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CONFINED SLAB SPALLING TEST (CSST): A SCREENING TOOL TO ASSIST CONCRETE MIX DESIGN IN TUNNEL PROJECTS

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ABSTRACT

Explosive spalling is one of the most challenging aspects in the design of segmental tunnel linings, due to the high concrete quality entailed by precast production, the severe design fire curves imposed by the design codes and the sustained compressive load borne by the tunnel vault. Since no established predictive models are yet available to account for the many variables governing the incidence of this phenomenon, experimental fire tests are generally regarded as the reference tool for optimizing the mix design and implementing the required mitigation measures (e.g. polypropylene fibre addition). A viable solution consists in testing square flat slabs under a biaxial confinement load. This symmetric configuration is more severe than uniaxial confinement and better replicates the isotropic effect of restrained thermal dilation in the central region of a lining segment. In the proposed Confined Slab Spalling Test setup (CSST), a 0.20 to 0.30 m thick slab is installed in the load frame and exposed to the prescribed fire curve on a 1.0 m side square area. The loading system comprises 8 hydraulic jacks restrained by a compact octagonal tense frame. The exerted load can range from 0 to 3 MN per axis, thus allowing to replicate the actual service conditions of most installations. Different sensors and monitoring systems can support a thorough analysis of the test results. In the paper, the testing setup is described together with the results of the validation tests performed.

Keywords: Explosive spalling, tunnel linings, fire tests.

1 INTRODUCTION

1.1 Fire performance and spalling sensitivity assessment in concrete

Tunnels can often be regarded as strategic infrastructures whose disruption may jeopardize the resilience of road and rail networks. In this context, structural fire safety is a pivotal requirement, which is frequently made demanding by the interaction of several aspects. Firstly, the geometrical layout, the type of combustible materials (mainly hydrocarbons) and the ventilation conditions promote the development of remarkably high temperatures (even higher than 1000° [1]). Secondly, the inherently redundant structural configuration and the compression-driven stress state in the lining bring in the formation of severe indirect actions during the development of a fire, with the consequent dramatic increase of the initial state of stress [2]. This may boost the incidence of explosive spalling, namely the expulsion of concrete chunks from the heated face of concrete due to the combined action of external force, thermal stress, and vapour pressure in the pores. The phenomenon is even more critical in the case of segmental tunnel linings, due to the high

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early-age strength entailed by the precast production process, which in the long term translates into sizably higher concrete grades than required by the design.

Several numerical models have been developed in the last decades [3] aimed at simulating the heating process in concrete elements including mass transfer and, in a few cases, the effect of stress development and mechanical damage. However, the calibration of such multiphysics models is challenging, due to the combination of complex aspects such as the mutual interaction between pore pressure and concrete fracture behaviour [4] and the variation with temperature and saturation of concrete physical and mechanical properties, something very difficult to characterize in hot conditions. As a result, no design-oriented predictive models are yet available to determine the thickness of the spalled layer and the consequent reduction of cross-sections and rebar protection.

As an alternative, experimental testing allows to directly assess concrete sensitivity to spalling, even though great attention should be paid to the definition of the test setup, given the huge variety of specimen geometry and applied loading, restraint and heating that can be found in the literature. In this regard, tests can be grouped in small-, medium- or full-scale tests, either on loaded or unloaded specimens [5].

Small-scale investigations can be found where temperature and pressure were monitored in unloaded prismatic specimens made of plain or fibre-reinforced concretes [6, 7]. In these cases, relevant spalling was usually not obtained, since stress was caused just by thermal gradients occurring in limited volumes. On the other hand, sizeable spalling was obtained in other small-scale tests where specimens were loaded thanks to a steel casing or a ring restraining thermal dilation [8, 9] or by means of a steel ring loaded via hydraulic actuators [10].

Medium-scale tests generally consist in loaded or unloaded slabs or prismatic specimens heated on one side. External uniaxial compression can be applied in a rather easy way according to several setups, such as internal or external post-tensioning systems [11-14], and actuators [15, 16]. External biaxial compression, on the other hand, requires a more complex setup [10, 11, 17]. The common evidence is that loading increases the susceptibility to spalling and that biaxial compression is far more severe than uniaxial compression [13, 15, 18].

Full-scale tests, especially in the design phase of tunnels, led to the design of quite demanding setups [19, 20], where a real scale arched segment is installed on the test furnace and loaded to service conditions, involving independent transversal and chord loads in the range of meganewtons (Figure 1). Local equilibrium in case of a curved shape establishes a connection between the circumferential compressive stress σ_c due to restrained thermal dilation and the gradient of radial stress $d\sigma_r/dz$, whose ratio equals the radius of curvature of the lining. Due to the limited thickness of the involved cover (some centimetres) compared to the radius of curvature (some metres) the result is a minor stabilizing radial stress (less than 1 MPa) which wouldn't develop in a flat specimen (making this latter slightly conservative).

