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RILEM TC 256-SPF: Spalling of concrete due to fire: testing and modelling

Recommendation of RILEM TC 256-SPF on fire spalling assessment during standardised fire resistance tests - Complementary guidance and requirements

Pierre Pimienta, Robert McNamee, Fabienne Robert, Lars Boström, Shan-Shan Huang, Katarzyna Mróz, Colin Davie, Siyimane Mohaine, Maria Cruz Alonso, Lenka Bodnarova, Josipa Bosnjak, Stefano Dal Pont, Vinh Dao, Dorjan Dauti, Frank Dehn, Roberto Felicetti, Izabela Hager, Rudolf Hela, Tomaz Hozjan, Michael Juknat, Ulla-Maija Jumppanen, Johannes Kirnbauer, Jerneja Kolsek, Manfred Korzen, , Hitesh Lakhani, Maxime Lion, Francesco Lo Monte, Cristian Maluk, Fekri Meftah, Md Jihad Miah, Alain Millard, Jean-Christophe Mindeguia, Bérénice Moreau, Yahia Msaad, Mitsuo Ozawa, Francesco Pesavento, Duc Toan Pham, Klaus Pistol, Ieuan Rickard, Joao Paulo Correia Rodrigues, Mohsen Roosefid, Martin Schneider, Umesh Kumar Sharma, Kosmas Sideris, Ludwig Stelzner, Benedikt Weber, Frank Weise

Abstract

The recommendation is based on the co-authors work organized by the RILEM TC 256-SPF "Spalling of concrete due to fire: testing and modelling".
It aims to provide useful information, guidance and best practices in fire spalling assessment to laboratories that perform large-scale tests based on fire resistance test standards. It provides guidance on the spalling observation techniques during testing, as well as post-test spalling quantification/assessment methods.
This document is intended to be used in conjunction with the fire resistance test standards, e.g. EN 1363-1 and ISO 834-1.

Note: This recommendation has been prepared by the Work Group WG3 within RILEM SPF-256 to provide the method to evaluate concrete propensity to fire spalling in terms of material behaviour. The recommendation has been reviewed and approved by all members of the TC SPF-256.

TC Chair: Pierre PIMIENTA, CSTB, France

TC Deputy Chair and Secretary: Robert MC NAMEE, Research Institutes of Sweden and Lund University, Sweden

TC Task 3.1 – Large scale spalling Test Chair: Fabienne ROBERT, CERIB, France

TC Members: Lenka BODNAROVA (Czech Republic), Josipa BOSNJAK (Germany), Lars BOSTRÖM (Sweden), Maria CRUZ ALONSO (Spain), Stefano DAL PONT (France), Vinh DAO (Australia), Colin DAVIE (United Kingdom), Frank DEHN (Germany), Roberto FELICETTI (Italy), Izabela HAGER (Poland), Rudolf HELA (Czech Republic), Tomaz HOZJAN (Slovenia), Shan-Shan HUANG (United Kingdom), Michael JUKNAT (Germany), Ulla-Maija JUMPPANEN (Finland), Johannes KIRNBAUER (Austria), Jerneja KOLSEK (Slovenia), Manfred KORZEN (Germany), Hitesh LAKHANI (Germany), Maxime LION (France), Francesco LO MONTE (Italy), Cristian MALUK (Australia), Robert MC NAMEE (Sweden), Fekri MEFTAH (France), Md Jihad MIAH (France), Alain MILLARD (France), Jean-Christophe MINDEGUIA (France), Siyimane MOHAINE (France), Bérénice MOREAU (France), Katarzyna MRÓZ (Poland), Yahia MSAAD (France), Mitsuo OZAWA (Japan), Francesco PESAVENTO (Italy), Duc Toan PHAM (France), Pierre PIMIENTA (France), Klaus PISTOL (Germany), Ieuan RICKARD (United Kingdom), Fabienne ROBERT (France), Joao Paulo Correia RODRIGUES (Portugal), Mohsen ROOSEFID (France), Martin SCHNEIDER (Austria), Umesh Kumar SHARMA (India), Kosmas K. SIDERIS (Greece), Ludwig STELZNER (Germany), Benedikt WEBER (Switzerland) and Frank WEISE (Germany)

