On the tensile behaviour of thermally-damaged concrete

P. Bamonte & R. Felicetti
Department of Structural Engineering, Politecnico di Milano, Milan, Italy

ABSTRACT: The mechanical properties of thermally-damaged concrete have been the subject of many investigations in the last fifty years. Nonetheless, a noteworthy impulse in this field has been promoted in recent times by the advent of high-performance concrete, because the wide range of materials at issue makes the well-established references difficult to be generalized. This is particularly true for the tensile response, due to the challenging experimental conditions and to the still not standardized test methods. In this paper the results collected by the authors on a number of different concrete mixes are drawn together with the twofold objective to clarify the relations among the most common direct- and indirect-testing techniques and to sketch any possible general trend in the tensile properties of ordinary and special concretes exposed to high temperature.

1 INTRODUCTION

Concrete is known to exhibit a good behaviour at high temperature, owing to its incombustible nature and low thermal diffusivity, that guarantee a slow propagation of thermal transients within the structural members. Nevertheless, a series of chemo-physical transformations occur in the material at increasing temperature (Khoury, 2000): the physically-combined water is released above 100°C; the silicate hydrates decompose above 300°C and the portlandite is dehydrated above 500°C; some aggregates begin to convert or to decompose at different temperatures (release of bound water, α→β SiO_2-conversion of the quartz, decomposition of the limestone). At the same time, the conflicting strains of the aggregate (which expands) and of the cement paste (which shrinks as a consequence of drying) activate a diffuse set of micro-cracks in the transition zone between these two phases. In some cases the thermal strain and the vapour pressure build-up lead to spalling, i.e. the sudden expulsion of concrete chips, that has the effect of exposing deeper layers of concrete to fire, thereby increasing the rate of heat transmission.

The mechanical response of the material is considerably weakened by the above-mentioned phenomena and the compressive strength decreases slowly below 450-500°C and rapidly above 500°C (RILEM, 1985a). Given the irreversible nature of the cited transformations, the decay keeps unchanged after cooling down to room temperature and only minor differences usually occur between the "hot" and the "residual" mechanical properties.

Concerning the other constitutive parameters, a more marked decrease of the Young's modulus is generally observed, whereas the tensile strength often exhibits the most temperature-sensitive behaviour (RILEM, 1985a). However, the decay may be partly offset by the increased ability of thermally-damaged concrete to undertake inelastic strains, by the smoother softening of the cohesive stress along the cracks and by the almost constant fracture energy resulting from the increased crack roughness and branching (Felicetti & Gambarova, 1998). These latter favourable effects are of particular interest when the resistant mechanisms governed by the tensile behaviour of the material are at issue, as in the case of the shear capacity of beams and slabs (Beltrami et al., 1999; Felicetti & Gambarova, 2000), of the bond strength of rebars and fasteners (Bamonte et al., 2006) and of the sensitivity to spalling (Gawin et al., 2006).

Nonetheless, the beneficial influence of the reduced brittleness should also be considered in the characterization of the material tensile behaviour via the indirect testing techniques (bending, splitting, etc), because the actual strength decay may be masked to some extent by the better "structural" response of the small-size concrete specimens (Figure 1). For this reason, well-controlled direct tests are often preferred for material characterization. However, since testing in direct tension at high temperature is hardly possible, these tests are performed in residual conditions (Felicetti et al., 2000).

These general trends are liable to significant variations depending on the mix-design, to the point that the strength of some concretes may be negligible at 500°C (Felicetti & Gambarova, 1998), whereas other concretes still keep a remarkable share of their initial performance (Khoury, 2000). Furthermore, the advent of High-Performance Concretes is leading to a variety of different behaviours: high-strength concrete is usually more temperature-sensitive, because of its high stiffness, low porosity and smaller defects; light-weight concrete has the advantage of the soft and thermally-stable aggregate, but it is prone to explosive spalling; self-compacting concrete is more susceptible to drying and creep strains in the cement paste.

In this paper the main experimental issues concerning the characterization of thermally-damaged concrete in tension will be discussed, in order to recognize the possible connections among the different testing techniques. Then, the results collected by the authors in the last decade will be summarized in a rather harmonized form, with the aim to outline any general relationship between the fracture parameters and the thermal damage experienced by the material.

