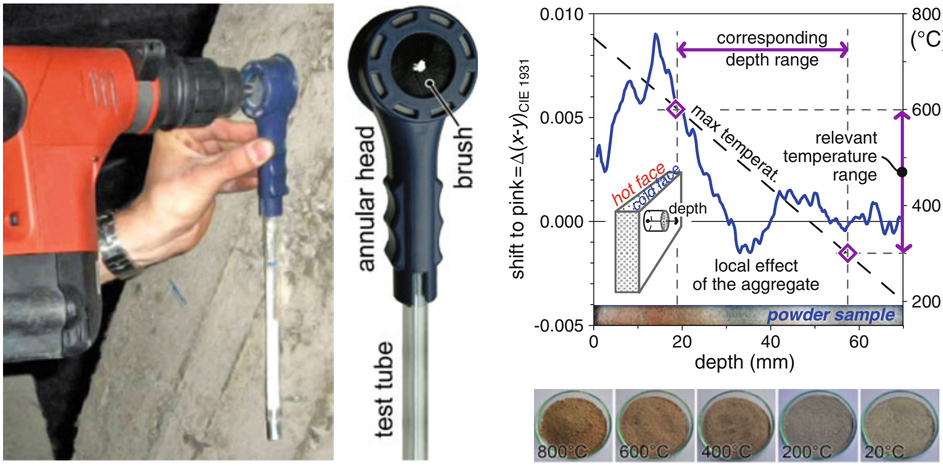


Figure 7. The Carbontest® tool for collecting the drilling powder and discoloration of the ground concrete taken from a heated panel (saturation of pictures uniformly emphasized for readability).

hole depth (about 2:1 for 10 mm bits), the discoloration profile can be plotted (Figure 7). Compared to the conventional analysis of cores, an increased noise is observed, because of the random influence of the coarse aggregate [33]. Nonetheless, the general trend of this material alteration can still be detected by averaging the results of some repeated tests.

It should be noted that discoloration can occur also as a consequence of carbonation and then the depth of penetration of this reaction should be ascertained when old structures are investigated [9]. Moreover, the main source of alkalinity in the pores is portlandite (calcium hydroxide), that decomposes gradually above 450°C and whose content in the cement mortar can be considered as a marker of the maximum experienced temperature [38]. Although the de-hydroxylation of portlandite is a reversible process [39], the actual reinstatement of the pH conditions requires a sustained post-fire moist curing [40], which can be usually ruled out at the time of testing.

In order to check the significance of this aspect in post-fire damage assessment, the cited device has been used to determine the de-alkalinization depth in the same concrete panel that was the object of the Hammer-Drill Pulse Velocity tests (see also Figure 10). An almost uniform 26 mm depth was found (Figure 8), corresponding to a maximum temperature of 455°C. This is in good agreement with the generally accepted range for portlandite decomposition. The result has important implications also on the residual durability of the structure, which may be further impaired by the increased gas permeability of thermally damaged concrete [9].

One further application of the collected drilling-powder regards the Differential Thermal Analysis (DTA), a test that involves the heating of a small sample of ground concrete together with a similar amount of inert material (e.g. aluminium

