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

Recommendation of RILEM TC 256-SPF on the method of testing concrete spalling due to fire - material screening test

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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". The Committee has defined two types of screening tests for characterization of concrete propensity to fire spalling: Material screening tests and Product screening tests. Definitions of both types of tests are given in the paper. The following recommendations apply to Material screening tests.

The material screening tests described in these recommendations are a set of minimum requirements to test concrete spalling propensity (for example, the minimal specimen size). This document covers the aspects of concrete characterization, specimen geometries, storage conditions, test methods and measured parameters.

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.

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Introduction and scope

Fire spalling of concrete is a phenomenon leading to a loss of cross section during the heating phase of fire exposure of structures. Especially concrete structures including much free water and/or high strength concrete have been seen to spall during real fires.

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.*

During real fires and standardized fire resistance testing, fire spalling influences the fire resistance of the element. However, 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, these guidelines for performing ***Material screening tests*** *are given to promote a sound methodology.*

The RILEM Technical Committee 256-SPF has analysed a variety of spalling tests, from simplified screening tests to the final assessment of fire resistance based on large scale tests. Based on this analysis this recommendation is given.

Screening tests should be simple and allow to sort, in a reliable way, different concrete mixes in a relative spalling propensity scale. The aim of large-scale fire resistance tests is to determine the behaviour of the final products and, if the documentation is done in a more detailed manner than required in the fire resistance standards, to provide detailed information on the nature and extent of fire spalling, i.e., giving absolute values of the amount of fire spalling in the standardized fire scenario.

The Committee has defined two types of screening tests: Material screening tests and Product screening tests. Definitions of both types of tests are given below.

> ***Material screening tests*** *are generally a need for teams which are working on material development and do not yet know the end use of the material. At this stage, the final application of the concretes (column, slab, beam, wall …) is generally not known. The goal of the tests is then to compare the spalling behaviour of concrete mixes: for example, the influence of different natures and dosages of constituents (aggregates, cement, fibres…).*

Product screening tests *are screening tests when the test setup is optimized to replicate a specific end use as well as possible. Their purpose is to optimize the concrete mix before testing the fire resistance of concrete elements with standardized test methods. Product screening tests should not be directly used to assess the behaviour of real elements due to the limited knowledge regarding scaling laws for fire spalling.*

The following recommendations apply to Material screening tests. Recommendations on complementary measurements for fire spalling characterization during large scale fire resistance tests are given in a separate document.

Then, it is important to emphasize that the aim of these tests is not to provide results that could be directly used for assessing the spalling behaviour of concretes for particular applications (columns, slabs, beams, walls, etc.) i.e., the results cannot be used to assess the fire resistance of particular applications.

It is important that the thermal and mechanical boundary conditions used during the material screening tests are severe enough to be able to make a relative grading between concrete mixes. In the case the test conditions are not severe enough, most of the tests lead to no spalling and then it is not possible to compare the different mixes. The application of external compressive stresses can be used to adjust this severity. Then, depending on the tested concretes (compressive strength), it could be necessary to adjust the severity (compressive stress) of the tests to be able to do the relative grading of the concrete mixes.

The material screening tests described in these recommendations are a set of minimum requirements (for example, the minimal specimen size).

This document covers the aspects of concrete characterization; specimen geometries, storage conditions, test methods and measured parameters.

This document is for guidance only.

1. DEFINITIONS, REFERENCES AND SYMBOLS

1.1. General definitions

The following definitions are used within 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.

Screening test - test performed to verify the propensity of concrete to spalling during fire exposure. The screening test is used when pre-selection of concrete mix is required before fire resistance testing and for comparative studies.

Material screening tests - test performed to compare the spalling behaviour of concrete mixes: for example, the influence of different natures and dosages of constituents (see section Introduction and scope).

Product screening tests - tests performed to optimize the concrete mix before testing the fire resistance of concrete elements with standardized test methods (see section Introduction and scope).

Unexposed rim - part of a concrete slab edge that is not directly exposed to the heating source, usually protected during the fire test with an insulation material. During the fire test, this unexposed rim, especially if reinforced, restraint the thermal dilation of the concrete cross section.

Fire exposed area - the surface area of the element being directly exposed to a prescribed heating scenario during the test (m^2).

Reference compressive strength - compressive strength determined at the time of the spalling screening test, measured for 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 spalling screening test, measured for 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.