P. Pimienta (corresponding author); ORCID: 0000-0002-9087-5657
CSTB, Departement Securite, Structures et Feu
84, avenue Jean Jaures, F-77447 Marne la Vallee Cedex 02, France

R. Mc Namee; ORCID: 0000-0002-0380-9548
RISE and Lund University, Sweden
Ideon, Beta 5, Scheelevägen 17, 22370 Lund, Sweden

F. Robert
CERIB, Fire Testing Centre
1 rue des Longs Réages, CS 10010 – 28233 Épernon Cedex, France

Contributors: Steffen Anders (Germany), Harris Angelakopoulos (United Kingdom), Luke Bisby (United Kingdom), Hélène Carré (France), Ulrich Diederichs (Germany), Andre Klimek (Germany), Sergei Leonovich (Republic of Belarus), Asif Hussain Shah (India), Fariza Sultangaliyeva (France), Jiayi Wang (United Kingdom), Matthias Zeiml (Austria), Yiming Zhang (Austria)

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Version 20/07/2023 after review

Abstract

The fire-induced spalling of concrete is a phenomenon leading to loss of cross section during the heating phase of fire exposure. Concretes of relatively high free water content and/or of high strength are particularly vulnerable to fire spalling, as observed in real fires.
During standardized fire resistance testing, fire spalling may influence the fire resistance of an element. This recommendation aims to provide useful information, guidance and best practices in fire spalling assessment to laboratories that perform large-scale tests based on fire resistance test standards.

Keywords

Concrete - Fire Spalling - Large scale tests - Standardised fire resistance tests

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1. INTRODUCTION AND SCOPE

The fire-induced spalling of concrete is a phenomenon leading to loss of cross section during the heating phase of fire exposure. Concretes of relatively high free water content and/or of high strength are particularly vulnerable to fire spalling, as observed in real fires. During standardized fire resistance testing, fire spalling may influence the fire resistance of an element. This recommendation aims to provide useful information, guidance and best practices in fire spalling assessment to laboratories that perform large-scale tests based on fire resistance test standards.

This document provides guidance on the spalling observation techniques during testing, as well as post-test spalling quantification/assessment methods.

The fire-induced spalling can be influenced by several inter-related parameters, including thermal exposure, loading and restraint conditions, geometry, and concrete composition and properties. The examples of concrete composition and properties include the type and size of aggregate, the type and amount of cement and additives, air content, fibre dosage, moisture content, permeability, and strength.

Usually, the most influencing parameters are considered as compressive strength, moisture content and loading conditions. The risk and severity of fire spalling may increase with:

- higher compressive strength;
- higher moisture content;
- higher compressive stresses.

Large-scale fire tests primarily aim to assess the fire resistance of the final products. They could also provide useful information on the nature and extent of fire spalling. However, this usually requires the test report to be produced in a more detailed manner than required by the fire resistance test standards.

This document is intended to be used in conjunction with the fire resistance test standards, e.g. EN 1363-1 “Fire resistance tests - Part 1: General requirements” and ISO 834-1 “Fire-resistance tests — Elements of building construction — Part 1: General requirements”.
This document is based on the state-of-the-art testing procedures that are used in different laboratories. The proposed guidelines have been developed as a joint effort of the Technical Committee 256-SPF and present

the result of discussions and exchange of best practices among the members of this group.

For practical and economic reasons, there is a need for simpler screening tests to optimize the concrete composition before scaling up to element size fire resistance testing. As many different factors are influencing the phenomena of fire spalling of concrete, the guidelines for performing Material screening tests are given in a separate document “Recommendation of RILEM TC 256-SPF on the method of testing concrete spalling due to fire - material screening test”.

This document is for guidance only.

2. DEFINITIONS, REFERENCES AND SYMBOLS

2.1.General definitions

The following definitions are used in this document.

Fire spalling - the sudden breaking off of layers or fragments of concrete from the fire-exposed surface of a structural element. Depending on the severity of the phenomenon, it may or may not influence the performance of the structural member.

Fire exposed area - the surface area of the element being directly exposed to a prescribed heating scenario during the test (m2).

Reference compressive strength - compressive strength determined at the time of the fire test, measured from concrete samples that are cast from the same batch of concrete and stored under the same conditions as the test specimens (MPa).

