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On the application of the Double-Edge Wedge Splitting Test to thermally-damaged concretes

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ABSTRACT: A new testing technique, named Double-Edge Wedge Splitting Test (DEWST), for determining the direct tensile strength of quasi-brittle materials – such as concrete – has been recently developed at the Politecnico di Milano. The principal aim is to simplify the loading device and the test set-up generally used in direct-tension tests: for example, the specimens need not to be glued to the press platens. Moreover, the crack pattern observed in a few preliminary tests is regular, and cracking can be easily controlled via the stroke of the loading machine. The present work aims to investigate the possibility of applying such technique to characterize thermally-damaged plain concrete specimens. Three different concretes were considered (f_c = 50, 80 and 90 MPa) and the results are compared to those obtained by means of traditional and well-defined techniques (splitting tests on cylinders, four-point bending displacement-controlled tests on prisms), in order to highlight the pros and cons of the proposed technique.

1 INTRODUCTION

Concrete is generally considered as a “fire resistant” building material, most probably because of its incombustible nature and low thermal diffusivity, that guarantee a slow propagation of thermal transients within the structural members, and offer a remarkable protection to the reinforcement (if any). Nevertheless, the several chemo-physical transformations occurring in the material at increasing temperature (Khoury 2000) can significantly impair concrete mechanical behavior. One of the most important phenomena to be cited is the incompatibility between the strains of the aggregate (which expands), and those of the cement paste (which first shrinks, as a consequence of drying and later starts expanding): this incompatibility results in diffused microcracking. This phenomenon and the chemical reactions are irreversible; therefore, the decay remains unchanged (or even increases) after cooling down to room temperature, and generally only minor differences are observed between the “hot” and the “residual” mechanical properties.

Being traditionally the most investigated mechanical property, the compressive strength is generally not markedly affected by the temperature below 300-400°C, but at higher temperature it exhibits a pronounced decay. As for the other mechanical properties, a more marked decrease is generally observed in the elastic modulus. It is the tensile strength, however, that often exhibits the most temperature-sensitive behavior (RILEM 1985). Nevertheless, the hierarchy of the aforementioned decays of the main mechanical properties is generally highly dependent on such characteristics as aggregate type, mix-design, cement type, and strength class (Bamonte et al. 2008). These general trends exhibit large variations, to the point that the strength of some concretes may be negligible at 500°C (Felicetti & Gambarova 1998), whereas other concretes exposed to the same temperature still keep a remarkable share of their initial performance (Khoury 2000). Furthermore, the advent of “new” cementitious materials has contributed to make concrete behavior very variable depending on concrete mix: high-performance and high-strength concretes are usually more temperature-sensitive, because of their great stiffness, low porosity and smaller defects; light-weight concrete has the advantage of thermally-stable aggregates, but is prone to explosive spalling; finally, self-compacting concrete is more susceptible to creep and shrinkage strains in the cement paste.

The large decay experienced by the tensile strength is 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). Some recent results in the “hot” state, on the contrary, show that also the fracture energy can experience significant reductions (Watanabe & Horiguchi 2008). The low decay of the fracture energy is of particular interest when the resistant mechanisms governed by the tensile behavior 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 bar-concrete bond and of the bearing capacity of fasteners (Bamonte et al. 2006), as well as in the case of concrete spalling (Gawin et al. 2006; Dwaikat & Kodur 2009). The reduced brittleness should also be considered in the characterization of concrete tensile behavior via indirect testing techniques (bending, splitting, etc), because the actual strength decay may be masked to some extent by the better "structural" response of specimens, where significant redistributions of the stresses can occur between the elastic phase and the attainment of the ultimate load. For this reason, well-controlled direct tests are often preferred for concrete characterization. However, since testing in direct tension at high temperature is hardly possible, these tests are usually performed in residual conditions (Felicetti et al. 2000).