1.2.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

1.3. List of symbols and notations

T temperature (°C)
ΔT temperature difference or temperature rise (K)
t time (min)
RH relative humidity (%)
D thickness of specimen (m)
L length of element side or diameter of element (m)
a length of the fire exposed area side or diameter of the circular fire exposed area (m)
b width of unexposed rim (m)

2. TESTED MATERIALS - TYPES AND CHARACTERIZATION

2.1. Material type

The recommendation applies to all families of concretes used in construction works, including ordinary concrete, high-performance concrete, lightweight concrete, fibre reinforced concrete, self-compacting concrete, etc.

2.2. Concrete mix proportions

Concrete mix proportions shall be determined according to the concrete designed in practice. The tested concrete mix, type and reference of the constituents and mix proportions, (kg/m^3) should be provided in the test report. It is particularly important to state the nature, type, and size of aggregate used.

2.3. Concrete properties

The standard and reference compressive strength shall be tested.

The standard compressive strength shall be determined at 28 days according to EN 12390-3 on samples prepared and cured according to EN 12390-2.

The reference compressive strength of concrete shall be determined at the time of the spalling screening test,

using samples of the same geometry as for the standard compressive strength test, cast from the same batch and stored in the same conditions as the spalling screening test specimens.
The reference moisture content shall be determined as described in Chapter 5.

Other information about concrete properties that are relevant to spalling may be provided but are not mandatory, i.e.:

- Physical properties: density, porosity, gas permeability, thermal strains during heating, etc.
- Mechanical properties: tensile strength, modulus of elasticity.
- Other.

A description of the test methods used for this additional characterization shall then be provided.

If mechanical properties are determined at high-temperature, the RILEM TC Recommendations: Test methods for mechanical properties of concrete at high temperatures: Part 1 – 10, should be applied.

3. SPECIMENS

The concrete specimens for screening tests shall be square, rectangular, or round slab-shaped samples.

The number of specimens for each concrete mix depends on the testing purposes and shall be adjusted so that it can be justified that the test allows correct interpretation of the results.

The specimens referred to in these recommendations may be laboratory cast or field cast. It is necessary to provide appropriate specimens casting conditions and formwork quality to ensure dimensional accuracy.

If thermocouples or other sensors are used inside the specimen, it may affect the spalling behaviour.

3.1. Geometries

The recommended geometries of specimens for unloaded, loaded, and restrained tests are as follows:

3.1.1. Square or rectangular slab specimens

For square or rectangular slab specimens, the following dimensions are recommended:
- min. length of element sides *L,* 0.50 m;
- min. length of the fire exposed area sides *a*, 0.40 m;
- min. slab thickness *D*, 0.30 m- when the slab is tested unloaded;
- min. slab thickness *D*, 0.20m - in case of restrained samples;
- min. slab thickness *D*, 0.15 m - in case of applied load.

3.1.2. Round slab specimens

For round slab specimens, the following dimensions are recommended:
- min. diameter of the slab *L*, 0.6 m;
- min. diameter of the circular fire exposed area *a*, 0.5 m;
- min. slab thickness *D*, 0.30 m - when the slab is tested unloaded;
- min. slab thickness *D*, 0.20 m - in case of restrained samples;
- min. slab thickness *D*, 0.15 m - in case of applied load.

3.2. Reinforcement

Specimens may be tested with or without reinforcement. Reinforcement can be used in unexposed rim to provide restraint. The description of this approach is given in section 4.3.

3.3. Curing and storage conditions

After demoulding, the concrete samples should be stored for 7 days wrapped in plastic to prevent drying. Then the plastic is removed, and the samples can be stored in room conditions. The room conditions shall be specified, and the temperature and RH % range shall be reported. All sides of the sample shall have a free air space of min 10 cm in each direction.

If other curing and storage conditions are applied, they should be described, and the reasons for such discrepancies should be indicated in the test report.

3.4. Age at the time of testing

All concrete samples that are used for comparing the spalling behaviour of concrete mixes should be tested at the same age.
If there are no specific requirements provided, the age of the concrete at the time of testing should be at least 90 days. If concrete is tested at an earlier age, the reason for this deviation shall be reported.

4. TEST CONDITIONS AND MEASURED PARAMETERS

Concrete spalling screening tests may be performed on concrete slabs positioned vertically or horizontally and heated from one side. The following categories of tests are defined:

a) with no external mechanical load; or
b) with external in-plane compressive loading using: (i) a post-tension system; (ii) a steel frame and lateral hydraulic jacks or (iii) other setups applying compressive load; or
c) with restraint to thermal dilation of concrete element using (i) a steel ring, (ii) continuous steel frame or (iii) unexposed concrete rim with steel reinforcement.