Despite the high representativeness of this scheme, it may be argued that loading and heating several square metres is not strictly required to represent a phenomenon whose scale is ruled by the thermal gradient and the consequent profiles of stress, moisture content, and pore pressure developing in the exposed cover. Moreover, the concrete mix has generally to be defined well before the construction of the segment formworks, requiring a simpler yet representative specimen geometry.

1.2 Fire testing on biaxially compressed slab - Confined Slab Spalling Tests (CSST)

In order to find a compromise between representativeness and cost/time effectiveness, a viable solution consists in testing square flat slabs under biaxial confining load [17], as hinted before in the case of intermediate-scale tests. Such symmetric configuration is more severe than uniaxial confinement and better replicates the isotropic effect of restrained thermal dilation in the central region of a tunnel segment.

Figure 2 shows the first version of the setup, aimed at testing small slabs (0.8x0.8m, with a heated area of 0.6x0.6m and a thickness ranging between 0.1 and 0.2m). As shown in the same figure, numerical studies were also performed via non-linear thermo-mechanical models to assess the influence of possible parasitic effects of confinement. In this regard, a key role is played by the unheated perimetral rim of the specimen, which acts as a thermal barrier for limiting the temperature of the actuators. This colder rim would restrain the thermal dilation of the heated region of the specimen and take an unknown share of the applied load. Numerical analyses proved that the introduction of a set of perimetral slits minimizes the disturbance to the confining stress without affecting thermal protection of the load system. The actuators are also fitted with spherical seatings to accommodate the thermal curvature. The consistency with full-scale tests has been also ascertained via experimental tests [19].

Figure 3 shows that in a slab heated at the bottom face, the hot layer is characterized by compression, while tension arises in the cold core for translational equilibrium. Finally, compression again develops in the cold side due to rotational equilibrium. In absence of external confinement, the tensile strength would be exceeded in the core, leading to internal cracks parallel to the thermo-hygral flux, thus favouring the migration of vapour and the decrease of pressure in the pores, with consequent decrease of spalling severity. On the other hand, at increasing values of external confinement, cracking is prevented, and compression embraces the most hygrally-active zone (d_{ha}), thus keeping concrete sound and raising pressure in the pores, with an increased spalling severity [17]. Thus, in the plot of average spalling depth versus applied load, two regions can be defined: (I) low compression range, where at increasing external load a higher share of the hot layer undergoes compression and cracking in the core is reduced, and (II) high compression range, where increasing the external load leads only to higher mechanical stress in the hot layer, with minor effects on the thermo-hygral transient. In the first region the increase of spalling severity as a function of external compression is expected to be far higher than in the second region. This behaviour is evident in ordinary concrete, since its higher permeability makes d_{ha} larger. On the opposite, in (Ultra) High-Performance Concretes, the far lower permeability makes d_{ha} so small, that cracking in the cold core of the specimens does not significantly influence spalling severity. For this kind of concrete, therefore, just region (II) is recognized.

Starting from the above-discussed considerations, Webuild Group and PoliMi started a collaboration to develop this type of testing in the form of an in-house standard to support the optimization of concrete mixes in new tunnel projects. The main objective is to determine, for each investigated concrete mix, the amount of polypropylene fibre required to not exceed the acceptable spalling depth according to the structural design of the tunnel.

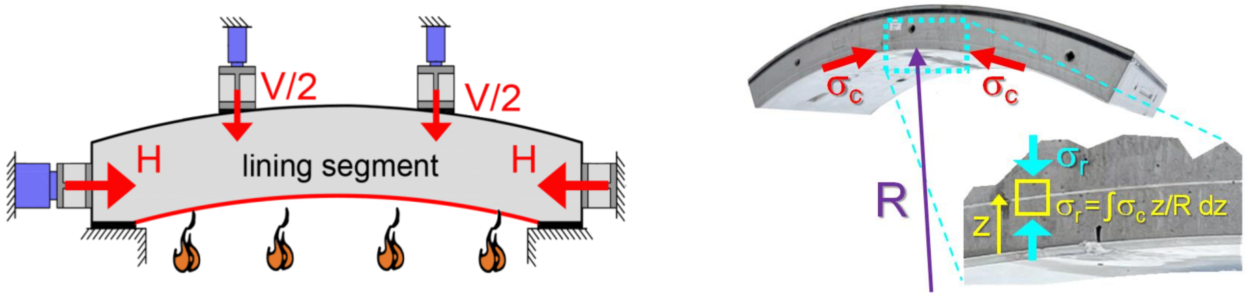

Figure 1. Arched segment load scheme and ensuing radial stabilizing stress.