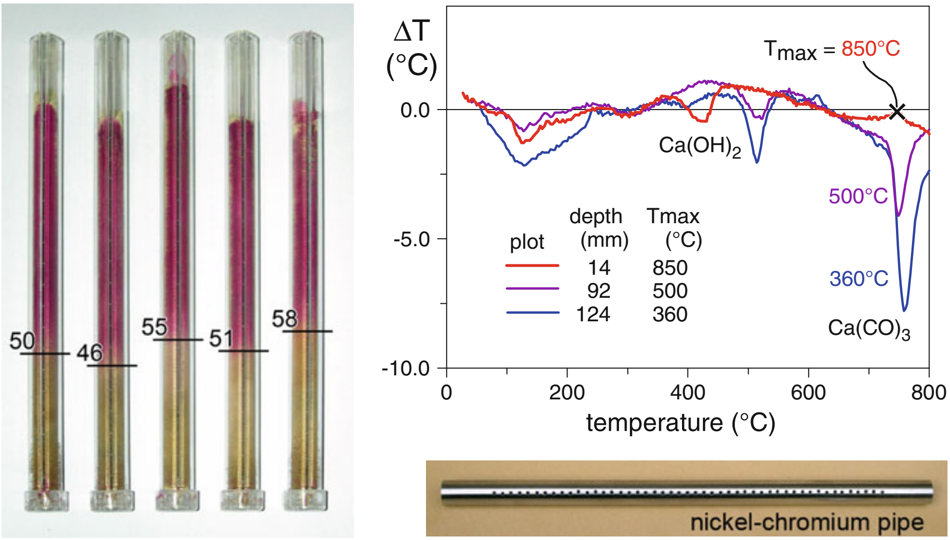


Figure 8. De-alkalinization depth (in mm, scale 2:1) and Differential Thermal plots in powder samples taken by drilling two concrete panels exposed to steep thermal gradients (840–120°C/130 mm and 910–230°C/150 mm, respectively).

oxide Al_2O_3). Their temperature differential is continuously monitored, allowing to reveal any transformation (mostly endothermic) occurring in the tested material. The method has been proposed as a way for analyzing fire damaged concrete, because during this second heating minor or different transformations occur until the maximum temperature already experienced during the fire is exceeded [38]. In the case of a steep temperature gradient in the cover, the DT analysis should be repeated on a series of samples taken at increasing depth, which is quite a demanding procedure.

In order to overcome this limitation, the above described device has been fitted with a metal test tube. The pipe (Figure 8) is made of a thermally stable alloy (nickel–chromium) and is perforated at regular steps along one generatrix, so as to allow to vent the developing gases and to insert a series of thin shielded thermocouples. After collecting the drilling powder, a small amount of aluminium oxide is then added for reference on top of the extracted sample. By heating the pipe in a split-tube furnace (5°C/min) several DT analyses can be performed in one take. Though less rigorous than adopting the standard test procedure and a dedicated device, this method is far less time demanding and still allows to detect the onset of the relevant transformations. The results seem in good agreement with the trends reported in the literature [39]. The anticipated dissociation, compared to unheated portlandite, of the re-hydrated calcium-oxide (350–500°C) and the disappearance of the peak ascribable to the calcium-carbonate dissociation (700–800°C) are the main features to trace on these thermo-differential plots concerning a 150 mm thick concrete panel submitted to a uniform thermal gradient (T = 910–230°C).

It has to be noted that the Carbontest® tool in its present form is suitable just for collecting the drilling powder from almost vertical members. A modified version has to be developed for overhead operation in the tunnel ceiling.

5. Ultrasonic Pulse Refraction

As already discussed, the velocity of sound in concrete is one of the most responsive indicators of the thermal damage, due to the pronounced temperature sensitivity of the Young's modulus and to the synergistic effect of pore drying (see the Ultrasonic Pulse Velocity plots in Figures 4, 5). In the case of a strongly layered material, useful information on the pulse velocity profile can be gained via the indirect UPV technique, which is based on the refraction of ultrasonic compression (P) waves [13, 14]. In this method the measurement of the pulse arrival time