4.1. Installation of specimen

The specimen shall be installed in a vertical or horizontal position. In the case of horizontal positioning, the specimen may be hung on a sling or simply supported on the frame of the furnace. One or several samples can be tested at once.

4.2. Heating system, heating scenario and test duration

The heating system shall be capable of heating the test specimen to obtain a homogeneous thermal exposure.

During the test, the specimen shall be heated to follow a prescribed fire exposure. The recommended fire exposure is the standard fire curve as defined in ISO 834-1. In this document, the relationship T (t) represents the temperature T, at 100 mm from the surface of the tested element as measured by a plate thermometer defined in ISO 834-1. This temperature is a function of time t in minutes:

$$T(t) = 20 + 345\log_{10}(8t + 1) \quad (°C)$$

Test duration should be at least 30 minutes and shall be the same for all tested specimens in the test campaign.

If the fire exposed area is larger than one metre in one of the dimensions, it is recommended to introduce at least two plate thermometers for temperature measurements in the furnace.

If the shadowing effect of the plate thermometer in front of the test specimen is deemed to be significant, it is possible to calibrate the furnace with the reading of the plate thermometer as a reference. In practice, a non-spalling element is tested with a plate thermometer and an ordinary shielded thermocouple in parallel according to Figure 1. During the calibration experiment, the furnace is regulated to follow the standard fire curve measured with the plate thermometer. Then the recording of the temperature of the shielded thermocouple in this calibration run is used as the new reference to follow when only a shielded thermocouple is used in the test setup. When testing with this calibrated setup, the shielded thermocouple can only be positioned in the exact same position as during the calibration run.

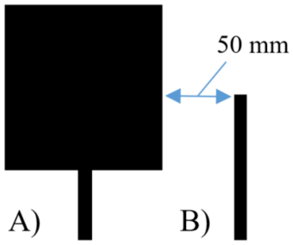

Figure 1: (A) Plate thermometer and (B) ordinary shielded thermocouple in parallel 100 mm from the surface of the test specimen. The measurement point of the shielded thermocouple is 50 mm from the side of the plate thermometer.

4.3.Mechanical boundary conditions

4.3.1. Tests on externally loaded specimens (loaded)

The compressive load shall be applied in-plane uniaxially or biaxially on the specimen using:
- a post-tension system, or
- lateral hydraulic jacks, or
- other systems enabling the in-plane uniaxial or biaxial loading.

In loaded slabs, a uniform distribution of the load is required. The specimen and the loading device shall be designed to meet this requirement (ex. specimen surfaces transferring the load shall be plane and parallel; the surface of steel platens distributing the load shall be plane).

The external load shall be adjusted to compare in an efficient way the spalling behaviour of the concrete mixes. The recommended applied stress is 2 MPa. Load shall be applied statically, and the load level shall be stabilised before the heating starts. During the test, the change of the load should be continuously monitored.

If allowable by the loading system (ex. hydraulic jacks), a constant load should be maintained during the test.

4.3.2. Tests on specimens with restraint to thermal dilation (restrained)

Restraining the thermal dilation of specimens can be achieved by:
- an external steel frame (Figure 2) or
- an unexposed concrete rim with steel reinforcement stirrup (Figure 3) or

- a steel ring (Figure 4).

In case of the restraint to thermal dilation by a reinforced unexposed concrete rim, the unexposed rim width *b* shall be of minimum 0.10 m (Figure 3).

If a steel frame or a steel ring is used to restrain the concrete thermal dilation:
- the steel shall be cleaned from rust and oil before casting;
- there shall be no gap between steel and concrete before the fire test;
- the heating up of steel shall be minimized.