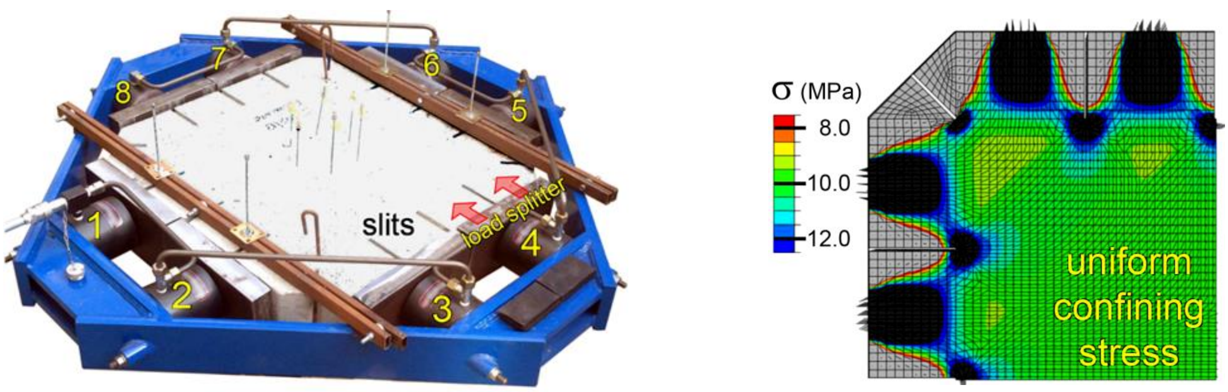

Figure 2. Original setup with the biaxially-loaded flat slab and stress uniformity allowed by the slitted rim.

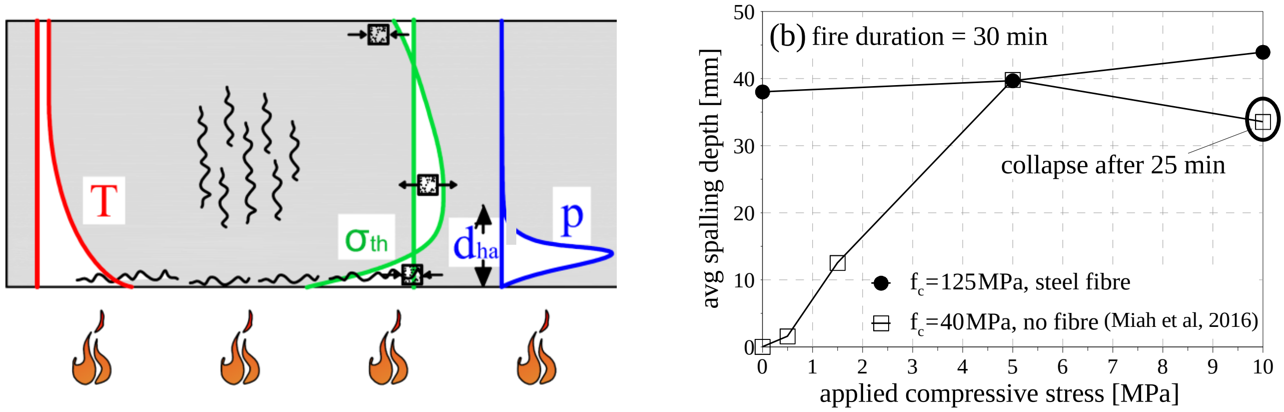

Figure 3. Schematic representation of temperature, thermal stress and pore pressure profiles across the lining thickness and dependency of spalling depth on the biaxial confining stress.

2 EXPERIMENTAL SETUP

2.1 Design requirements

In the original proposal, the heated area (0.6x0.6m) and the slab thickness (0.1-0.2m) were oriented to the study of unreinforced elements undergoing limited spalling depth. To go beyond these limitations, the new project has been launched to further develop this approach in the following directions:

- scaling up the original setup to 1.0x1.0m heated area and thicknesses in the range 0.2-0.3m, allowing the reproduction of the intrados reinforcement layer;
- increasing the load capacity up to 3MN per axis so to allow the application of a membrane compression up 15MPa for a specimen thickness of 0.2m;
- controlling the initial moisture content of samples to offset the detrimental effect of limited ageing;
- submitting the loaded sample to the RWS hydrocarbon fire curve in a vertical furnace;
- real-time monitoring of temperature profiles, concrete damage and reducing thickness.

As depicted in Figure 4, the specimen consists of a square slab with 1.3x1.3m in-plane dimension and a thickness ranging from 0.2 to 0.3 m. Considering the heated area is 1.0x1.0m, the cold rim has a width of 0.15 m. Its confinement effect is smoothed down by the realization of perimetral slits as already discussed in the previous section.

The loading system consists in an octagonal welded steel restraining frame. Thanks to load symmetry and positioning of the 1.5MN hydraulic jacks at the vertexes, the frame works mainly in tension, this allowing the design of a relatively light structure (recurring section 40x250mm). The jacks are connected to a hand operated pump (p_{max} = 700bar) and the hydraulic circuit is fitted with an in-line flow control valve to allow smooth release of pressure when the load tends to increase due to the thermal dilation of the specimen.

According to the devised installation procedure, the frame is laid horizontally on the laboratory floor and the concrete slab is positioned between the loading platens. Then, the jacks are preloaded, and the whole system (about 3t weight) is lifted with an overhead crane and installed on a vertical stand facing the vertical test furnace (2.1x2.1m exposed area). A stainless-steel frame lined with ceramic fibre blankets reduces the furnace opening to the required exposed area (1.0x1.0m) as shown in Figure 4. The stand can be translated on its high-capacity wheels to press the specimen against the ceramic fibre screen and provide tightness to the exhaust smoke.