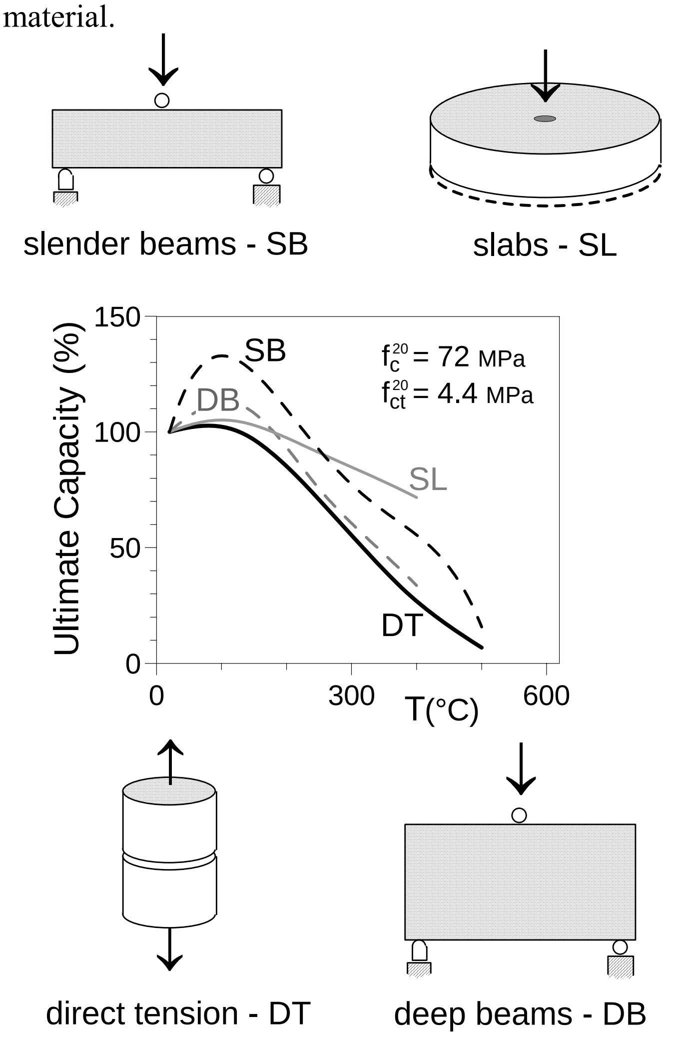

Figure 1. Decay of the residual capacity exhibited by different plain-concrete specimens.

2 MATERIALS AND TESTING TECHNIQUES

In the last decade a number of research projects have been carried out at Politecnico di Milano, on different types of thermally-damaged concrete. Since the objective was in all cases to investigate the material constitutive behaviour, an important issue was to rule out all possible "structural" effects, such as thermal gradients and spalling. This is the reason why the thermal cycles were always slow enough to allow an almost uniform distribution of the thermal damage inside the specimen (heating rate v_h = 0.5-2°C/min).

Given the minor differences from the "hot" response, most of the tests were performed in the residual state, in order to allow a complete control of the testing conditions and an accurate monitoring of the results. The different types of concrete herein considered are as follows:

A. High-Performance Concretes for massive structures: two concretes were examined in order to check their viability in the construction of the secondary containment shells of nuclear power plants (in the framework of the EC project "CONT", Felicetti & Gambarova, 1998). Owing to the relatively-small content of slow-reacting cement, these concretes are characterized by a low hydration heat and are suitable for thick structures. Another distinctive feature is the highly-siliceous aggregate (mostly flint consisting of quartz, opal and calcedonium) which is commonly used in certain regions of Central Europe for its good mechanical properties. However, the relatively-high content of zeolitically-bound water makes flint-based concrete very sensitive to high temperature, since the water is slowly expelled between 100 and 600°C, with relevant volume changes and subsequent splitting.

B. Normal- and High-Performance Light-Weight Concretes: besides a reference ordinary concrete (B1), the main interest in this case was to ascertain the role played by light-weight aggregates in fire conditions, both in a normal-strength (B2, expanded clay) and in a high-performance concrete (B3, dense expanded clay) see Felicetti et al., 2002.

C. High- and Ultra-High Strength Concretes: these concretes were studied in the framework of the Project Brite-Euram HITECO III, including a high-strength concrete (hyposiliceous gabbro aggregate) and two steel fibre-reinforced Ultra-High Strength Concretes (a Compact Reinforced Concrete and a Reactive Powder Concrete, not reported in this paper). Owing to the fruitful co-operation with the research team at the Imperial

College of London, it was possible to run the first-ever reported direct tensile tests in hot conditions (Felicetti et al.,2000).

D. Ordinary concretes for fastener testing: the properties of these concretes are not very peculiar, but particular attention was devoted to the characterization of their tensile behaviour, since the research project was focused on the residual capacity of undercut fasteners (Bamonte et al., 2006).

E. Self-Compacting Concretes of different grades: not many research projects have been carried out so far on the fire behaviour of this type of concrete (Persson, 2004), especially if the tensile properties are at issue.

The previous list does not include several results on steel fiber-reinforced concrete, because in this case the main resistant mechanism is governed by the pull-out of the fibers rather than by the fracture properties of the concrete matrix, that are the object of this paper.

Table 1 summarizes the most significant factors (RILEM, 1985a) influencing the performance at high temperature of the 12 concretes examined in this paper:

- type of aggregate (TA);
- maximum size of the aggregate (d_{max});
- aggregate/fines ratio by mass (a/f);
- water/binder ratio (w/b);
- compressive strength at ambient temperature (f_c^{20}).

With reference to the type of aggregate (TA), its influence on the performance of concrete in tension at high temperature is two-fold. The nature of the aggregate, i.e. its mineralogical composition, usually influences its mechanical decay at high temperature. On the other hand, the structure of the aggregate (crushed or natural round) can influence its fracture properties, especially the fracture energy.