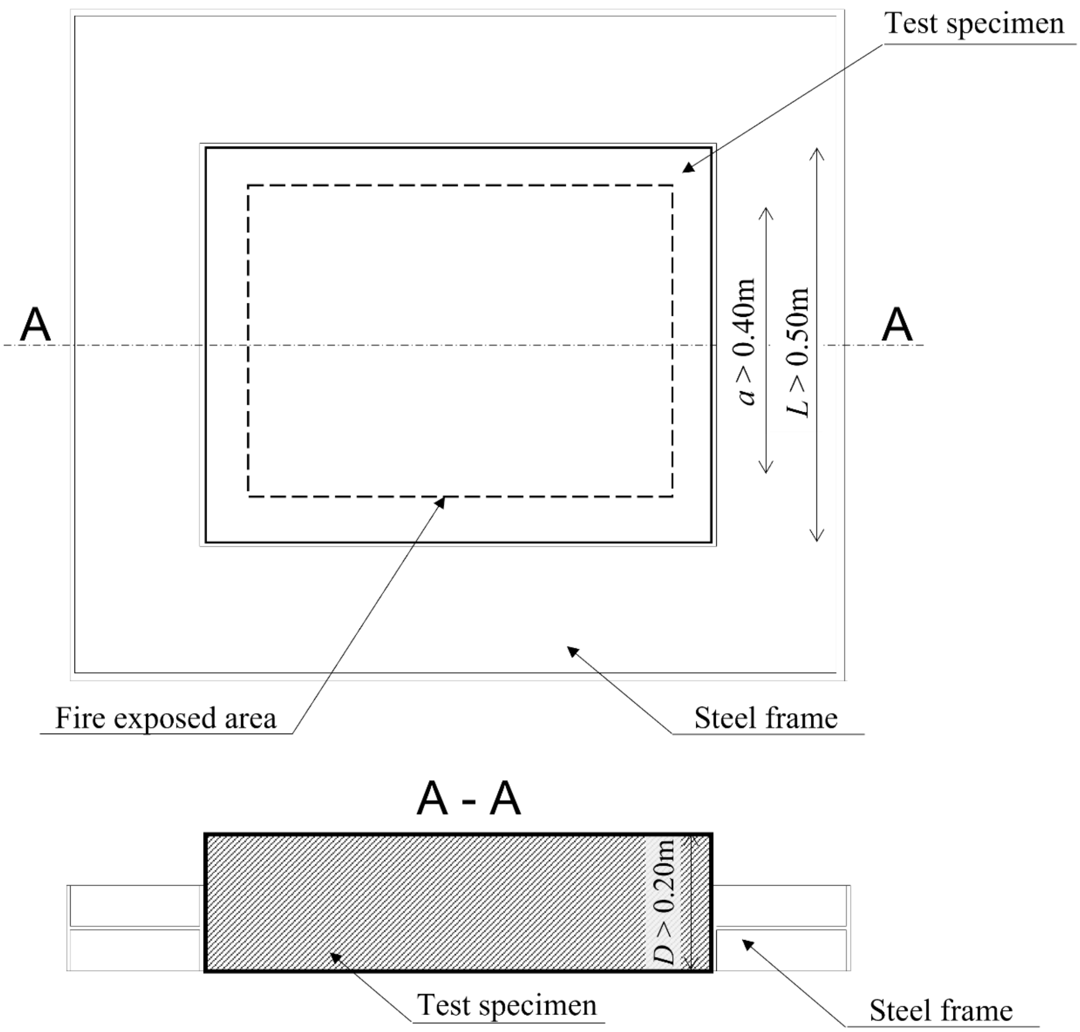

Figure 2: Example of restraint with an external steel frame.

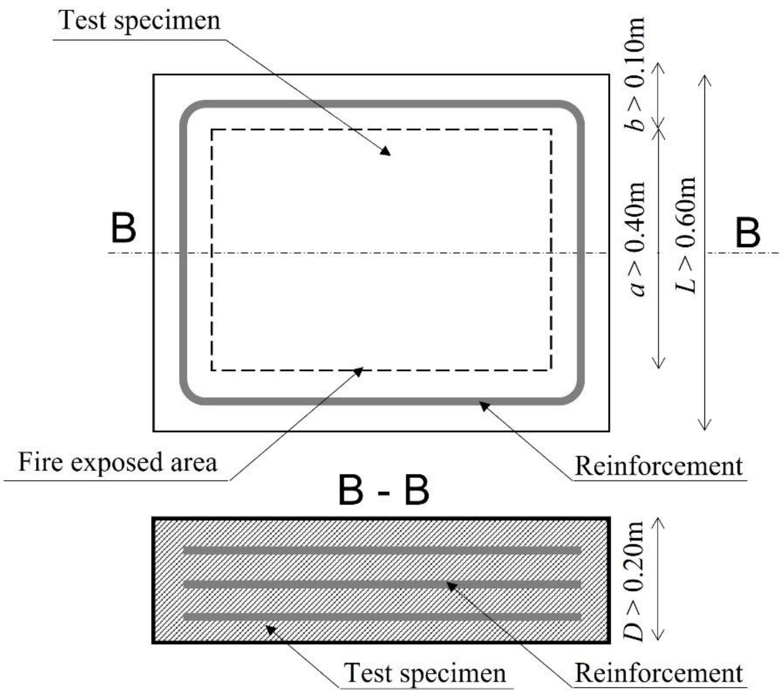

Figure 3: Example of restraint with steel reinforcement in the cold rim of the specimen.