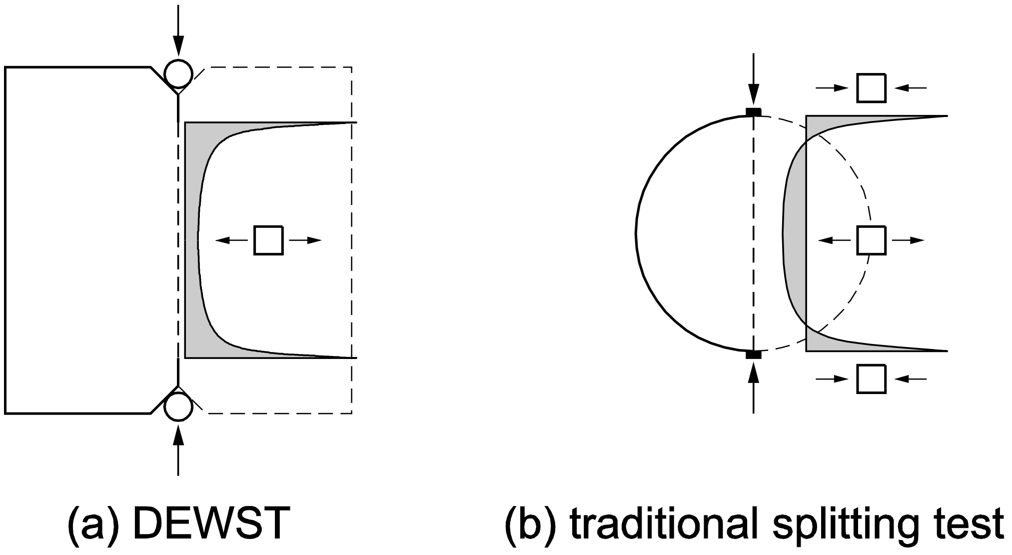
General issues concerning tensile testing at high temperature were explicitly addressed in a previous paper (Bamonte & Felicetti 2007), where the different techniques were compared on the basis of the results obtained on some 15 concretes tested in the last decade in Milan. The main findings were that the best way to measure the tensile strength is testing in direct tension with no rotations at the end sections of the cylindrical specimen. As for indirect tensile tests by splitting, the ratio between the splitting and the direct tensile strengths is almost constant throughout a broad range of temperatures, thus confirming that the splitting test can be considered as a viable alternative for assessing the relative strength decay. Tensile strength in bending, on the contrary, can be far too much affected by the increasing ductility of thermally-damaged concrete.

In this paper, the preliminary results of an experimental campaign on the tensile behavior of thermally-damaged concrete are presented. The tests were carried out taking advantage of a new test set-up.

2 THE TESTING TECHNIQUE

The tests presented in the following were carried out using the so-called "Double-Edge Wedge Splitting Test" (see also di Prisco et al. 2010), from now on DEWST. The basic idea of this technique, aimed at measuring the toughness of cementitious materials (especially fiber-reinforced concrete), is more or less the same that led to the development of the Wedge Splitting Test (WST, Brühwiler & Wittman 1990), where the principal idea was to reproduce (on small specimens) the state of stress typical of the mid-span portion of a notched beam loaded in three-point bending; as a consequence, the resulting stresses are partly compressive and partly tensile. DEWST, on the contrary, aims to reproduce the state of stress experienced by the sections of a notched specimen loaded in pure tension, without compressive stresses (Figure 1a), contrary to what occurs in the Brazilian test, where compressive and tensile stresses act on the splitting plane (Figure 1b). Note that, on the whole, the stress distribution in the two test specimens is rather similar.

A possible advantage of the DEWST, shared with traditional splitting tests on cylinders, is the possibility of carrying out tensile tests by applying compressive loads, thus avoiding the typical complications of the direct application of a tensile load on the specimen (like gluing specimen's extremities to the press platens, or providing the specimen with particular load-transferring devices). Moreover, the absence of highly-localized compression stresses is a plus in the case of ductile materials, where the small loaded area may undergo significant plastic deformations.


(a) DEWST

(b) traditional splitting test

Figure 1. Typical stress distribution in the (a) Double-Edge Wedge Splitting Test; and (b) simple Splitting test.

As matter of fact, DEWST was specifically conceived for the characterization of fiber-reinforced concrete. Finally, the particular arrangement used to apply the compressive loads, namely two steel cylinders acting on a 45°-shaped notch provided with steel/brass plates, makes sure that two “arches” of compressive stresses are established between the loading punches: in this way, the mid-span section is subjected to uniaxial tensile stresses, and the measured strength will be very close to that in uniaxial tension, without the need of taking into account the simultaneous presence of compressive stresses in the vertical direction (= biaxial stress state), as it is the case in splitting tests.