It has to be mentioned that the hottest stage of the RWS fire curve (T_{max} = 1350°C) often involves the incipient melting of the exposed concrete. In the case of a vertical furnace, gravity induces shear in the melted layer and more substantial flow compared to dripping from a horizontal surface. This effect, not addressed by fire testing standards, required to equip the insulating screen with a stainless-steel gutter to prevent tearing of the ceramic fibre.

The specimens are casted in plywood formwork panels and the perimetral slits are created by installing soft refractory panels (Millboard) which remain embedded in concrete. Different sensors and monitoring systems can support a thorough analysis of the test results [20,21]. Concerning temperature monitoring, 4 shielded “K-type” thermocouples were embedded in the slabs at 10, 50, 100 and 150mm depth from the exposed surface. A horizontal arrangement next to the measuring junction minimizes the possible disturbance to the thermal field.

The applied confining stress has been selected based on 3D Finite Elements analyses of the tunnel lining under the effect of sustained loads and thermal stress. The goal is to minimize the incidence of cracks parallel to the thermal flux and then prevent the anticipated drying of the exposed cover. Based on past experience, in this first series of tests a constant 5.0MPa biaxial confining pressure was maintained during fire exposure. This required releasing the actuators pressure a few times to balance the effect of thermal dilation. More advanced hybrid testing techniques may be implemented to simulate the structure to soil interaction, through deformation monitoring of the tested specimen and feedback into a numerical model of the lining ring embedded in the soil.

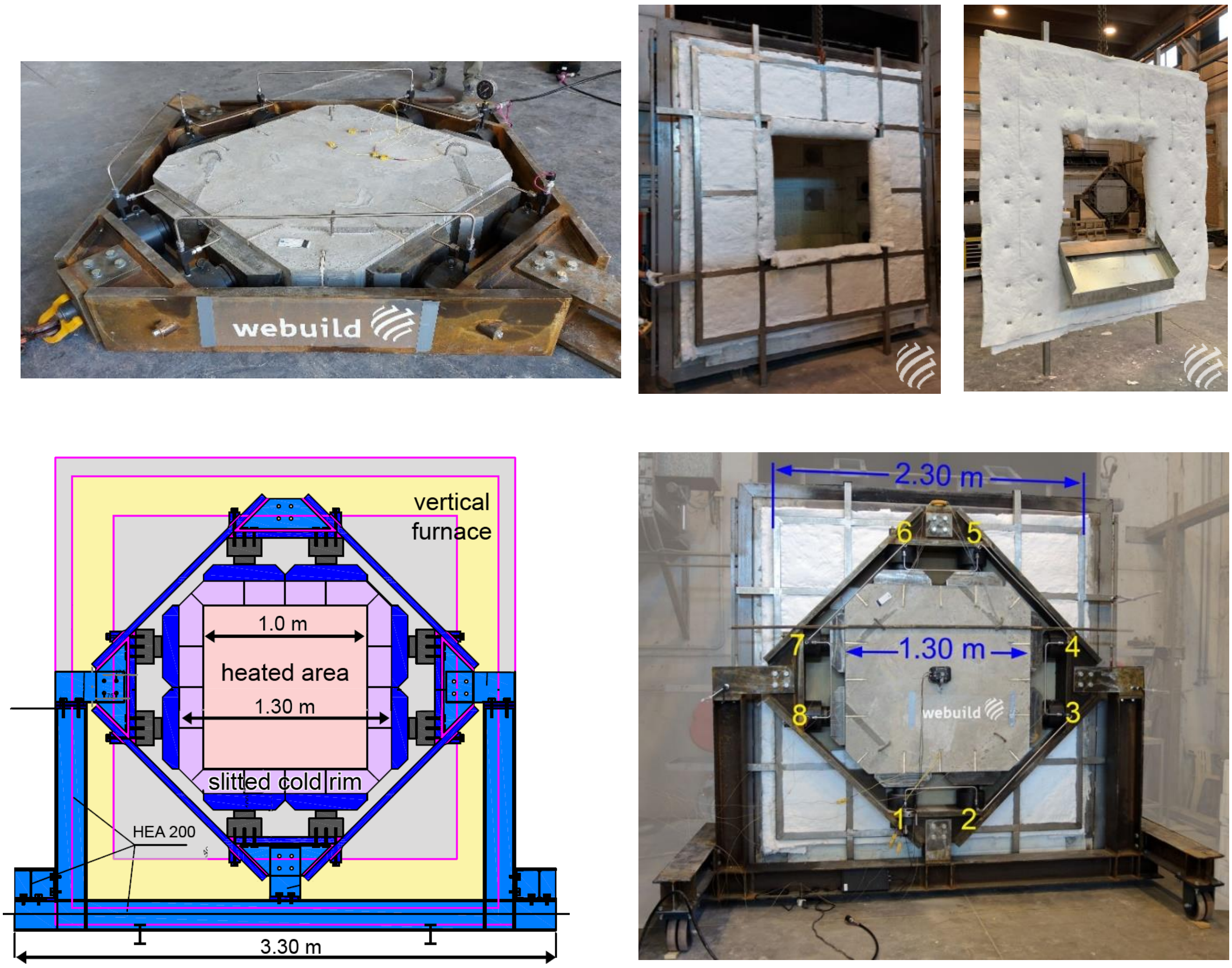

Figure 4. Specimen installation in the loading frame, insulating screen for reducing the exposed area, design sketch and final setup including the loaded specimen and the frame on the movable stand.