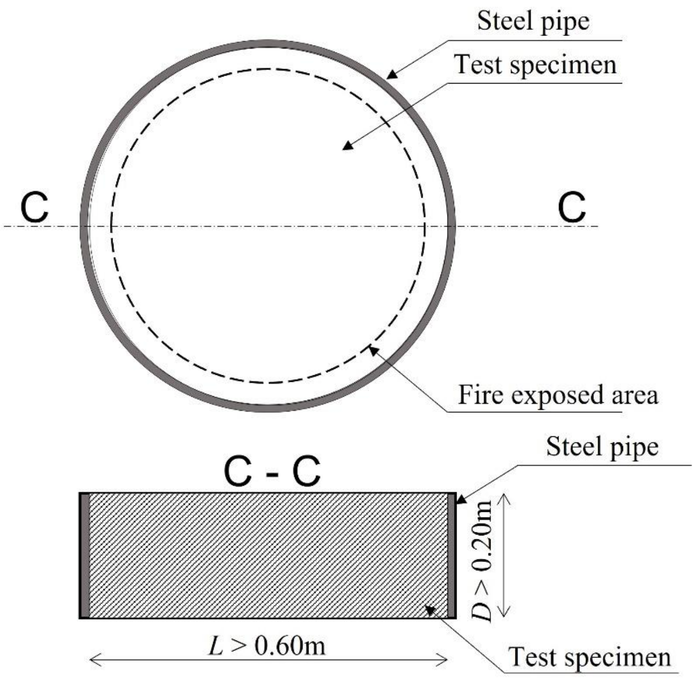

Figure 4: Example of restraint with steel ring in the cold rim of the specimen.

4.4. Measurements and observations taken during the fire test

Recording of all measurements shall start before the fire test.

4.4.1. Temperature measurement

The temperature of the plate thermometer (or the shielded thermocouple if using the calibration procedure as described in paragraph 4.2) shall be recorded with a frequency of at least 1 record per 10 seconds.

4.4.2. Load measurement

The applied load shall be determined by means of load cells, by measuring the hydraulic pressure or by other relevant equipment.

The load shall be recorded with a frequency of at least 1 record per 1 minute.

4.4.3. Spalling observations

In case of spalling occurrence, observations describing spalling progress and spalling extent should be provided.

The parameters that should be noted are related to the test and the spalling progress description:

- time of first spall and spalling duration until no spalling occurs, if applicable (min),
- general description of the spalling events with time and character description (estimation of the size and the shape of the flakes if possible).

Also, the time of occurrence of the reinforcement exposure (if applicable) shall be reported.

4.5. Measurements and observations taken 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 process 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

It is crucial that all the measurements in a test series are taken in the same manner.

Fire exposed area, spalled area and assessment area are illustrated in Figures 5, 6 and 7.

All spalling investigations shall be performed in an assessment area. The assessment area shall exclude the transitional spalling that occurs between non spalled area close to the boundaries and homogenous region of spalled area (Figure 5).

The assessment area shall remain the same in all samples tested in a series to compare the concrete behaviours. The assessment area shall then be determined as the smallest assessment area within all the tested specimens (Figure 6).

If there is no possibility to determine an assessment area with homogenous spalling depths as illustrated in the example given in Figure 7, it is recommended to assume the assessment area as the area being 10 % smaller than the fire exposed area.