Other important parameters are the maximum size of the aggregate (d_{max}) and the aggregate/fines ratio (a/f): the former because of its role in the bridging effect across a crack, the latter because of its influence on the roughness of the crack surface. Moreover, the aggregate/fines ratio seems to have a significant effect on the strength decay of concrete exposed to high temperature, since the relative decay is smaller for lean mixes than for rich mixes (RILEM, 1985a).

Finally, the last four columns of Table 1 summarize the different mechanical characteristics investigated in the various concretes and the symbols used in the plots throughout the paper: reference is made to the direct- and indirect- (bending and splitting) tensile strengths, taht are the most common in concrete testing (RILEM, 1985a).

Figure 2a summarizes the decay of the compressive strength as a function of the temperature for the 12 concretes under examination. Most of the plots lie below the Eurocode 2 decay curves as a possible consequence of the relatively high values of initial strength. Moreover, the results appear to be very dispersed, because the temperature is not the best parameter to quantify the thermal damage, since the same temperature might be more or less detrimental, depending on the characteristics of the concrete. If concretes with different characteristics are to be compared, as it is the case in this paper, it is more appropriate to refer to a damage variable D, defined on the basis of the decay of the elastic modulus:

$$D(T) = 1 - E(T)/E^{20} \tag{1}$$

Figure 2b confirms that the compressive strength tends to be less sensitive to high temperature than the elastic modulus, since all the diagrams are in the upper part of the plot for almost the whole range of thermal damage.

Table 1. Main characteristics of the concretes considered in this paper.

	TA	d_{max} [mm]	a/f	w/b	f_c^{20} [MPa]	E_c^{20} [GPa]	G_f [J/m^2]	f_t	$f_{t,fl}$	$f_{t,sp}$	symbol
A1	flint	25	4.35	0.43	72	47	245	×	×		◇
A2	flint	25	4.17	0.30	95	53	229	×	×		◆
B1	siliceous	12	5.88	0.67	30	25	64	×		×	✚
B2	sil. + exp. clay	12	4.76	0.63	39	16	64	×		×	✖
B3	sil. + exp. clay	12	3.13	0.33	56	17	65	×		×	✳
C	gabbro	16	3.13	0.29	92	44	161	×			✡
D1	siliceous	28	8.33	0.80	20	19	97		×		□
D2	siliceous	25	4.35	0.41	63	33	146		×	×	■
E1	normal	16	3.57	0.50	52	36	83		×	×	○
E2	normal	16	2.78	0.35	83	39	132		×	×	●
E3	normal	16	2.56	0.33	90	41	142		×	×	△
E4	siliceous	4.5	2.33	0.31	125	42	42		×		▲