Figure 5. Ultrasonic pulse-echo principle, sensor array (50kHz, shear waves) and wireless pulser/receiver for real-time monitoring of slab thickness and damage; 3D laser scanner for geometrical survey of the specimen after the tests.

Concerning the real-time monitoring of spalling, the well-validated ultrasonic pulse-echo technique is implemented via a new wireless pulser and wave digitizer (Figure 5). Moreover, the total erosion undergone by the specimens is surveyed after the test by way of a 3D laser scanner.

One crucial point when relatively young specimens are being tested is the moisture content of concrete, since it is well known that spalling sensitivity tends to decrease with ageing and the consequent reduction of pore saturation. One future development for improving the representativeness of young specimens is the implementation of an accelerated drying system in which the slab is wrapped in a drainage geo-composite and enclosed in a sealed polyethylene envelope, to be connected to a two-stage vacuum pump. Compared to heating, vacuum drying is expected to minimize the internal stress due to meso-scale heterogeneity.

So far, a series of 6 tests have been performed, including different types of reinforcement (ordinary rebars or steel fibre), different amounts and types of polypropylene fibre, and two fire curves (RWS and fast raise to 450°C). Given the practicality of the proposed setup and the consistency of the results, this test method will be the reference for mix design optimization in many ongoing tunnel projects.

2.2 Real-time test survey

Concerning the real-time monitoring of spalling, the well-validated ultrasonic pulse-echo technique [22,23] was implemented via a new wireless pulser and wave digitizer (A1560 by Acoustic Control Systems, Figure 5). The test principle is based on the generation of a short pulse of ultrasonic waves via an ultrasonic sensor array installed on the cold side. The pulse propagates through the slab thickness and is back-reflected at the interface between the heated face and air. After crossing the thickness one second time, the pulse is detected at the unexposed face by the receiving stage of the same ultrasonic sensor. The initial propagation time (two times the thickness divided by the pulse velocity) is expected to smoothly increase because of thermal damage undergone by concrete. However, sudden reductions of the propagation time are observed in case of spalling, due to the stepwise thinning of the tested element.

Figure 6 shows several waves recorded in a former test [23]. By monitoring a reference feature of the wave (e.g. a negative peak) at different fire durations, a shift towards longer propagation times is observed (echo delay), due to material deterioration. It can be noticed that also the wave amplitude decreases, due to the higher attenuation in damaged concrete.

When spalling occurs, a sudden decrease in thickness is observed (at 36 minutes in Figure 6) due to the expulsion of a layer of hot concrete, this yielding to an anticipation of the reference feature of the wave (echo advance). Monitoring the echo delay, once known the temperature profile, can allow to real-time estimating the ultrasonic wave velocity variation with temperature thanks to inverse analysis.

An accurate assessment of the effect of thermal damage would require an inverse analysis in which the material decay with temperature (reduction of pulse velocity) is described via a parametric function whose coefficients are tuned so that the integral of the propagation time across the measured temperature profiles (Figure 7) matches the observed pulse delay [23]. Spalling events entail the loss of the most damaged layer, whose thickness can be determined based on the sudden echo delay reduction.

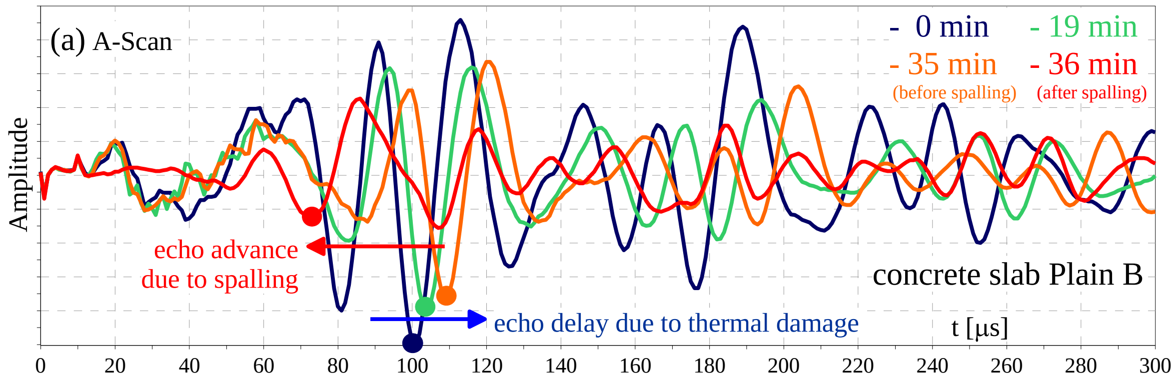

Figure 6. Ultrasonic Pulse-Echo method: waves at the receiver showing the echo delay increase due to heating and the sudden decrease due to spalling.