Reference moisture content - moisture content determined at the time of the fire test, measured from concrete samples that are cast from the same batch of concrete and stored under the same conditions as the test specimens (% per weight).

Standard compressive strength – The compressive strength determined at 28 days, according to concrete testing standards, e.g. EN 12390-3.

2.2.List of normative references

ISO 834-1: Fire-resistance tests - Elements of building construction - Part 1: General requirements.
EN 1363-1: Fire resistance tests – Part 1: General requirements.
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendation, Part 1: Introduction. Materials and Structures 40(9), 855- 858 (2007)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations, Part 2: Stress-strain relation. Materials and Structures 40(9), 841-853 (2007)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations, Part 3: Compressive strength for service and accident conditions. Materials and Structures 28, 410-414 (1995)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations, Part 4: Tensile strength for service and accident conditions. Materials and Structures 33, 219-223 (2000)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations, Part 5: Modulus of elasticity for service and accident conditions. Materials and Structures 37, 139-144 (2004)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations Part 6: Thermal strain. Materials and Structures, Supplement March 1997, 17-21 (1997)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations, Part 7: Transient creep for service and accident condition. Materials and Structures 31, 290-295 (1998)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations, Part 8: Steady – state creep and creep recovery for service and accident conditions. Materials and Structures 33, 6–13 (2000)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations, Part 9: Shrinkage for service and accident conditions. Materials and Structures 33, 224-228 (2000)
RILEM TC: Test methods for mechanical properties of concrete at high temperatures, Recommendations, Part 10: Restraint stress. Materials and Structures 38, 913-919 (2005)
EN 12390-2: Testing hardened concrete - Part 2: Making and curing specimens for strength tests

EN 12390-3: Testing hardened concrete - Part 3: Compressive strength of test specimens
EN 60584-1: Thermocouples - EMF specifications and tolerances

3. TEST EQUIPMENT

The information given in below are intended to be used in conjunction with the fire resistance test standards, e.g. EN 1363-1 “Fire resistance tests - Part 1: General requirements” and ISO 834-1 “Fire-resistance tests — Elements of building construction — Part 1: General requirements”.

3.1.Furnace

A higher heating output is required to sustain a certain fire curve when concrete spalls and exposes the inner cooler concrete. The power of the furnace should, therefore, be high enough for testing that expects fire spalling. This is particularly necessary when adopting higher heating rates such as RWS.

Note: In order to achieve the RWS curve, modified hydrocarbon curve or any other fire curves where a rapid rise of furnace temperature is needed, insulation blankets/boards can be installed on the bottom of the furnace to minimise heat loss.

3.2.Furnace thermocouples

Some thermocouples in the furnace could be damaged due to spalling, thus it is suggested to adopt additional thermocouples in case of failure during testing.

Note: Despite type K thermocouples not being calibrated for temperatures higher than 1200°C [EN 60584-1], they are still sufficient based on past experience.

4. TEST CONDITIONS

4.1.Furnace atmosphere

The heating and pressure conditions and the furnace atmosphere shall conform to those given in general fire resistance standards and other documents specifying furnace conditions.
Alternative heating regimes, such as slow heating rates, ramps, RWS, and modified hydrocarbon curve, may be used depending on the scope of the testing.

4.2.Loading and restraint/boundary conditions

The load and restraint shall conform to the requirements given in general fire resistance standards or other documents specifying loading and restraint/boundary conditions.

Note 1: The loading and restraint/boundary conditions are of high importance and can induce very different spalling behaviour.
Note 2: The risk and severity of fire spalling increase when compressive stresses increase. Since continuous beams can also be subjected to compression over support, it is essential that the test configuration can reproduce this stress state.

5. TEST SPECIMEN(S)

5.1.Size and design

The size of specimens shall conform to the requirements given in general fire resistance standards or other documents specifying the size of the tested specimen.

The size and shape of specimens shall reflect the end-use conditions in terms of curvature and internal stresses due to non-uniform temperature distribution.

- **Note 1**: Spalling is significantly influenced by the geometry of a specimen.
- **Note 2**: It is important to report the specifications (size, position, spacing, etc.) of the reinforcement bars.