As previously mentioned, this technique was specifically conceived for the characterization of FRC. Such characterization, that considers FRC as a composite material, is always accompanied by the separate characterization of its main components (matrix + fiber). Therefore, an open question is whether the DEWST is applicable also to plain concretes, where the increased ductility offered by the fibers is absent. Trying to answer this question will be one of the objectives of the present paper.

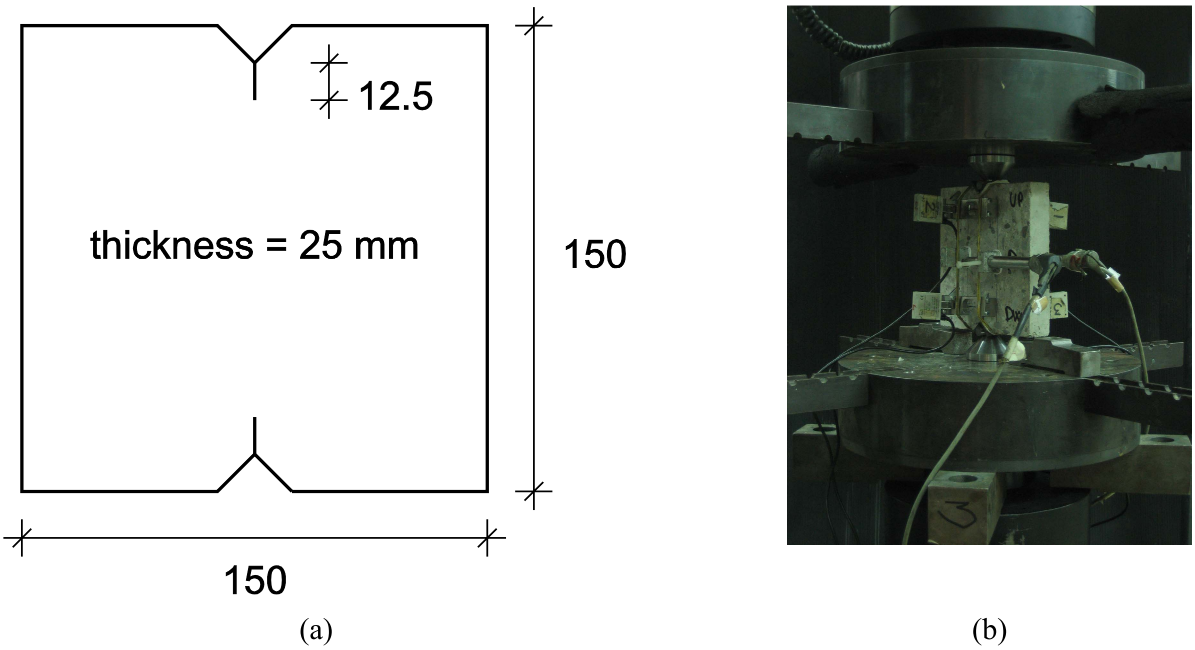
One of the key aspects of DEWST, namely the absence of compression stresses in the governing section, is of particular importance also in the case of thermally-damaged concrete (in “hot” or “residual” conditions), since significantly different behaviors in compression and tension are the rule. Of course, since the tensile properties are generally much lower, the structural behavior, and also the response of a laboratory specimen, is dominated by the tensile properties. Nevertheless, as previously emphasized, testing techniques where the stress distribution is mainly tensile (such as in direct tensile tests and splitting tests) are generally better. The second objective of this paper is to ascertain whether DEWST can be considered as a viable alternative to the usual tensile tests carried out on thermally-damaged concretes, for the evaluation of the mechanical decay of the material.

3 MATERIALS AND TEST SET-UP

In this research project, the tensile properties of three Limestone Self-Consolidating Concretes (called NSC, HPC and HSC) were investigated. The compressive strength f_c measured at ambient temperature was close to 50, 80 and 90 MPa respectively.