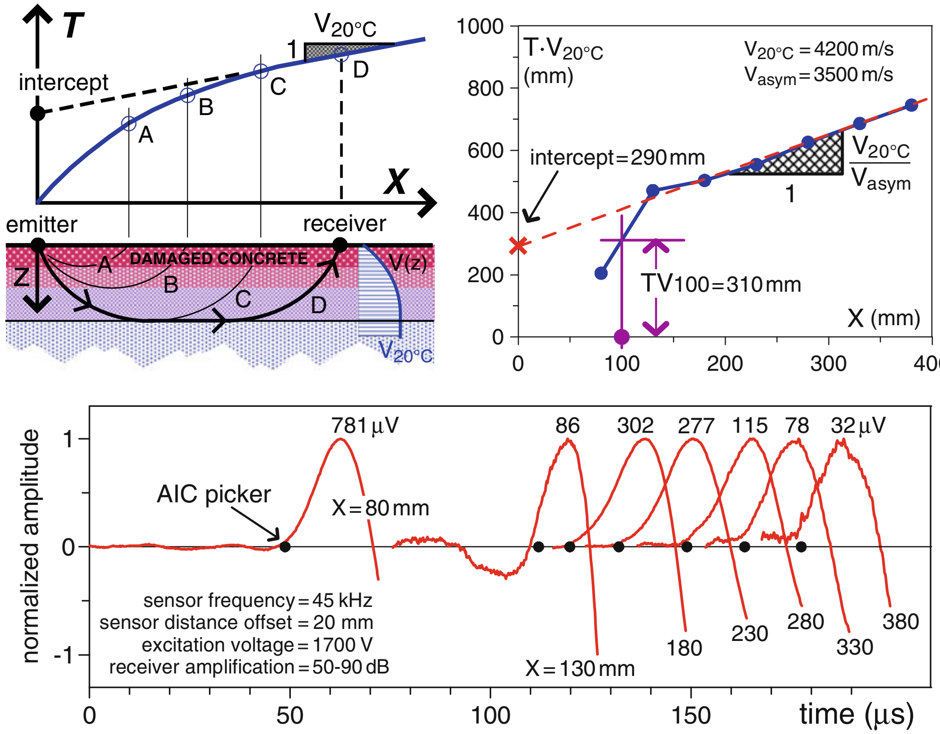


Figure 9. Minimum travel-time path in the Ultrasonic Pulse Refraction method and shape parameters of the experimental X-T·$V_{20°C}$ curve obtained from a thermally damaged concrete panel; onset time picking and first peak amplitude for different distances between the probes.

is performed by applying both the emitting and the receiving probes on the same face of the investigated element (Figure 9). Under the assumption that the material velocity rises at increasing depth (that is the rule after a fire), the curved trajectory of the sound wave corresponding to the minimum travel time is the best compromise between reducing the covered distance via a shallow path and exploiting a longer but faster way through the deep undamaged layers [41]. Therefore, the maximum depth involved in this pulse propagation is a function of the distance X between the probes, and a series of repeated measurements of the pulse arrival time T at increasing distance allows to sound deeper and deeper layers of the structure. The outcome is a plot on the X-T axes whose interpretation has been the object of different studies in the literature [2, 42].

One important property of this experimental diagram is that the final slope corresponds to the reciprocal of the asymptotic velocity V_{asym} of the deepest concrete inspected. This tends to the value $V_{20°C}$ in the undamaged material for thick members and relatively short fire durations. After multiplying the ordinate by the velocity in pristine concrete ($T \rightarrow T{\cdot}V_{20°C}$), the geometric features of this normalized plot are controlled just by the profile of the relative velocity $V(z)/V_{20°C}$. Among them, 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 sizably damaged concrete (Figure 9). On the other hand, the arrival time with adjacent transducers ($X = 100$ mm) is strongly related to the pulse velocity in the most damaged concrete at the surface. A series of numerical simulations of different thermal transients involving a broad range of concretes revealed a little influence on this relationship of either the heating conditions or the inherent material sensitivity to high temperature [34]. Then, no preliminary information on the member under investigation are needed for the application of this method.

Besides the problem of interpreting the results, there are some technical difficulties to be solved in order to obtain a reliable onsite measurement of the arrival time for each relative position of the sensors. In fact, the indirect pulse transmission is based on the very weak compression edge waves propagating from the emitter in the radial direction. These are to be distinguished from the slower and more intense Rayleigh wave train which follows [43]. Also the influence of the surface cracks may considerably influence the results by precluding some transmission paths.

As an example, the method has been implemented on the same concrete panel that was the object of the above discussed Hammer-Drill Pulse Velocity tests (see Figure 6). A customized ultrasonic pulse generator has been used (IMG 5100 CSD—pulse amplitude 1700 V), fitted with 45 kHz probes, a high sensitivity amplifier (0–100 dB) and a 12 bit/10 MHz digitizer. In order to accurately recognize the pulse onset from the background noise in the received signal, an automatic time picking algorithm based on the Maeda formulation of the Akaike Information Criterion was implemented [44]. The unsteady attenuation of the first received peak at increasing distance is a sign of the random effect of some surface cracks (see the $X = 130$ mm plot in Figure 9).