5.2.Material characterisation

The following material characteristics should be determined:

- Standard compressive strength (see 2.1 and 5.2.1)
- Reference compressive strength (see 2.1 and 5.2.1)
- Reference moisture content (see 2.1 and 5.2.2)

Note 1: It is particularly important to report the following parameters:

- Nature of constituents
- Concrete mix
- Fibre dispersion

Note 2: The mixing technique (mixing time, vibration, etc.) can also be reported

Note 3: The field of application of test results will depend on the information given in the report (a larger quantity of information should allow to assess a larger field of application).

Note 4: If mechanical properties at high temperature are to be determined, RILEM TC Recommendations: Test methods for mechanical properties of concrete at high temperatures: Part 1 – 10, can be followed.

5.2.1. Compressive strength

The risk and severity of spalling increase when concrete compressive strength increases. Therefore, care shall be taken to ensure that concrete strength of the tested element is representative of the one used in practice.
It is recommended to determine the standard compressive strength at 28 days according to concrete testing standards, e.g. EN 12390-3, as well as the reference compressive strength as close as possible to the testing date with samples stored next to the tested specimen with the same curing conditions as the core of the specimen (generally sealed conditions).

5.2.2. Moisture content

The moisture content of the tested specimen shall be determined as close as possible to the testing date. Moisture equilibrium is in general reached after a few years and a moisture gradient will be generally observed. It is thus recommended to determine moisture content at the surface of the exposed side (in the first 5 cm, and even if possible from 0 to 2.5 cm depth and from 2.5 to 5 cm depth) and in the inner region of the cross-section (more than 5 cm depth).

The recommended procedure to determine the moisture content in the first 5 cm is to mould cylindrical specimens with the following dimensions:

- a minimum diameter of 0.10 m,
- length equal to the thickness of the specimen being tested.

To provide the same curing conditions, the perimeter of the specimens shall be left in plastic moulds to the time of testing or demoulded and sealed with aluminium tape around the sidewall of the cylinder.

To determine the moisture content, the specimen shall be cut by splitting or dry sawing.

This sample should be weighed, and then dried in an oven operating at a temperature of (105 ± 5) °C until a mass equilibrium is reached. The mass equilibrium is defined as when two successive weight measurements at 24 h intervals during the drying process differ by less than 0.1%. The moisture content is then calculated with the difference between the original and dried mass divided by the dried mass.

Three specimens from each batch are required.

6. CONDITIONING

The condition of the test specimen should, at the time of test be similar with respect to its strength, moisture content and moisture profile to the element as it would be in normal service. Conditioning has an impact on the spalling propensity of concrete. Therefore, it is important to define the conditioning in relation with the end use of the element. It could take a very long time to reach a stabilised state, therefore a minimum 3 months storage period is recommended in the standards.

Note: When the unique aim of the test is to determine spalling propensity (no temperature measurement is intended to be performed for any assessment related to the fire design) and when the microstructural properties are considered to have reached a stabilised state, the tests can be performed before 3 months. The higher moisture content of specimens tested before 3 months can lead to more severe spalling. This shorter conditioning can then lead to over conservative results.

The conditioning of the fire-exposed side of the element must be carefully done and reported. For example:

- the exposed side should not be in contact with the floor of the conditioning room;
- when several specimens are stored together, it is mandatory to allow air circulation in between the specimens.

Accelerated conditioning is mentioned in several fire resistance standards, however, it is not recommended for the fire testing of concrete elements that includes fire spalling assessment. This is because accelerated conditioning may impact particularly the moisture profile and alter the spalling behaviour. In fact, there is insufficient scientific evidence to confirm that accelerated conditioning:

- does not alter the material properties of concrete;
- delivers the targeted moisture content and moisture profile that are representative of those in service;
- does not alter the spalling propensity of the test specimens, compared to those stored in conditions that allow the target moisture equilibrium to be reached naturally.

7. APPLICATION OF INSTRUMENTATION

7.1.Furnace thermocouples (plate thermometers)

The debris of explosive fire spalling could damage furnace thermocouples. It is recommended to install additional furnace thermocouples or allow the flexibility of replacing damaged thermocouples during testing. Fixing of the furnace thermocouples should consider the possible impacts of flakes.

7.2.Unexposed surface thermocouples

Adhesion of the thermocouples should be waterproof as water frequently leaks from the unexposed surface.