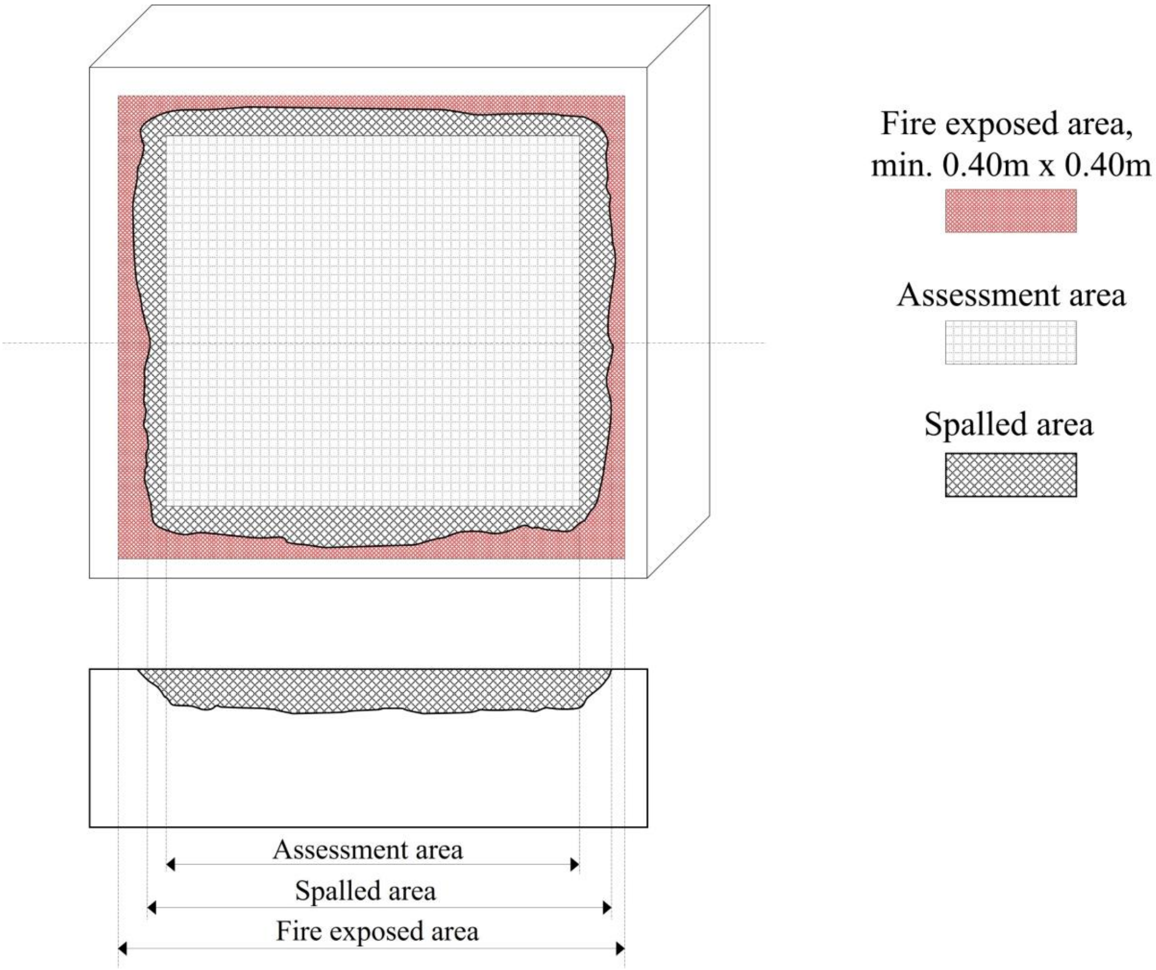

Figure 5: Options for determination of the assessment area and spalled area.