These results have then been interpreted by using the cited numerical correlations (Figure 10). They are intended to assess the depth at which the concrete

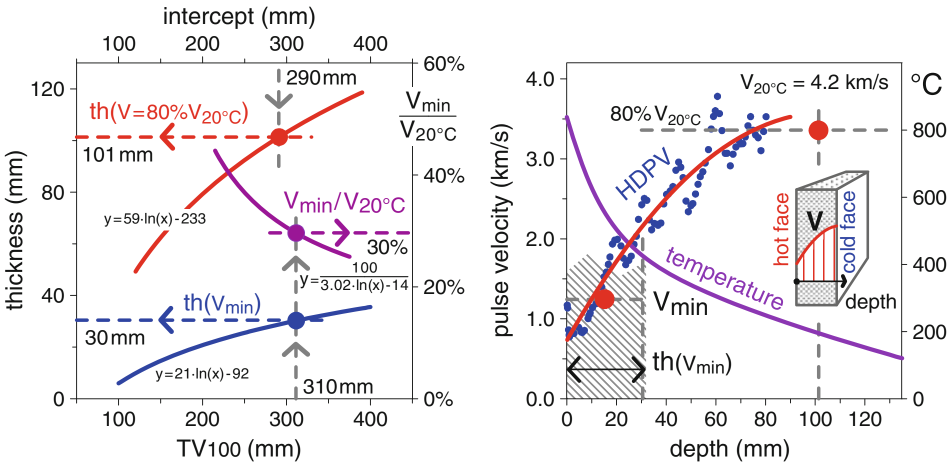


Figure 10. Correlation chart for the assessment of the pulse velocity profile (V_{min} at the surface and 80% $V_{20°C}$ threshold) and comparison with the Hammer-Drill Pulse Velocity (see Figure 6).

exhibits a fairly low decay of the pulse velocity (V = 80% $V_{20°C}$) and the residual velocity V_{min} in the most exposed layer of thickness TH(V_{min}). The estimated values are consistent with the velocity profile worked out by differentiating the time-distance plots of the Hammer-Drill Pulse Velocity method (Figure 6).

Summing up, the Ultrasonic Pulse Refraction is a sensitive and truly non-destructive technique with good potentials in the assessment of the fire damage undergone by concrete tunnel linings. As already stated, the onsite recording of the X-T plot is generally a demanding task (about half and hour per test), especially in the presence of cracks. Moreover, the method cannot be easily implemented on rough surfaces, as in the case of shotcrete or in the occurrence of spalling.

6. Concluding Remarks

The assessment of fire damage in concrete tunnel linings is a multifaceted problem involving different branches of expertise at different scales of observation, from the whole fire scenario to the local material condition at a point.

As in any concrete structure surviving a fire, the strongly layered nature of the damaged material, with possible formation of cracks, delamination of the cover and more or less violent separation of fragments (spalling), require some discernment in the selection of the appropriate investigation techniques. This is even more so for tunnels, due to the higher fire severity, the difficult operational conditions and the need to limit the duration of the traffic disruption.

As concerns the local inspection of the lining, a general overview on the available test methods revealed that most of them are rather unsatisfactory, being either fast but sketchy or accurate but time consuming. Some new techniques have been developed to this purpose, keeping in mind the requirements of the in situ viability and the prompt availability of the results.

Among them, the core- and hammer-drilling techniques stand out for their fast and easy implementation, with no influence of cracking, surface roughness and spalling. Of particular interest is the Hammer-Drill Pulse Velocity method, that proved to be very sensitive to fire damage gradients while keeping the ease of use of a battery powered drill.

This latter method can be profitably combined with the following analysis of the drilling powder. A special tool was developed aimed at collecting the ground concrete in a sorted way, so to keep trace of the original location in the liner thickness. The assessment of colour alteration, the measurement of the de-alkalinization depth and the Multiple Differential Thermal Analysis are possible investigations on the powdered concrete which may corroborate the drilling resistance results.

The correct implementation and the easy interpretation of the Ultrasonic Pulse Refraction test are the object of a third line of research. The method confirmed to be responsive and truly non-destructive, but a special attention is required in order to rule out the possible influence of cracks, not to speak about the requirement of an almost flat surface, which makes it generally not appropriate for shotcrete or in the occurrence of spalling.

In conclusion, some directions for future progress in this still open issue can be traced. The added value provided by the combination of different techniques in terms of efficiency, reliability and completeness is a first important aspect that might be increasingly considered already while planning the general strategy for the assessment of a fire damaged tunnel [45]. Also some advanced interpretation techniques, like the 3D imaging of the pulse-echo results and the study of surface waves (velocity, spectrum and modes), are promising tools to exploit, provided that a parallel development in contactless sensors and automated implementation systems will allow to reach the efficiency required by such a demanding large-scale onsite application.