7.3.Internal thermocouples

Sometimes, internal thermocouples are positioned in order to provide some complementary information on the progress of spalling. However, this information should be used with care, since it may lead to misinterpretation due to localised spalling, which is not monitored with this method.

Internal thermocouples are also used to record the evolution of the temperature distribution in a specimen, which can be used to validate thermal models. For thermal model validation, thermocouples could be embedded in the specimen at the following depths from the heated surface: very close to the heated surface, 20 mm, 30 mm, 40 mm and 50 mm.

It is also useful to install internal thermocouples onto the reinforcements and to measure the rebar temperatures for the assessment of the load bearing capacity of the specimens. Preferably, the thermocouples should be positioned where the maximum and minimum temperatures of the rebars are expected (see Figure 1), or, at the mid-depth of a rebar.

Figure 1: Example of thermocouple installation for rebar temperature measurements

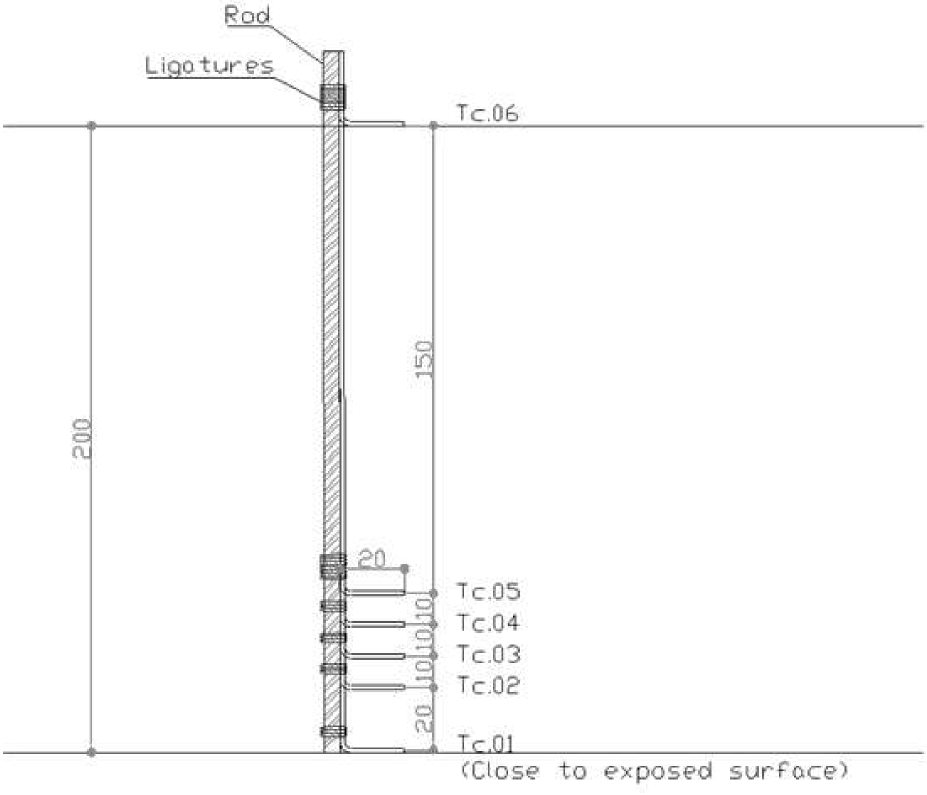

Figure 2: Example of thermocouple tree arrangement

The thermocouple wires should be positioned along an isotherm for a distance of at least 10 mm depending on the type and fixing of the thermocouples (Figure 2). The stiffer the thermocouples wire is, the longer the bent zone should be in order to avoid damaging the thermocouple and consequently the higher the radius of curvature should be. The positioning of the thermocouple (embedded depth of the thermocouple from the exposed surface) is very crucial. During casting, pouring fresh concrete directly onto the thermocouple trees should be avoided. In addition, the flow of concrete and vibration could also alter the thermocouple positions, so special attention should be paid to prevent that.

8. TEST PROCEDURE

8.1.General

The general requirements for test procedures, such as load application and furnace temperature that are given in the fire resistance testing standards should be followed. The following sections provide additional guidance on measurements that are specifically needed for the assessment of spalling behaviour.