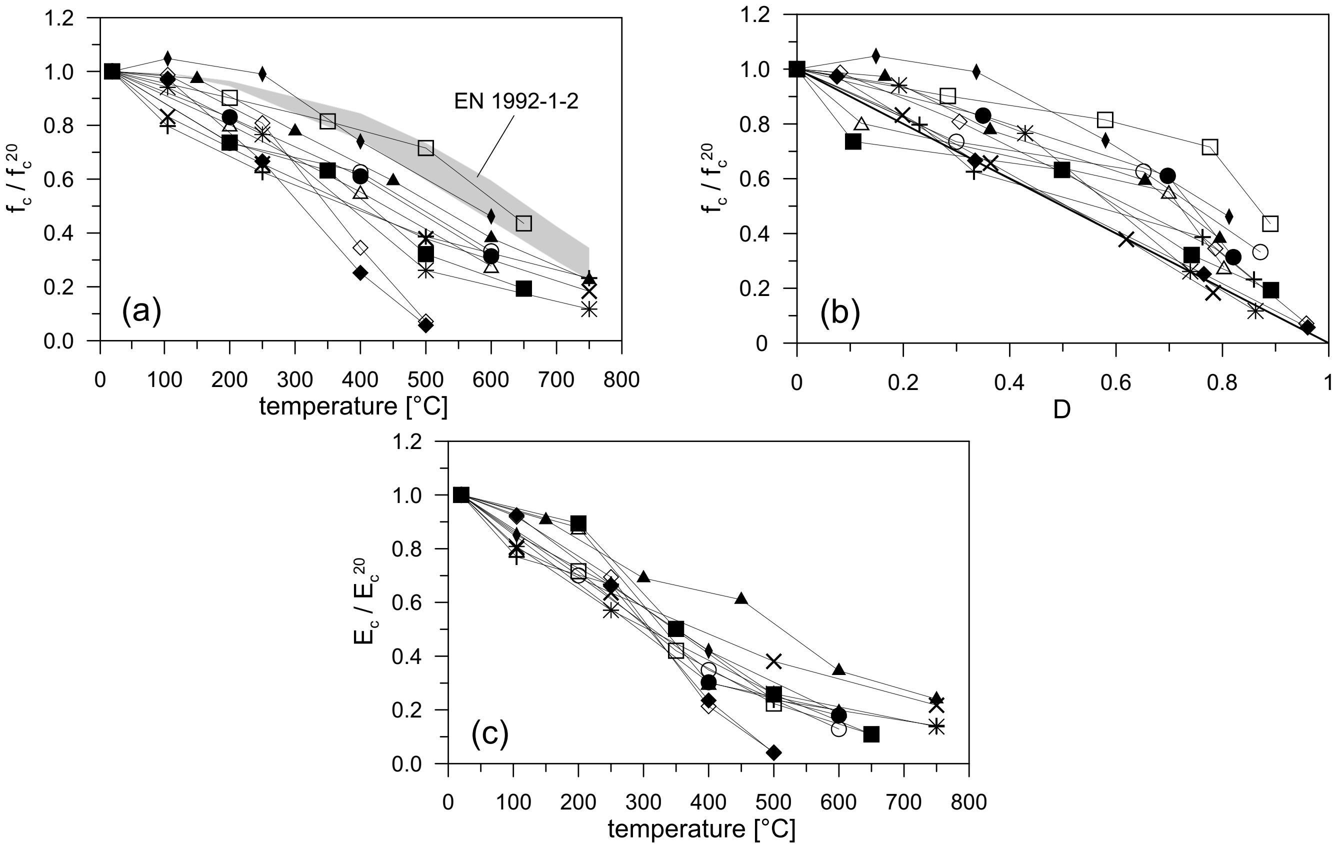

Figure 2. (a) Compressive strength decay of the different concrete mixes herein investigated and (b) its relation with the thermal damage, namely the decay of the elastic modulus, (c).

3 EXPERIMENTAL ISSUES IN TENSILE TESTING OF THERMALLY DAMAGED CONCRETE

As is generally recognized, the most straightforward experimental technique to ascertain the tensile response of concrete is the direct-tension test. Though very simple in principle, this test is greatly influenced by the end restraints of the specimen, since preventing – or not preventing – the end rotations affects the inherent tendency of the specimen to bend, due to the buckling instability triggered by the softening behaviour of the material (Bazant & Cedolin, 2003).

As a result, the crack is likely to start opening along one side of the fracturing cross-section, while the opposite side turns to compression (Figure 3b). This effect is particularly evident in slightly-damaged high-strength concretes (Figure 4a), that combine the heterogeneity ascribable to the thermally-induced flaws with a still remarkable brittleness (namely a steep softening behaviour).

The phenomenon can be prevented by forcing an almost uniform crack opening via specially-designed test setups and rather short specimens (Felicetti & Gambarova, 1998; Felicetti et al., 2000), but they are hardly practicable inside a hot furnace (RILEM, 2000). Nonetheless, the effect of the testing environment is generally less pronounced than the influence of specimen shape and boundary conditions (Figure 4b). Hence, the restrained-end residual test seems at present the most objective way to determine the fracture properties of concrete in the whole range, from pristine to completely damaged material.

The restrained-end direct-tension test not only makes it possible to accurately evaluate concrete tensile strength (that coincides with the stress at the peak of the stress-crack opening curve, Figure 4a), but allows also to determine the slope of the softening branch, which is a measure of the cohesive-stress reduction associated with the increase of the crack opening. As already stated, the thermal damage makes fracture more branched and tortuous, and then remarkably smoothens the post-peak response (Figure 5a).

One consequence of the milder response is the better correspondence between the restrained- and the hinged-ends direct-tension tests in the case of severely-damaged concretes (Figure 4b). Moreover, the improved cohesion of the cracks generally prevails over the increasing tendency to open (as a result of the increased deformability of the damaged material). A clear indication on the mutual roles of these conflicting trends is provided by the increasing values of the ratio of the elastic modulus E to the softening slope k at increasing damage levels (Figure 5). The ratio is equivalent to the Hillerborg's characteristic length, i.e. the span of a totally-developed fracture process zone, where the crack is assumed to be able to open but still capable to transfer the cohesive stresses.

This parameter is of crucial importance in the interpretation of the results of the indirect test methods, given the variable width of the fractures activated in such tests (Figure 3). In the case of bending, the equivalent strength of the material is usually worked out from the moment at peak M_{max} under the limit assumption of an elastic-brittle tensile response, which seems reasonable for pristine concrete (Figure 6). As a matter of fact, some stable propagation occurs beyond the incipient formation of the crack and the equivalent strength is higher than the true tensile strength. The divergence rises up to a ratio of about 3 for severely-damaged small concrete specimens, denoting a deeply-propagated process zone subjected to an almost uniform cohesive stress. Under these conditions, the opposite assumption of perfect plasticity in tension seems closer to the real stress pattern within the fractured cross section.

Furthermore, the bending response is markedly affected by beam depth and the benefit of the increased material ductility is definitely more pronounced in laboratory specimens than at the scale of real structural members (e.g. the deep beams of Figure 6). For this reason, the bending test appears to be not an objective method for the assessment of concrete strength decay, unless more complex models are adopted in the interpretation of the results.

Things are expected to improve if the splitting tests are considered, owing to the better uniformity of the crack opening at the load peak, especially in the case of short cylinders, which are less affected by fracture propagation through specimen thickness.