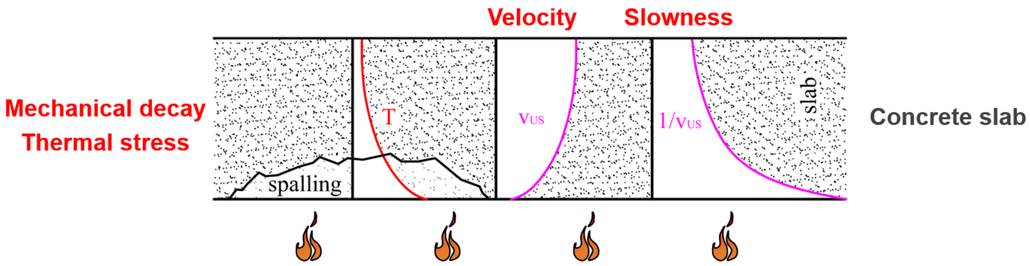

Figure 7. Concrete slab under heating: temperature and ultrasonic wave velocity and slowness profiles.

3 INITIAL EXPERIMENTAL RESULTS

3.1 Spalling depth and exposed face at the end of testing

In this paper, the results are reported from the first 6 CSST fire tests aimed at investigating the sensitivity to spalling of one Steel Fibre Reinforced Concrete mix (SFRC) for precast tunnel lining applications. In particular, the effectiveness of different dosages and types of polypropylene (PP) fibers have been studied.

The SFRC mix (characterized by CEM I type and steel fibre) is classified as C45/55 for compression (according to Eurocode 2) and 4C for tension (according to Model Code 10). Two different typologies of polypropylene fibres were considered, characterized by different geometry and Melt Mass-Flow Rate - MFR [24,25]: conventional PP fibre (CPP) with 12mm length, 34μm diameter and 25 MFR, and high-performance PP fibre (HPP) with 6mm length, 20μm diameter and 1000 MFR. One test has been performed on a reference specimen made of plain reinforced concrete (thus without any fibre).

Depending on the length of the tunnel for which the mix were intended, two different fire curves were considered according to the indications provided in [26]. The first one is the well-known RWS curve (Rijkswaterstaat, the Netherlands), also adopted by the Italian standard UNI 11076 [27] with 1350°C maximum temperature, which applies to tunnels longer than 2000 m. On the other hand, a fast raise up to the 450°C target temperature was considered for tunnels shorter than 2000 m. In all the cases, the duration of the fire test was 120 min.

In Table 1 the main information regarding the 6 tests is reported, together with the average spalling depth measured at the end of the test via the 3D laser scan. The heated face of the specimen at the end of the test is reported in Figure 8 (first column for the 450°C-fire curve and second and third columns for the RWS fire curve).

Figure 9 shows a comparison of the specimen conditions right after the RWS fire test. Specimen SFRC F27 includes PP fibre, while specimens SFRC F03 and RC (Reinforced Concrete) F08 are both without PP fibre. The incremental beneficial effect of using steel fibre especially in combination with PP fibre appears evident if compared with traditional reinforced concrete.

Table 1. Main features and results of the tested specimens.

	Test duration	Specimen	Fire curve	PP fibre	PP fibers dos. [kg/m^3]	Sample age [days]	Avg spalling depth [mm]
SFRC	120 min	F01	450°C	-	0.0	25	42
SFRC	120 min	F12	450°C	CPP	1.5	23	0
SFRC	120 min	F03	RWS	-	0.0	336	87
SFRC	120 min	V2	RWS	CPP	1.5	85	40
SFRC	120 min	F27	RWS	HPP	1.5	337	3
R/C	60 min	F08	RWS	-	0.0	366	>150