8.2.Measurements before the test

It is recommended to measure the reference compressive strength (see 5.2.1) and moisture content (see 5.2.2) of the test specimens, as close as possible to and before the testing date.

For specimens with uneven surfaces exposed to heating, the initial surface profile should be measured before testing to enable the measurement of the spalling profile after testing.

8.3.Measurements and observations during the test

The recommended measurements and observations to characterise spalling behaviour during a test are:

- visual and acoustic observations of spalling, including the time (initial and final) and the type (local, generalised or corners, size of flakes, severity, etc.) of the spalling events.
- time at which the reinforced bars at different depths are exposed due to the occurrence of spalling.

Video and acoustic recording throughout the test is recommended.

8.4.Measurements after the test

Measurements of the spalling depth should be performed as soon as possible after cooling down without any treatment of the surface, e.g. brushing.

> Note: In some cases, especially when calcareous aggregates or limestone filler are involved, rehydration processes during cooling could lead to an additional loss of surface concrete after a test. In this case, measurements should be performed as soon as possible after the test, taking into account the safety of the operators and equipment.
> The chemical transformations taking place are the following:
> $CaCO_3 \rightarrow CO_2 + CaO$ decarbonation of calcareous aggregates during the heating phase. It usually occurs at about 700°C
> $CaO + H_2O \rightarrow Ca(OH)_2$ rehydration, i.e. transformation from quicklime to slaked lime, during the cooling phase

8.4.1. Spalling depth

The measurements of spalling depth may be performed manually in a mesh. The mesh size should be determined to provide a good representation of the average spalling depth and the spalling profile. It is also recommended to have at least 100 measurement points throughout all the heated surfaces of a specimen (Figure 3). In the case of localised spalling, the number of measurement points may be increased over the spalled areas (Figure 4). The number of measurement points may also be increased if the test specimen has a complex geometry. In terms of very large test specimens, a maximum 50 cm mesh size is recommended. For slender specimens (e.g. slender columns and beams), no less than three lines of measurements per direction for each heated face are recommended.
The measurement points adjacent to the edges of a heated surface should locate at half of the mesh spacing away from the edge in the relevant direction (an example can be seen in Figure 3).

Other methods like automatic 3D scanning or digital planimetry to map the spalling profile may be used.

The accuracy of the measurement devices shall be less than ± 2 mm.

The spalling behaviour may not be homogeneous on the whole surface, therefore, the average spalling depth across the entire heated surface, as well as the average spalling depth within each spalled area should be obtained.

Based on the measured data, the following information should be obtained:
- Area of the spalled surface (spalling area);
- Average spalling depth across the entire heated surface;
- Average spalling depth within each spalled area (omitting the non-spalled areas);
- Maximum spalling depth (separate measurement is needed if the point at which the spalling depth is the maximum is none of the points of the measurement mesh).

Examples of spalling depth analysis are shown in Figures 3-5.
The spalling profile analysis on a beam of dimensions 460 cm x 60 cm x 25 cm is shown in Figure 3. It was exposed to heating on three sides in a 4 m length furnace and was mechanically loaded. A 40 cm x 10 cm mesh is adopted to measure the spalling depths at the cross points of the mesh. The red dot indicates the location of the maximum spalling depth. The spalling depth at each measurement point is given in the Table 1. The calculated spalled area, average spalling depths and maximum spalling depth are also given in the table.

Figure 3: An example of grid for spalling depth distribution analysis on a rectangular beam

Table 1: Spalling depth determined on the beam presented in Figure 3 at each measurement point and calculated spalled area, average spalling depths and maximum spalling depth.

Spalling depth (mm)		Measurement points along the length of the beam (cm)									
		20	60	100	140	180	220	260	300	340	380
Measurement points along the heigth of the beam (cm)	5	15	17	25	21	19	20	17	16	10	12
	15	18	21	28	24	23	22	25	23	22	21
	25	5	0	20	32	33	31	18	16	32	15
	35	0	0	0	0	4	8	12	11	13	11
	45	0	0	0	0	0	0	0	3	0	6
	55	0	0	0	0	0	0	0	0	0	0

Spalled area (%)	0.62
Average spalling depth across the heated surface (mm)	11
Average spalling depth within the spalled area (mm)	18
Maximum spalling depth (mm)	35

Another example of the spalling depth distribution analysis, when localised spalling is observed, is shown in Figure 4. This beam is tested in the same project as for the specimen shown in Figure 3. They are of the same dimensions and subject to the same heating and loading. This beam contains polypropylene fibres, whereas the beam shown in Figure 3 does not. The spalling area of this beam is much smaller than that shown in Figure 3. The spalling measurement mesh has been adapted to accommodate such a localised spalling pattern. Apart from the mesh that distributes uniformly throughout the specimen surface, a finer mesh (10 cm x 10 cm) is used on each of the spalled areas. The red dot again indicates the position of the maximum depth.