The tensile properties of the three concretes were investigated in a previous research project (Bamonte et al. 2008), where the indirect tensile strength by splitting and in 4-point bending was measured in residual conditions, i.e. after the exposure of the specimens to 4 reference temperature (20, 200, 400 and 600°C), and the subsequent cooling to room temperature. In the splitting tests, the specimens were relatively thick disks (diameter D = 100 mm; thickness t = 40 mm), while in the bending tests notched prisms (150 × 150 × 600 mm, notch depth = 50 mm) were used. The results were rather surprising, since (a) the indirect tensile strength in bending at 20°C was very close to the direct tensile strength (MC90); and (b) the splitting strength was always larger than the corresponding tensile strength in bending. The temperature-triggered decay, however, was practically the same, with the splitting strength a little more temperature-sensitive than the indirect strength in bending, as should be expected.

The specimens used in this project were obtained from the prisms previously tested in bending. All specimens were sampled far from the mid-span section (= notched section) of the prisms, and therefore no sizable damage due to the previous bending tests



(a)

(b)

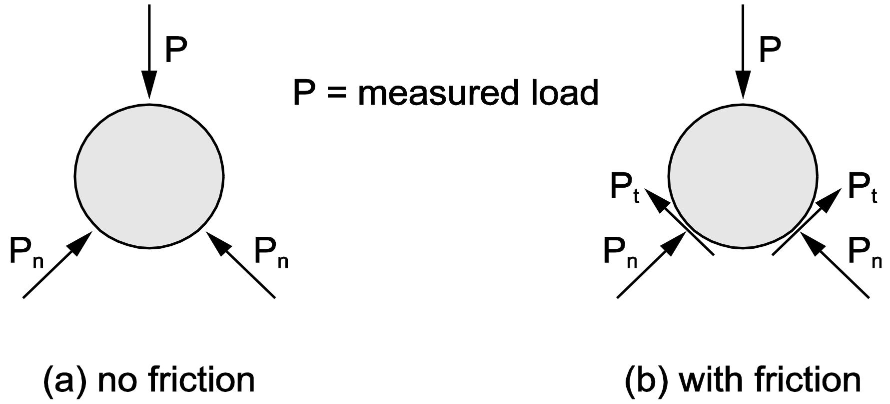


Figure 3. Loads transmitted by the loading cylinder (a) without friction between punch and specimen; and (b) with friction.

was expected. The geometry of the specimens is shown in Figure 2a: the shape is square, with two V-shaped notches, whose surfaces are at 45° to the horizontal axis (notch depth = 12.5 mm), where the loading cylinders are placed. Note that the two vertical linear notches (notch depth = 12.5 mm) starting from the tip of the V-shaped notches are a late improvement to make the reference section independent of any disturbances.

An electromechanical INSTRON press (maximum capacity = 100 kN) was used in the tests, that were displacement-controlled, by imposing a constant speed to the stroke of the loading machine, via the displacement transducer of the press. Each face of the specimens (Front and Rear) was instrumented with three displacement transducers (LVDT), at the tip of the upper notch, at mid-height, and at the tip of the lower notch, respectively (Figure 2b).

Some preliminary tests were carried out, in order to assess the friction between the punching cylinders, and the small steel plates glued on the specimen (to ensure a proper load distribution and thus to avoid local crushing of the concrete). If no friction is present, only a normal load P_n is transmitted from the punch to the specimen (Figure 3a), and the net tensile force acting on the reference section equals P_n. The presence of a tangential load was detected (P_t, Figure 3b) by means of some preliminary tests with a horizontal load cell; the friction coefficient f (with $f = P_t/P_n$) measured was approximately 0.08. Therefore, the net tensile force acting on the reference section was only 85% of the vertical load P_n.

4 TEST RESULTS

It is fair to say that, although all specimens were carefully instrumented and all due precautions were taken, it was hardly possible to control the tests in the post-peak phase, except in a few specimens exposed to the highest reference temperatures (400 and 600°C), and therefore characterized by an enhanced ductility. This consideration indicates that DEWST seems to be rather unstable for plain-concrete specimens. The rather typical set of load-stroke and load-CMOD (Crack Mouth Opening Displacement) are shown in Figure 4 (for the case of the HPC, f_c^{20} = 82 MPa). It is plain to see that the steepness of the load-stroke diagrams does not allow a proper control of the test via the stroke at the lower temperatures (20 and 200°C); on the contrary, the corresponding load-CMOD curves are definitely “softer”. At higher temperatures (400°C in this case), on the contrary, the