References

1. FIT—European Thematic Network Fire in Tunnels (2005) Technical report Part 1 'Design fire scenarios'. http://www.etnfit.net/. Accessed 20 November 2010
2. Abraham O, Dérobert X (2003) Non-destructive testing of fired tunnel walls: the Mont-Blanc Tunnel case study. NDT&E Int 36:411–418
3. Ulm FJ, Acker P, Lévy M (1999) The "Chunnel" fire. II: analysis of concrete damage. J Eng Mech 125(3):283–289
4. Karray M, Lefebvre G, Faure RM (2004) Results of surface waves testing in the investigation of the Mont-Blanc tunnel after the 1999 fire. In: da Fonseca AV, Mayne PW (eds) Proc ISC-2 Geotech & Geophys Site Charact Millpress, Rotterdam, pp 1481–1487
5. Pichler C, Lackner R, Mang HA (2006) Safety assessment of concrete tunnel linings under fire load. J Struct Eng 132:961–969
6. International Tunnelling Association—WG 6 Maintenance and Repair (2004) Guidelines for structural fire resistance for road tunnels. http://www.ita-aites.org/index.php?id=28&L=0. Accessed 21 November 2010

7. Leitner A (2001) The fire catastrophe in the Tauern Tunnel: experience and conclusions for the Austrian guidelines. Tunn Undergr Space Technol 16:217–223
8. Henke A, Gagliardi M (2004) The 2001 Gotthard road tunnel fire. Tunn Manag Int 7(1):33–39
9. CIB W14 report (1990) Repairability of fire damaged structures. In: Drysdale DD, Schneider U (eds) Special Issue Fire Saf J 16:251–336
10. Concrete Society (2008) Assessment and repair of fire damaged concrete structures. Technical Report 68
11. Beard A, Carvel R (eds) (2005) The handbook of tunnel fire safety. Thomas Telford, London
12. Laboratoire Central des Ponts et Chaussées (2005) Présentation des techniques de diagnostic de l'etat d'un béton soumis à un incendie. Report ME 62 (in French)
13. Bungey JH (1996) The testing of concrete in structures. Blackey, Glasgow
14. Naik TR, Malhotra VM, Popovics JS (2004) The ultrasonic pulse velocity method. In: Malhotra VM, Carino NJ (eds) CRC handbook on nondestructive testing of concrete CRC Press LLC, Boca Raton, FL
15. Aggelis DG, Shiotani T, Polyzos D (2009) Characterization of surface crack depth and repair evaluation using Rayleigh waves. Cem Concr Compos 31:77–83
16. Davis AG, Lim MK, Germann Petersen C (2005) Rapid and economical evaluation of concrete tunnel linings with impulse response and impulse radar non-destructive methods. NDT&E Int 38(3):181–186
17. Felicetti R (2010) Assessment of an industrial pavement via the impact acoustics method. Eur J Environ Civ Eng 14(4):427–439
18. Krause M, Bärmann M, Frielinghaus R et al (1997) Comparison of pulse-echo methods for testing concrete. NDT&E Int 30(4):195–204
19. RILEM (1985) Properties of materials at high temperatures: concrete. In: Schneider U (ed) Dep Civ Eng Univ Kassel, Germany
20. Felicetti R, Gambarova PG (2008) Expertise and assessment of materials and structures after fire. In: FIB Task Group 4.3: Fire design of concrete structures—structural behaviour and assessment. Fib Bull 46:63–114
21. dos Santos JR, Branco FA, de Brito J (2002) Assessment of concrete structures subjected to fire—the FB test. Mag Concr Res 54(3):203–208
22. Benedetti A, Mangoni E (2005) Damage assessment in actual fire situations by means of non-destructive techniques and concrete tests. In: Gambarova P, Felicetti R, Meda A, Riva P (eds) Proc Int Workshop Fire Design of Concrete Structures: what Now? What Next?—fib Task Group 4.3, Starrylink, Bergamo, pp 231–239
23. Annerel E, Taerwe L (2008) Approaches for the assessment of the residual strength of concrete exposed to fire. In: Alexander MG, Beushausen H, Dehn F, Moyo P (eds) Proc 2nd Int Conf Conc Repair, Rehabil Retrofit (ICCRRR08). Taylor & Francis, UK, pp 245–246
24. Short N, Purkiss J, Guise S (2001) Assessment of fire damaged concrete using colour image analysis. Constr Build Mater 15:9–15
25. Short N, Purkiss J, Guise S (2002) Assessment of fire-damaged concrete using crack density measurements. Struct Concr 3(3):7
26. Dilek U (2007) Assessment of fire damage to a reinforced concrete structure during construction. ASCE J Perform Constr Facil 21(4):257–263
27. ASTM C856 (2004) Standard practice for petrographic examination of hardened concrete. ASTM Int, Philadelphia
28. Ingham JP (2009) Application of petrographic examination techniques to the assessment of fire-damaged concrete and masonry structures. Mat Charact 60:700–709