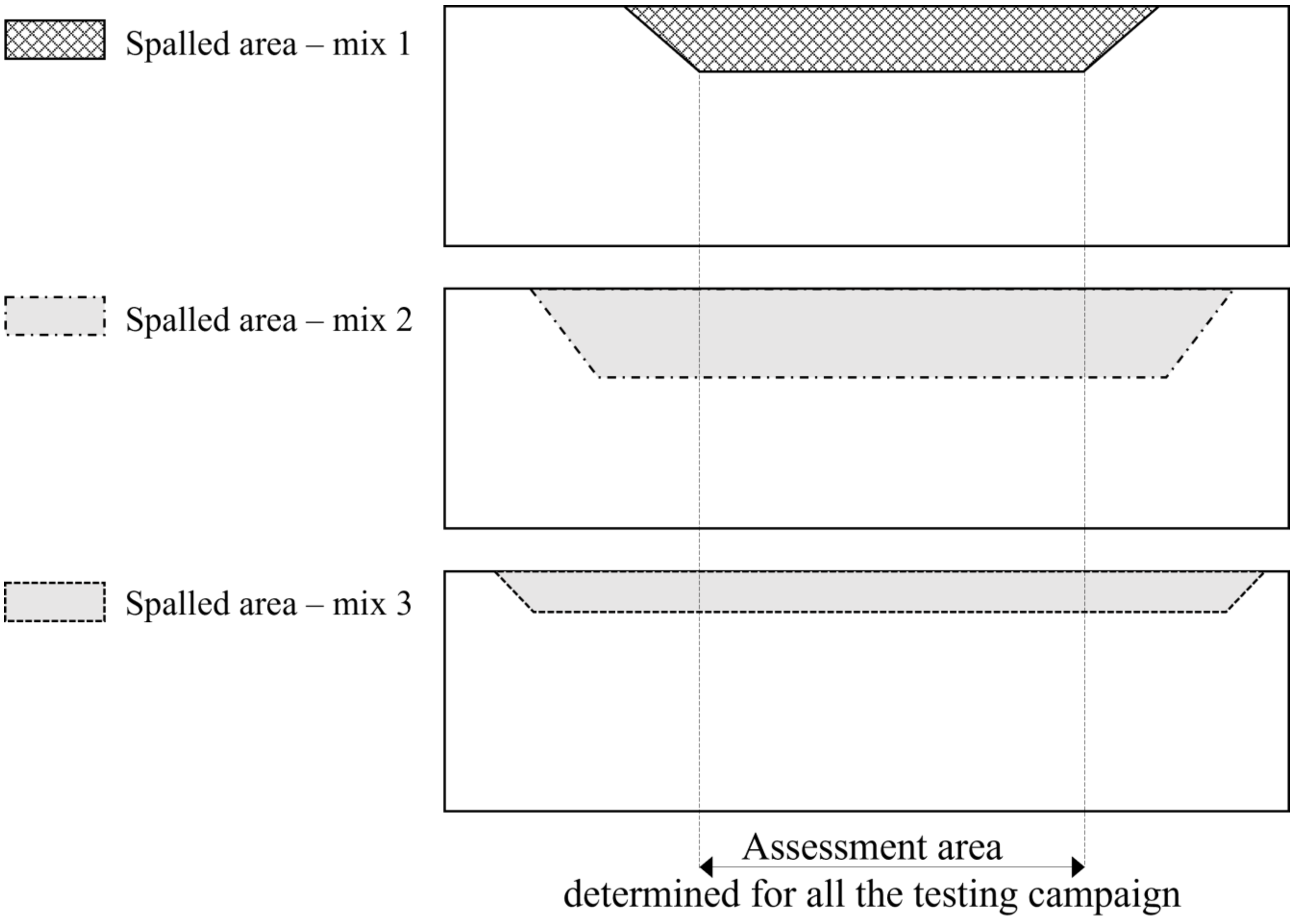

Figure 6: Determination of the assessment area for a test series.