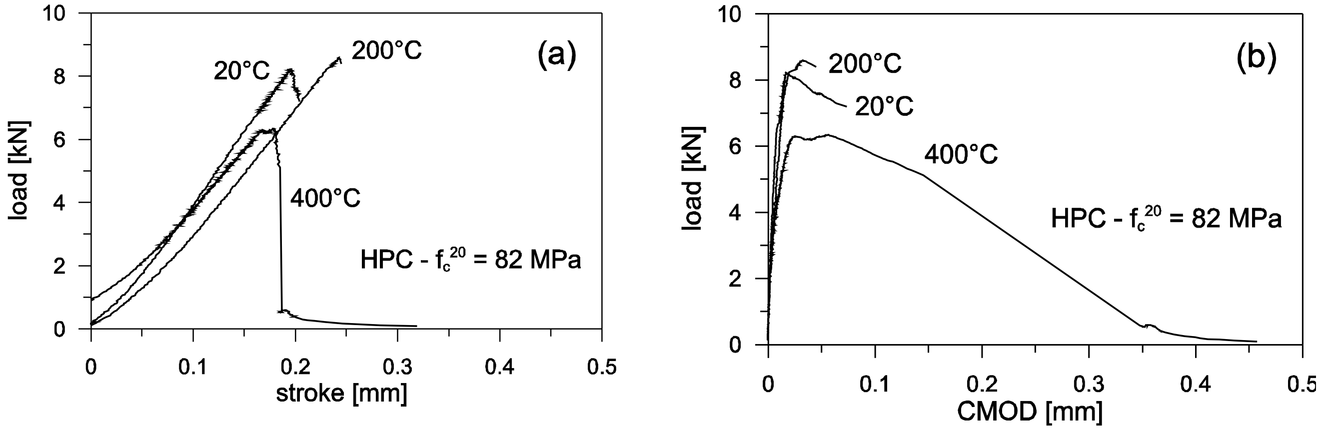


Figure 4. HPC, f_c^{20} = 82 MPa: (a) load-stroke diagrams; (b) load-CMOD (Crack Mouth Opening Displacements).

whole post-peak branch can be followed, even with stroke-controlled tests.

A summary of the test results in terms of maximum normalized load as a function of the reference temperature is shown in Figure 5. The scattering of the results in nominally identical tests was generally rather low (≤ 15% of the average value), provided that a few statistical "outliers" were discarded.

For the sake of comparison, in Figure 5 the abovementioned results obtained with different test set-ups (four-point bending and splitting) on the same three concretes are plotted as well. Plotting all the experimental results in a normalized form, as it is usually done, is based on the assumption that the stress distribution at failure, for each experimental set-up, does not change with the reference temperature, and thus with the thermal damage. This assumption is questionable, since, as previously mentioned, the role of fracture energy (and stress redistribution) increases with the level of thermal damage. When comparing different testing techniques, however, such a representation allows to better capture the role played by the "internal redundancy" and therefore the degree of possible stress redistribution of different specimens, and thus to highlight the main differences between various testing techniques.

It is interesting to note that the three concretes exhibit a rather different behavior. In the NSC ($f_c^{20} \approx$ 50 MPa), the average normalized curve is always above the normalized curves representing the bending and splitting tests. This could be an indirect confirmation of the greater role played by fracture energy in normal concretes, specifically when thermally-damaged specimens are considered, where the fracture energy exhibits a smaller decay (if any) if compared to that of the tensile strength, and the material tends to become more ductile. In the HPC ($f_c^{20} \approx$ 80 MPa) the thermally-induced strength decay seems to be in perfect agreement with that obtained in the previous tests; as a matter of fact, in higher-grade concretes, an brittleness increase is generally observed, and the role played by fracture energy tends to decrease. The trend observed for the HPC seems confirmed by the HSC ($f_c^{20} \approx$ 90 MPa), where the average curve representing the current tests seems to be below the average curves obtained in bending and splitting, and gives higher results only above 400°C (even though the experimental results at 400°C are missing because of lack of specimens). Summing up, the results obtained on the thermally-damaged specimens indicate that DEWST is at least as reliable (in terms of concrete thermal decay) as the traditional techniques.