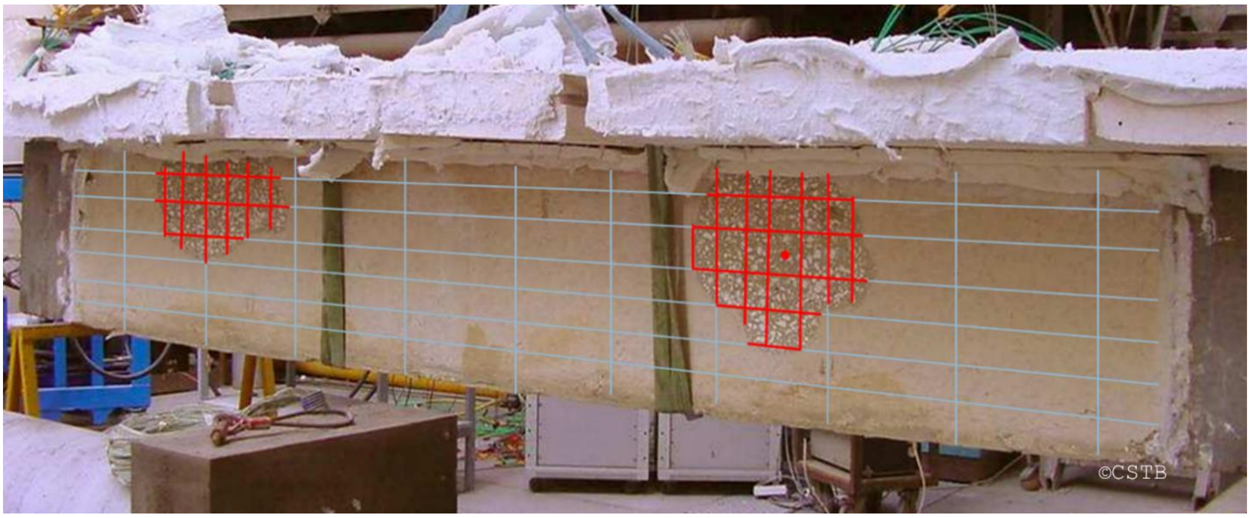

Figure 4: An example of spalling depth distribution analysis on a rectangular beam with localised spalling

Finally, Figure 5 provides an example of spalling depth distribution measured with automatic 3D scanning. The sample is a tunnel lining segment made with fibre reinforced concrete. The lower graph in the Figure 5 gives the histogram of the percentage of the spalled area versus the spalling depths.