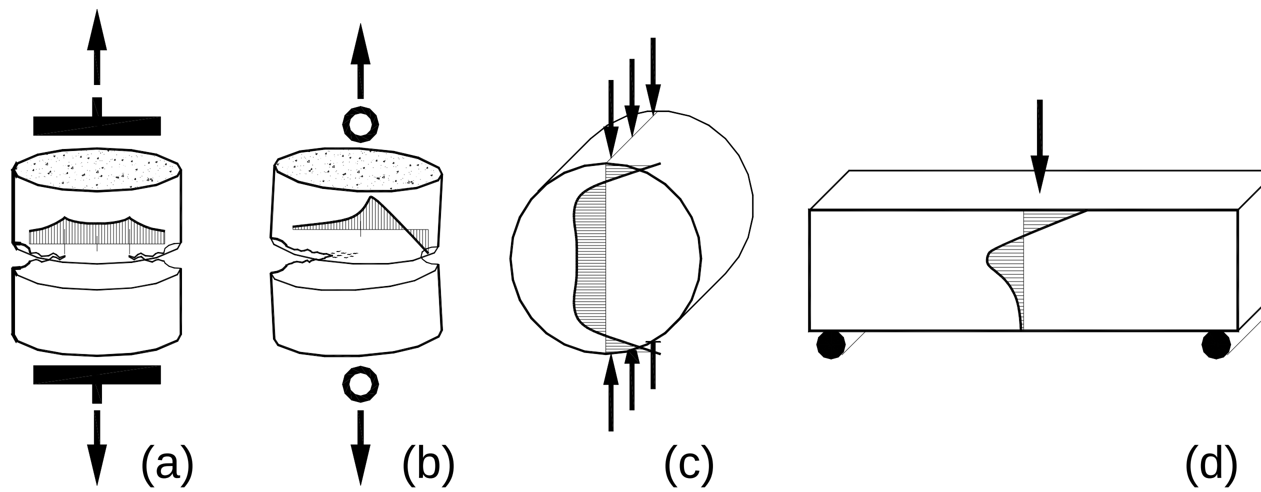

Figure 3. Outline of the stress patterns in the usual tensile tests: direct-tension with (a) restrained and (b) hinged ends; (c) splitting test; and (d) bending test.

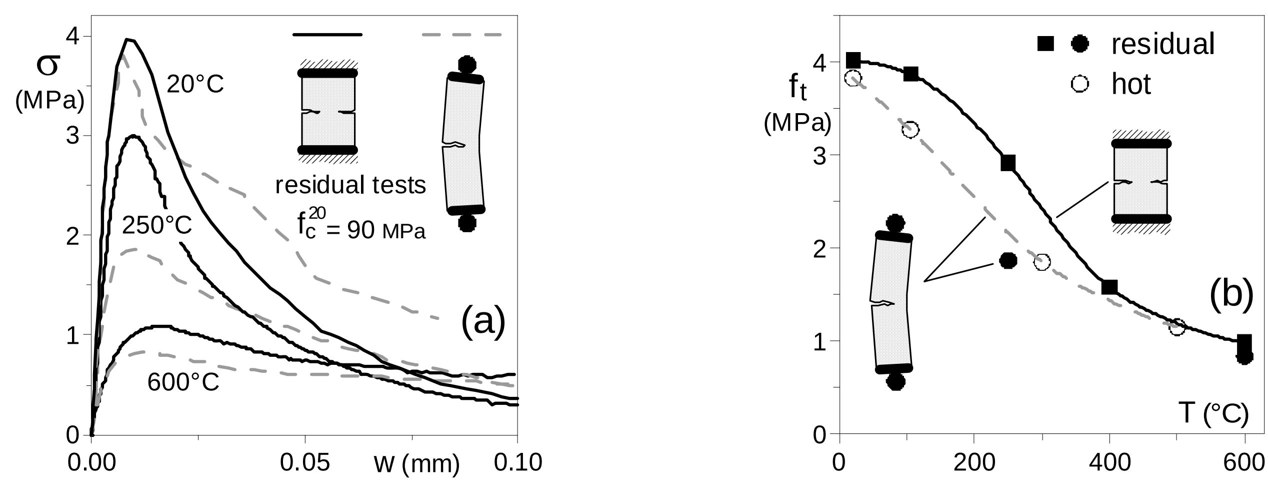

Figure 4. Effect of specimen shape and boundary conditions in direct-tension tests: (a) residual stress-crack opening curves of a thermally-damaged high-strength concrete (type C); and (b) tensile strength decay in hot and residual tests.