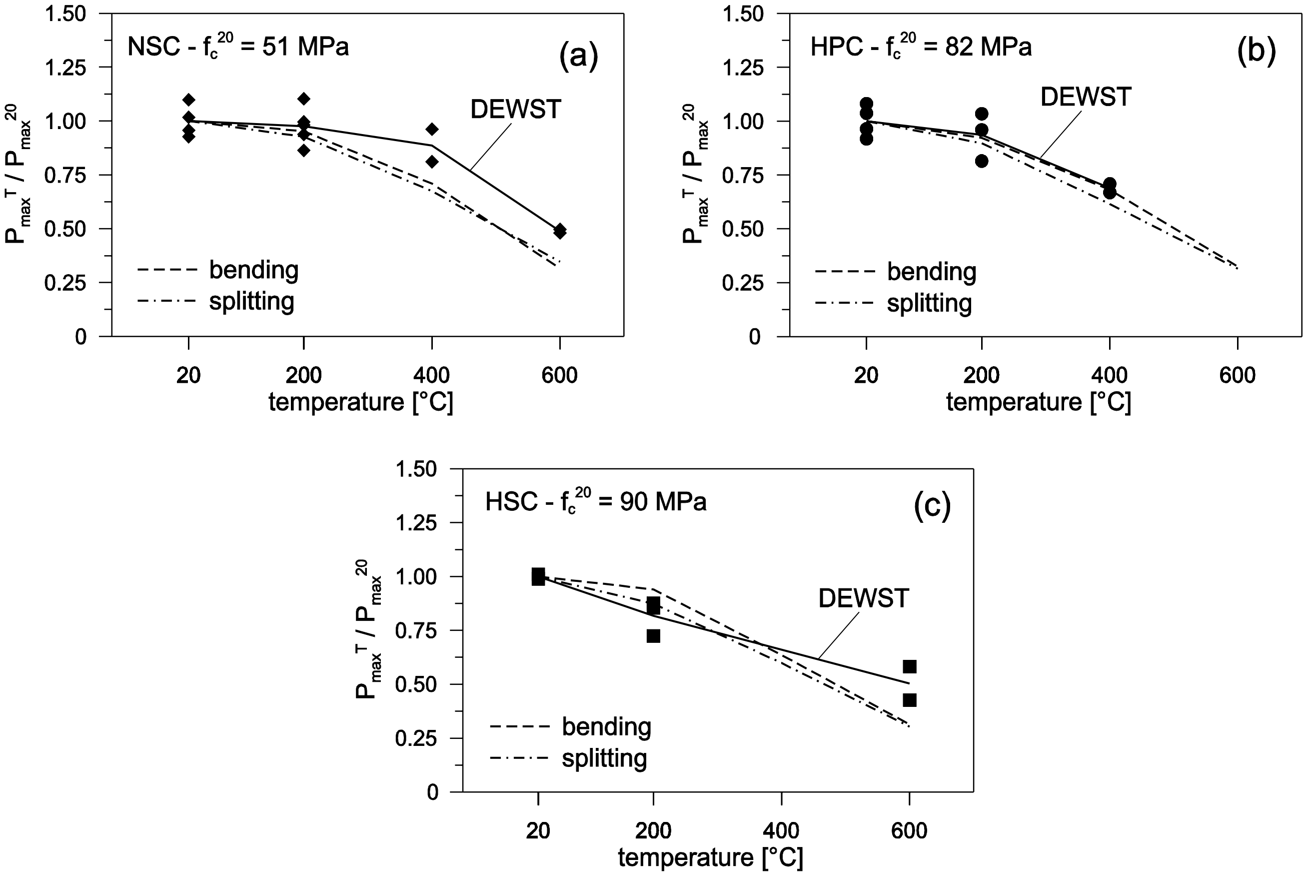


Figure 5. Normalized plots of the maximum loads, compared with previous results (Bamonte et al. 2008): (a) NSC; (b) HPC; and (c) HSC.

5 CONCLUDING REMARKS

Based on the results of a preliminary experimental campaign, the following considerations can be drawn:

- the application of the Double-Edge Wedge Splitting Test to plain-concrete specimens is rather difficult, at least if the tests are controlled via the stroke of the press: more refined control procedures could be considered, to the detriment of the simplicity of the test set-up;
- at rather high temperatures (T ≥ 400°C) it was possible to control the test via the stroke of the press, because of the extra-ductility achieved by the material after a thermal cycle;
- as for the application of DEWST to evaluate the thermal decay through the decrease of the normalized maximum load, the results are in good agreement with previous results obtained by means of more traditional testing techniques (bending and splitting tests).

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