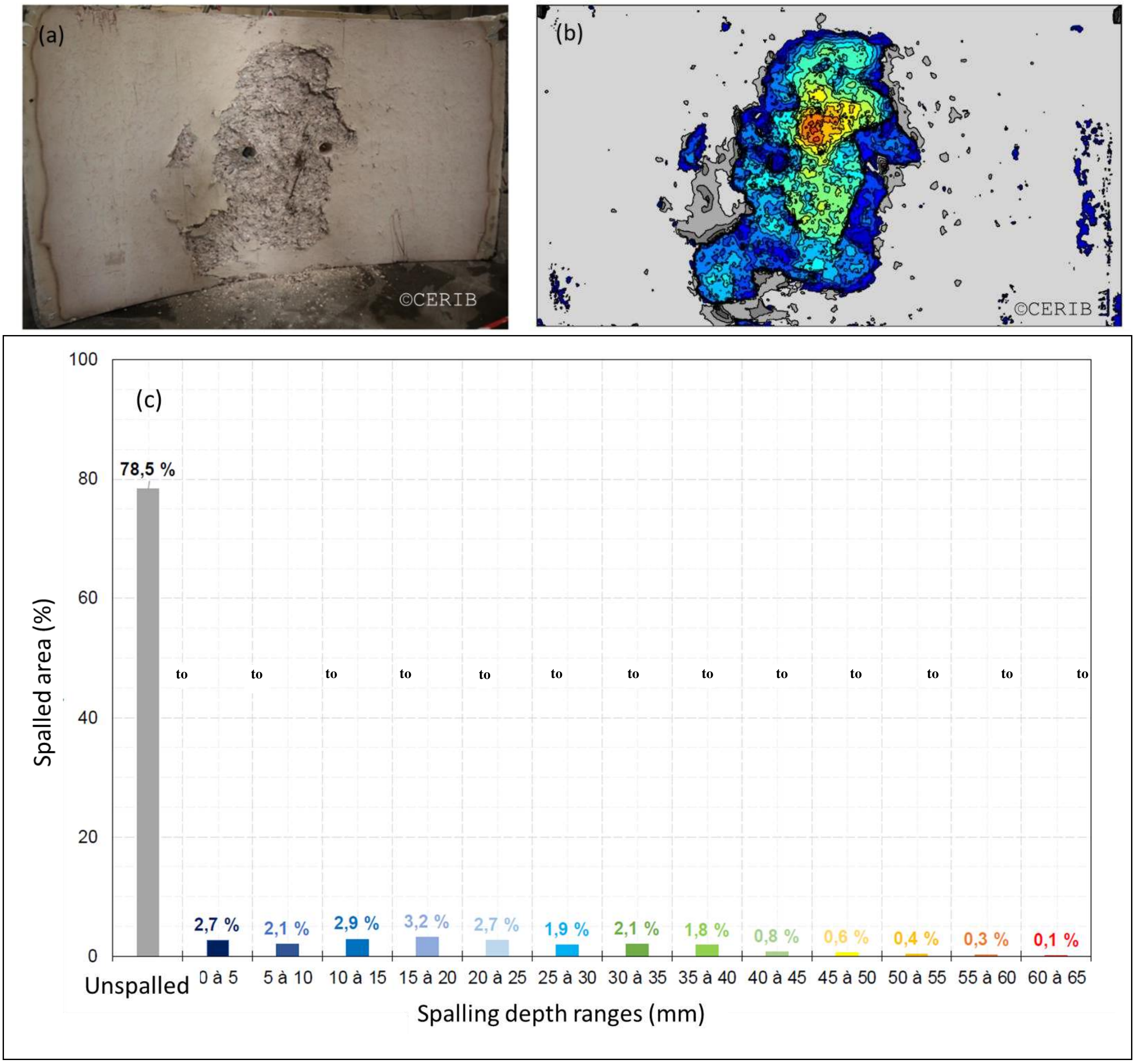

Figure 5: An example of spalling depth distribution measured with automatic 3D scanning including a picture of the spalled specimen after the fire test (a); the contours of the spalling depths (b) and the histogram of the percentage of the spalled area versus the spalling depths (c)

8.4.2. Spalled particle/flake observations

After the furnace chamber is cooled down, the inspection of the spalled material may be carried out. The description of the spalled particles shall contain the information about:

- Size of the representatives of particles, approximate volume and description of the shapes;
- Photograph of spalled flakes.

In case of a large amount of spalling, it is illustrative to provide the photograph of representative spalled particles along with the size reference, ex. with a linear ruler.

Note: the inspection described above can be made difficult in cases where several specimens are tested together.

9. TEST REPORT

The test report should follow the fire resistance standards that the testing has followed. The test report should include any test procedures that are different from those given in the test standards/recommendations. The following additional information should also be included:

- The actual (not nominal) concrete mix composition by volume, including water-cement ratio, cement type, size and type of aggregates, type of additives and admixtures;
- Fibre material (i.e. steel, polypropylene, etc.), type (i.e. monofilament, fibrillated, etc.), brand, shape, diameter, length and dosage, if fibres are used;
- Reinforcement bars position;
- The relevant properties of concrete, such as the standard compressive strength (see 5.2.1), reference compressive strength (see 5.2.1) and reference moisture content (see 5.2.2);
- Spalling measurements and observations as described in Sections 8.3 and 8.4.