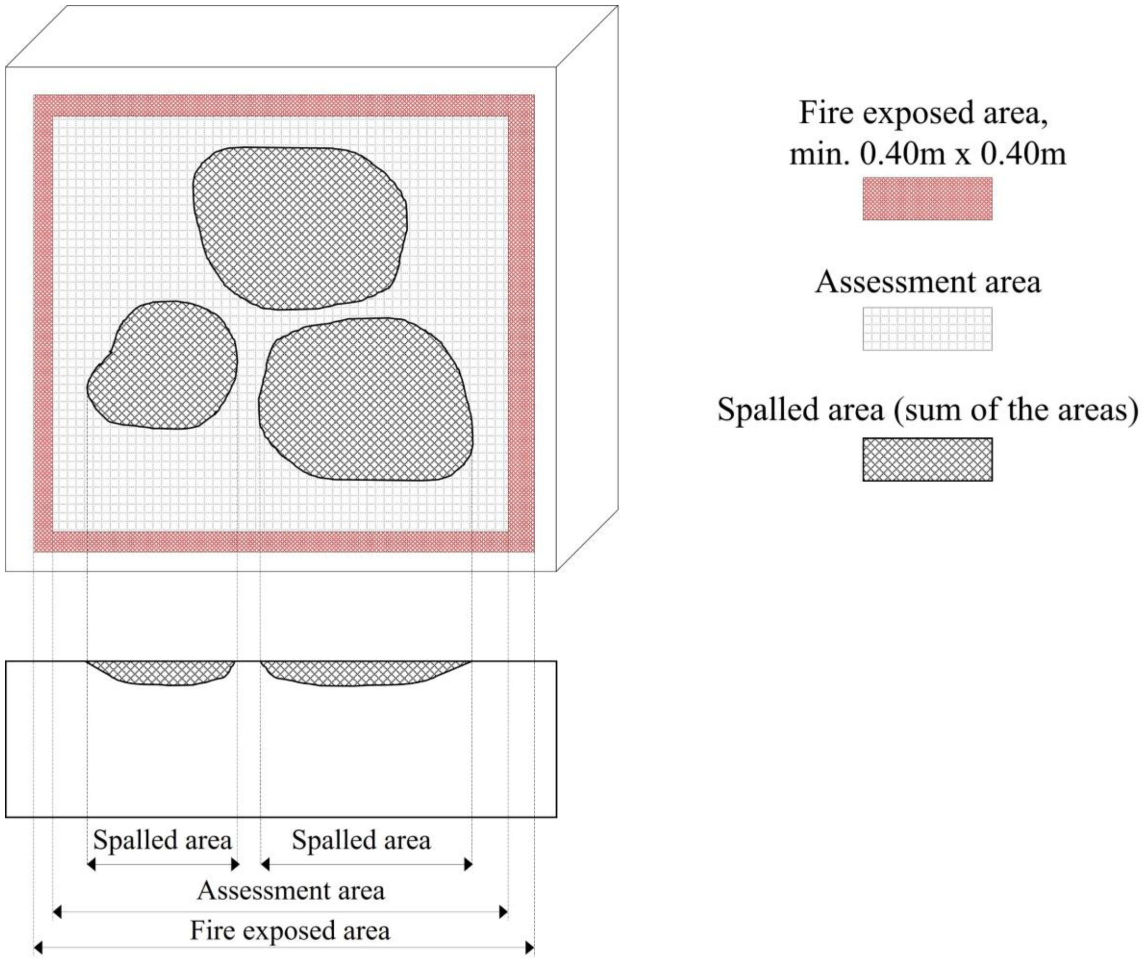

Figure 7: Determination of the assessment area and spalled area for non-homogenous spalling

4.5.1. Spalling depths field

The post fire examination consists of the evaluation of spalling depths. The measurements of spalling depths may be performed manually in a regular grid in at least 20 evenly distributed points, or by using other means, e.g., 3D scanning or digital planimetry to collect data enabling drawing of a spalling map.

From the collected data, the following information shall be provided:
- Area of the spalled surface (**spalled area**);
- Mean spalling depth in the assessment area;
- Mean spalling depth in the spalled area (if spalling does not cover the whole assessment area);
- Maximum spalling depth (even if the maximum spalling point is out of the regular grid).

4.5.2. Spalled particles/flakes 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;
- Picture of spalled flakes.

In case of large amount of spalling, it is illustrative to provide the picture 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.

5. METHOD OF MOISTURE CONTENT MEASUREMENT

The moisture content of the tested specimen shall be determined as close as possible to the testing date. Moisture equilibrium is generally reached after a few years, and a moisture gradient will be generally observed. It is thus recommended to determine the 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 until 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 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 as the difference between the original and dried mass divided by the dried mass.

Three specimens from each batch are required.

6. TEST REPORT

Any deviation from the test procedure described in these recommendations should be stated in the test report.

The test report shall contain the following information:

6.1. Concrete composition

The tested concrete mix composition per m^3 should be provided, including the following information:

- Concrete water-cement ratio, type of cement, nature, size and type of aggregates, type of mineral additives and plasticisers type, etc.
- If fibres are used, their nature (i.e., steel, polypropylene, etc.), type (i.e., monofilament, fibrillated, etc.), brand, shape, diameter, length, and amount used in concrete production should be included in the test report.

6.2. Concrete properties

- Standard compressive strength
- Reference compressive strength
- Reference moisture content
- Optionally: Other information about concrete properties that may be relevant to spalling, i.e.:
    - Physical properties: density, porosity, gas permeability, thermal strains, etc.
    - Mechanical properties: tensile strength, modulus of elasticity.
    - Other.

6.3. Specimens

- Shape and size of specimens
- Layout of reinforcement (if used)
- Curing and storage conditions
- Age of each individual specimen at the time of testing

6.4.Test conditions

- Installation of specimen
- Heating system, heating scenario and test duration
- Mechanical boundary conditions

6.5. Spalling results

- The measurements and observations taken during fire exposure (according to section. 4.4)
- The measurements and observations taken after fire exposure (according to section. 4.5).