29. Felicetti R (2006) The drilling resistance test for the assessment of fire damaged concrete. J Cem Concr Compos 28:321–329
30. Felicetti R (2009) Combined while-drilling techniques for the assessment of the fire damaged concrete cover. Int Conf Appl Struct Fire Eng, Prague, pp 208–215. http://eurofiredesign.fsv.cvut.cz/Proceedings/4th_session.pdf
31. Al Wardany R (2005) Caractérisation non destructive des structures en béton au moyen des ondes dispersives de Rayleigh et de Lamb, PhD dissertation, University of Sherbrooke (in French)
32. Piwakowski B, Safinowski P (2009) Non-destructive non-contact air-coupled concrete evaluation by an ultrasound automated device, In: Abraham O, Dérobert X (eds) Proc 7th Int Symp Nondestruct Test Civil Eng—NDT-CE'09, Nantes (France), pp 603–608 www.ndt.net/article/ndtce2009/papers/36.pdf
33. Felicetti R (2011) Assessment of the deteriorated concrete cover by combined while-drilling techniques. ASCE J Infrastruct Syst (in publication)
34. Colombo M, Felicetti R (2007) New NDT techniques for the assessment of fire-damaged concrete structures. Fire Saf J 42:461–472
35. Felicetti R (2011) Assessment of fire damaged concrete via the Hammer-Drill Pulse Transmission technique. In: Büyüköztürk O, Taşdemir MA, Güneş O, Akkaya Y (eds) Proc Int Symp Non-Destruct Test Mat Struct (NDTMS 2011) Springer, Istanbul
36. Felicetti R (2010) Analysis of sorted powder samples for the assessment of deteriorated concrete, In: Castro-Borges P, Moreno EI, Sakai K, Gjorv O, Banthia N (eds) Proc 6th Int Conf Concr under Severe Condit Environ Load (CONSEC'10). CRC Press, pp 1123–1129
37. Felicetti R (2005) Digital-camera colorimetry for the assessment of fire-damaged concrete. In: Gambarova P, Felicetti R, Meda A, Riva P (eds) Proc Int Workshop Fire Design of Concrete Structures: what Now? What Next?—fib Task Group 4.3. Starrylink, Bergamo, pp 211–220
38. Handoo SK, Agarwal S, Agarwal SK (2002) Physicochemical, mineralogical, and morphological characteristics of concrete exposed to elevated temperatures. Cem Concr Res 32:1009–1018
39. Alarcon-Ruiz L, Platret G, Massieu E, Ehrlacher A (2005) The use of thermal analysis in assessing the effect of temperature on a cement paste. Cem Concr Res 35:609–613
40. Poon C-S, Azhar S, Anson M, Wong Y-L (2001) Strength and durability recovery of fire damaged concrete after post-fire-curing. Cem Concr Res 31:1307–1318
41. Greenhalgh SA, King DW (1981) Curved raypath interpretation of seismic refraction data. Geophys Prospect 29:853–882
42. Benedetti A (1998) On the ultrasonic pulse propagation into fire damaged concrete. ACI Struct J 96(3):257–271
43. Qixian L, Bungey JH (1996) Using compression wave ultrasonic transducers to measure the velocity of surface waves and hence determine dynamic modulus of elasticity for concrete. Constr Build Mat 10(4):237–242
44. Kurz JH, Grosse CU, Reinhardt H-W (2005) Strategies for reliable automatic onset time picking of acoustic emissions and of ultrasound signals in concrete. Ultrasonics 43:538–546
45. Breysse D, Soutsos M, Felicetti R et al (2009) How to improve the quality of concrete assessment by combining several NDT measurements. In: Abraham O, Dérobert X (eds) Proc 7th Int Symp Nondestruct Test Civil Eng—NDT-CE'09, Nantes (France), pp 399–406. www.ndt.net/article/ndtce2009/papers/149.pdf