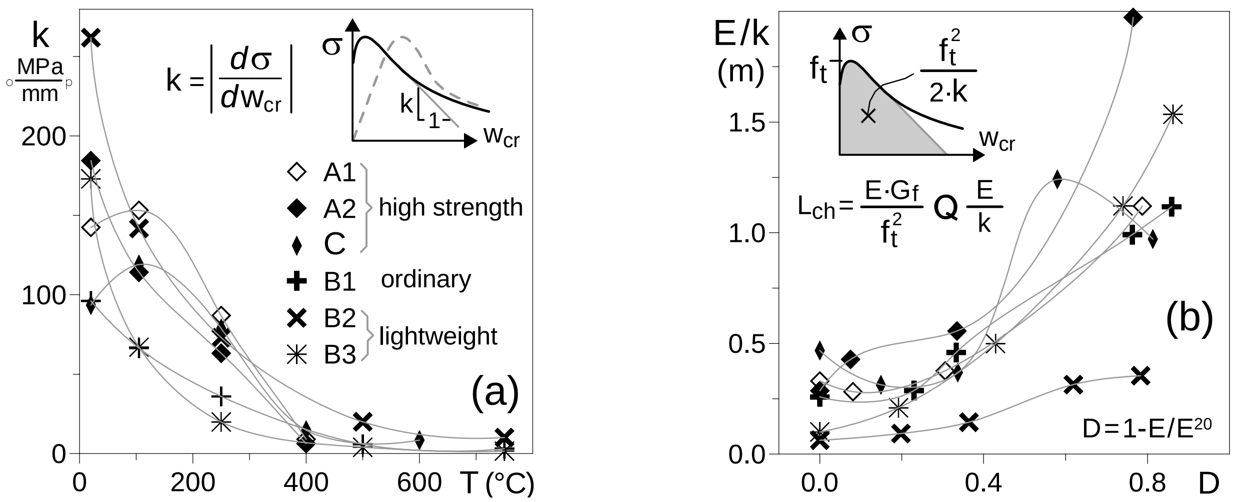

Figure 5. (a) Reduction of the slope k of the softening branch in thermally-damaged concretes; and (b) relationship of k with the material deformability (elastic modulus E); k is the mean slope of the descending branch past the peak and up to the counterflexure point.

Also in this case the equivalent material strength is generally worked out under the assumption of an elastic material, though some inelastic strains occur in the stressed regions of the specimen, be they in tension or in compression. The comparison with the actual material strength (Figure 7) shows a slightly variable ratio at increasing temperature, with a minor influence of the improved ductility on the assessment of the strength decay.

Besides the above considerations, the bending test still remains a viable method for determining the total work of fracture of the material, provided that special attention is paid to the design of the test setup. One critical aspect to be considered is the need to cut a notch at mid-span, whose optimum depth (generally in the range 0.2-0.3d) comes from the requirement to localize the failure in a single fracture, while preserving the extent of the ligament and preventing the formation of sizeable cracks during the thermal exposure. A second aspect to be considered is the accurate measurement of the net beam deflection, because of the increasing relevance of the inelastic local settlement over the loading rollers. Finally, the work performed by the specimen self-weight should be properly taken into account, since under increasing temperatures the specimen weakens, the displacements prior to failure become sizable, the work done by the self-weight is no longer negligible and the self-weight may even trigger the anticipated collapse of the specimen. Concerning this latter point, a series of weight-compensated bending tests (Felicetti & Gambarova, 1998) showed that the work W1 performed by the self-weight before specimen breaking into two pieces does not coincide with the area W2 below the tail of the load-deflection curve (Figure 8a), as postulated in the 80's (RILEM, 1985b). Then, a suitable counterweight system should be adopted in order to perform a fully-controlled test up to the complete breaking-up of the specimen.

If all these requirements are properly fulfilled, the works associated with the fracture assessed via the bending test and the direct-tension test are practically the same (Figure 8b) and they can be both adopted for determining the dissipation capacity of thermally-damaged concretes.