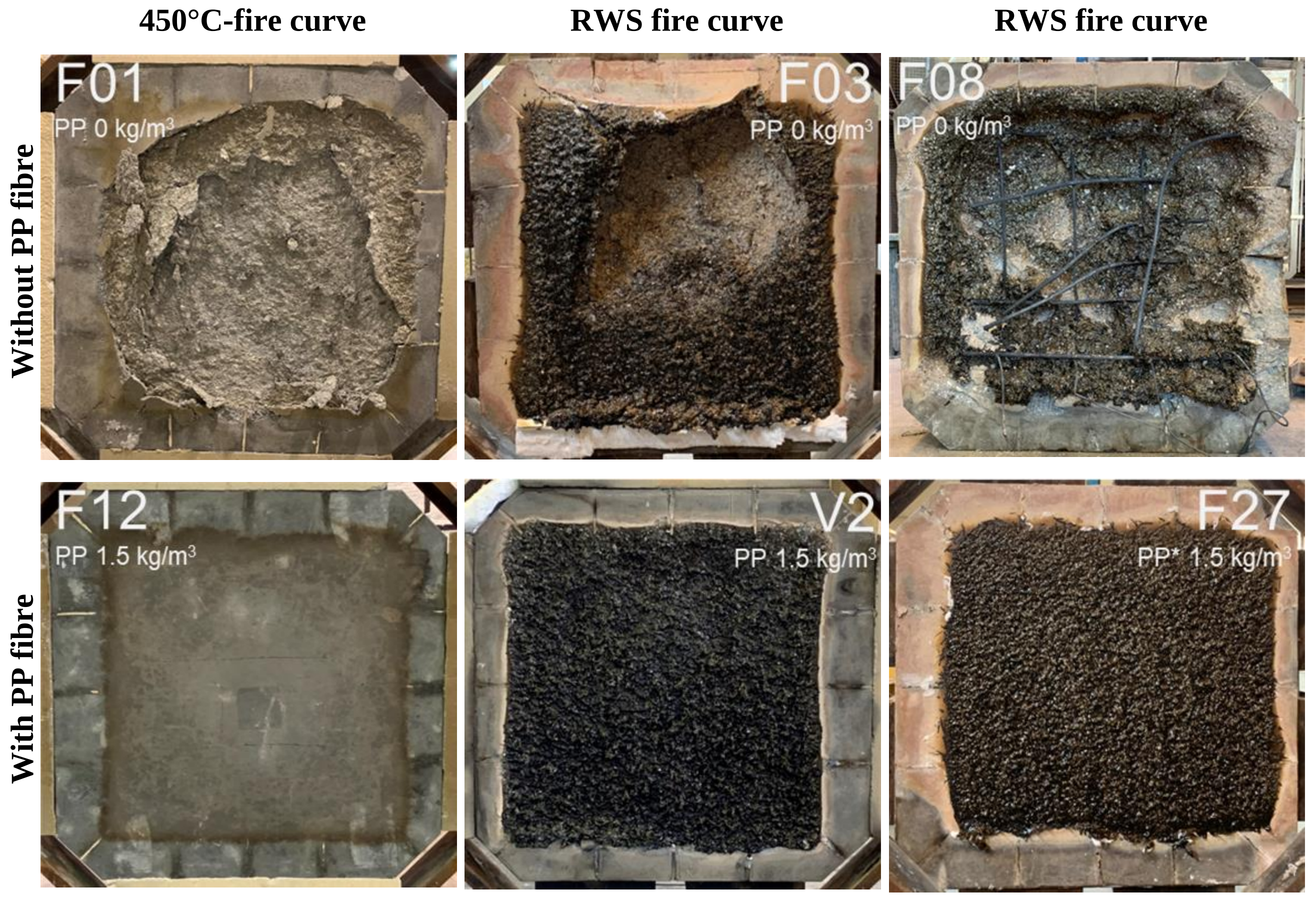

Figure 1. Exposed face of the specimens after testing (F08 is the reinforced-concrete specimen, the only with no steel fibre).

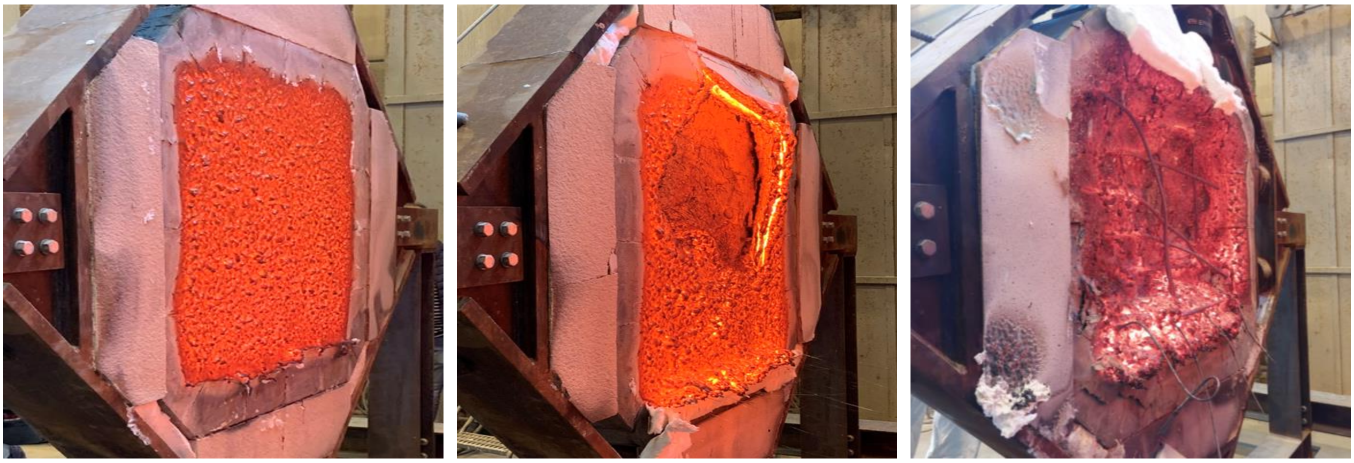

Fig. 9. Specimen SFRC F27 (left), SFRC F03 (center) and R/C F08 (right) as soon as they were extracted from the furnace.