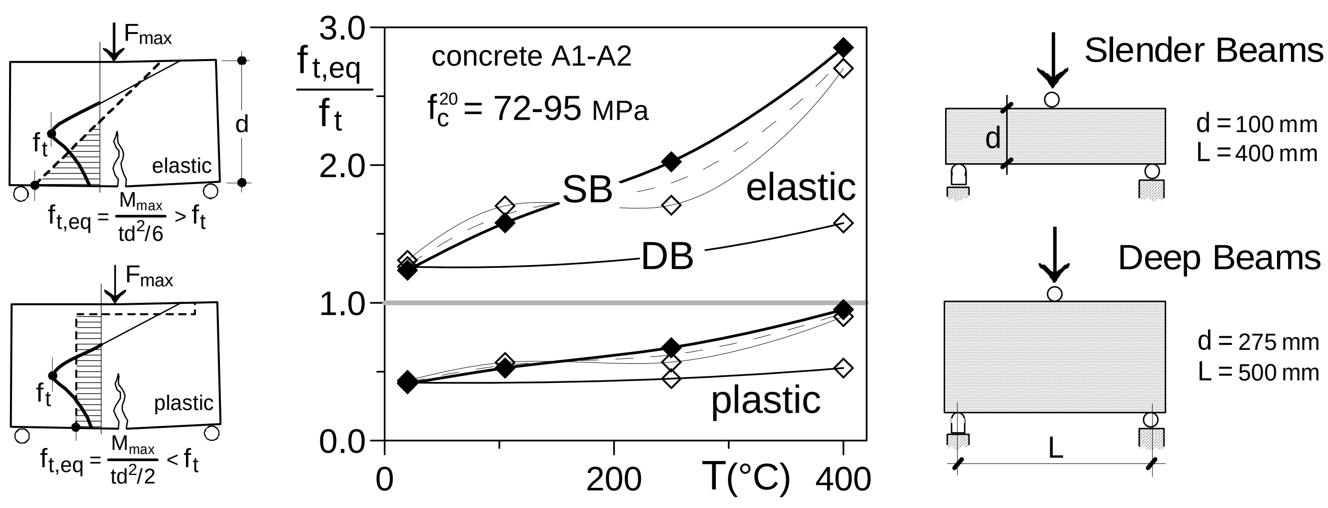

Figure 6. Possible extreme assumptions for the material response and corresponding equivalent tensile strengths obtained from three-point bending tests on specimens of different size.

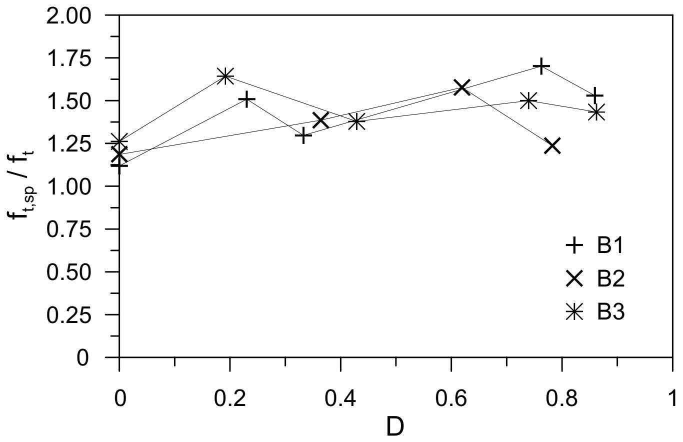

Figure 7. Effect of the thermal damage on the ratio between the splitting and direct tensile strengths.

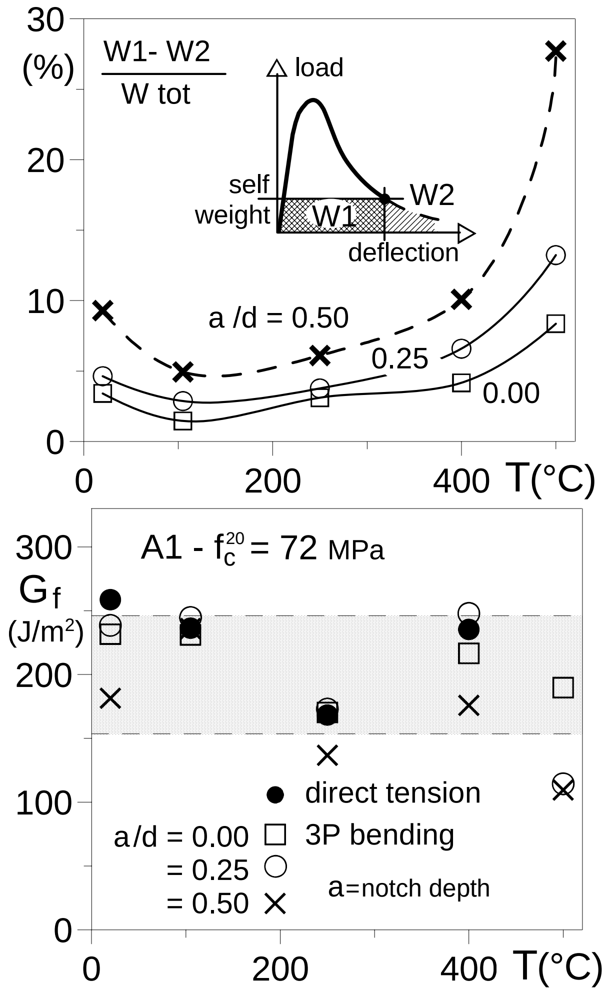

Figure 8. Work of fracture in three-point bending tests: (a) possible error in lack of counterweight system; and (b) influence of the notch depth.

4 EXPERIMENTAL RESULTS

Figure 9 shows a summary of the test results concerning the tensile properties of the concretes.

The direct tensile strength exhibits the same relative decay as the elastic modulus: this comes to no great surprise, since any possible non-linearity or redistribution due to structural effects is ruled out in this case, where all tests were performed in direct tension with fixed platens. The only exception is representted by the concretes B1 and B3, which seem to suffer a larger decay in terms of the tensile strength for low values of the thermal damage.

On the contrary, the afore-mentioned structural effects become evident should one consider the tensile strength in bending: most of the concretes seem to take advantage from this test modality, which allows some stress redistribution on the cross-section and thus leads to higher apparent values of the tensile strength. The same happens for the splitting strength, even though in this case the test set-up certainly allows less stress redistribution if compared to a bending test. Even in the case of the splitting tests, concrete B2 exhibits a behaviour which seems to be very different from the other concretes.

A further explanation of the increase in the bending and splitting strengths is to be found in the dependence of the fracture energy on the thermal damage: unlike the other properties, and even for the great variety of concretes herein examined, fracture energy does not decrease monotonically with temperature, but even increases in a certain range of values of the thermal damage D (generally between 150 and 350°C). This trend is responsible for the enhanced ductility of structural specimens at high temperature and for the subsequent increase of the indirect tensile strength.

5 CONCLUSIONS

This paper aims to give some general indications regarding the experimental techniques commonly used to measure the effects of the thermal damage on concrete. The principal conclusions are:

- the best way to measure the tensile strength is surely by testing in direct tension with restrained platens: in case of free rotation of the specimen ends, the tensile strength may be underestimated, especially for slightly-damaged concrete;
- the ratio between the splitting and the direct tensile strengths is almost constant throughout a broad range of temperatures, thus confirming the brasilian test to be a sound alternative to assess the relative strength decay;
- the tensile strength in bending, on the contrary, is far too much affected by the increasing ductility of the small-size bent specimens;
- the fracture energy can be equally-well measured in a direct as well as in a bending test, provided that some particular experimental arrangements are taken.

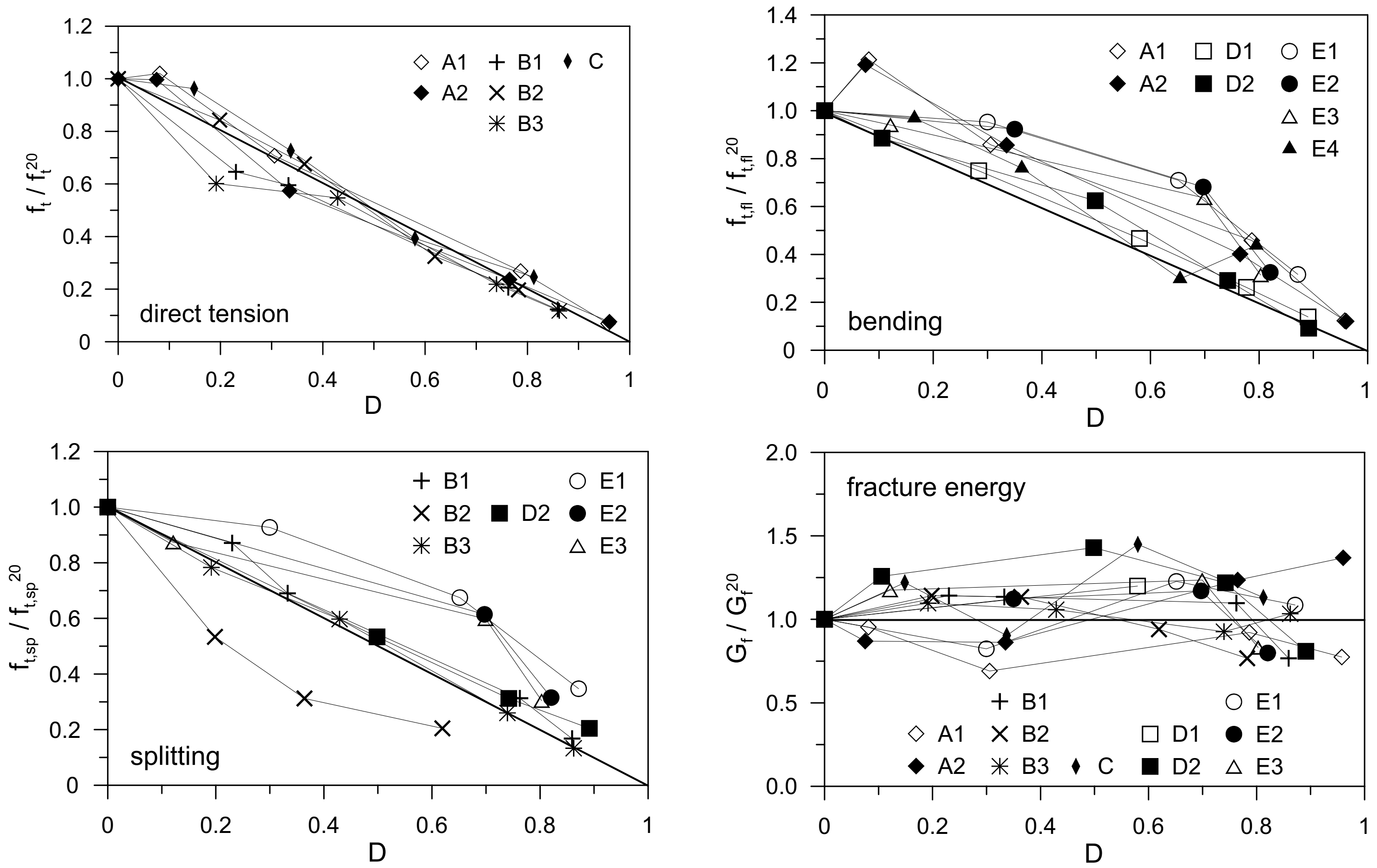

Figure 9. Plots of the materials properties as a function of the thermal damage.

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