3.2 Real-time test survey

The results of pulse-echo monitoring are summarized in Figure 10. A good consistency is observed between the echo delay trends and the final depth of erosion of each specimen. Plain concrete with ordinary rebar reinforcement (test F08) showed a remarkable spalling sensitivity, with a continuous stream of "pop corn" events which translates into a constant rate of thickness reduction. Since in this case concrete spalls before experiencing a sizable damage, the initial wave velocity (v = 2.65mm/µs) can be used to transform the echo delay reduction (140µs) into the assessed thickness of the section erosion (140µs · 2.65mm/µs / 2 = 185mm). This value is consistent with the final erosion (Table 1).

Steel fibre mitigates the impact of spalling, leading to less frequent events involving thicker splinters (test F03). In this case, the exposed face could reach higher temperatures before being detached, and the echo delay reduction should be multiplied by a smaller velocity (2.3mm/µs) to match the final thickness reduction observed via laser scans (75µs correspond to 85mm erosion). It can also be noticed that a marginal benefit is allowed by the conventional polypropylene fibre (CPP), whereas the high-performance counterpart (HPP) prevents any detachment of splinters from the heated face.

In the case of the milder fire curve (450°C), spalling gets less critical and can be prevented already by the conventional PP fibre (test F12). In case of SFRC with no PP fibre (test F01), spalling is delayed by more than one hour, when a loud blast yields to a sudden reduction of the specimen thickness.

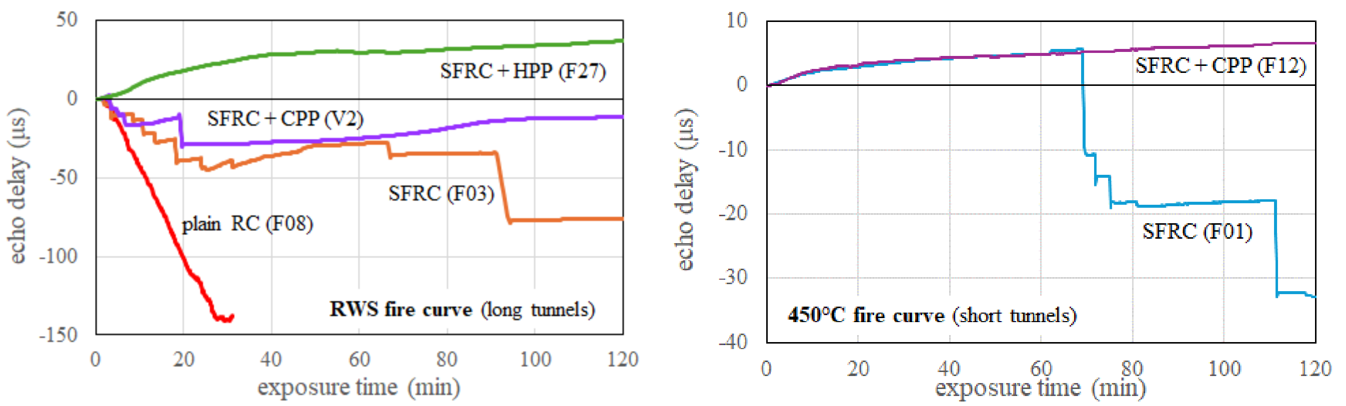

Fig. 10. Evolution of the delay of the ultrasonic pulse as a function of exposure time to the two adopted fire curves: progressive increase indicates thermal damage, stepwise decrease indicates a spalling event.

4 CONCLUSIONS

The phenomenon of explosive spalling occurring in concrete exposed to fire is a tricky as well as important aspect to be taken into account, especially regarding strategic infrastructures as tunnels. Since not reliable predictive models are yet available in Standards or Guidelines to estimate a priori concrete spalling, experimental testing is generally agreed to be the most effective way to assess spalling sensitivity in concrete mixes and structural members.

Typically, full-scale testing is considered as a reference, this however being possible to be performed only once segment production has been organized (thus not at the design stage), thus not being feasible for the initial screening of mixes. An alternative is represented by testing on unconfined slabs, this however not being representative of the final application due to the lack of external compression.

An effective compromise is represented by the herein presented Confined Slab Spalling Test (CSST). This solution consists in testing square flat slabs under biaxial in-plane compression aimed at replicating the isotropic effect of restrained thermal dilation in the central region of a precast segment.

A first series fire tests was conducted on concrete mixes with and without polypropylene fibre, exposed to two different heating curves. The observation of the final average spalling depth confirmed the beneficial effect provided by the introduction of polypropylene fibre to the concrete mix, confirming their effectiveness in reducing the likelihood of spalling in fire. Regarding the tests performed on a SFRC and on a R/C slabs with traditional reinforcement, both without PP fibers, a positive effect of steel fiber was observed, since spalling depth in SFRC specimen was significantly lower.

The role of PP fibers in preventing concrete fire spalling is well known and confirmed in the results herein presented, however there is a wide range of alternative in selecting PP fibers. Further tests are in progress to assess and evaluate the influences of different PP fiber parameters: geometry (length/diameter), quantity and melt viscosity (MFR).

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