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# Assessment of concrete susceptibility to fire spalling: A report on the state-of-the-art in testing procedures

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**Abstract**

The assessment of concrete behavior at high temperature is done by a variety of tests carried out on specimens of different sizes. Small-scale tests examine concrete's behavior when exposed to elevated temperature, while full-scale fire tests are carried out on full-sized concrete elements in which the boundary conditions, external load and conditioning correspond to design assumptions. Complementary to these is the medium-scale test carried out on a portion of a slab's surface area which has been exposed to fire, ca. $1m^2$. Such medium-scale tests are often used as a cost-effective solution to verify the behavior of a specific concrete mix in fire conditions. This paper reviews the existing furnaces, testing procedures and laboratory setups used to assess a material's tendency to spall. Its objective is to emphasize the need to unify spalling risk assessment procedures by establishing recommended guidelines for testing.


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## 1. Introduction

Laboratory tests of concrete which aim to investigate its susceptibility to fire spalling employ various testing procedures carried out on specimens of different sizes and shapes. Due to the lack of standardized testing guidance, there is a wide range of approaches to concrete fire spalling assessment. During such tests, different measurements

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are carried out in order to better describe the processes taking place in concrete during heating. These parameters are temperature and vapor pore pressure development, thermal strains or specimen deflection. Numerous experimental tests results can be found in the literature, all attempting to investigate the fire spalling phenomenon by indicating different parameters that may enhance spalling risk, such as the mix composition, the heating scenario, the initial water content and the geometry of specimen or mechanical boundary conditions. Unfortunately, the influence of specific spalling parameters is difficult to assess and compare with others due to differences in the testing procedures used to obtain these results. Generally, we can distinguish three main categories of testing methods for spalling behavior investigations: small-scale, medium-scale and full-scale tests. The subsequent paragraphs describe the diversity of furnaces, their components, testing instrumentations and procedures.

## 2. Experimental methods for the assessment of concrete susceptibility to fire spalling

### 2.1. *Small-scale concrete spalling tests*

Small-scale tests examine the material's behavior when exposed to elevated temperature. These tests are carried out on small concrete specimens: prisms, cubes or cylinders with the volume not exceeding ca. 4000 $cm^3$. High temperature conditions are mostly provided by electrical heating coils. In these tests only the spalling occurrence is detected and the number of specimens which spall is recorded.

In more elaborate techniques, the specimens are mechanically loaded during heating. In most cases, the furnace is placed in a loading ram along with a concrete specimen which is stressed during heating, ex. Connolly [1], Phan [2], Hager and Pimienta [3], Phan [4], Mindeguia [5], Huismann et al. [6]. Following the recommendation of RILEM TC 200-HTC [7], two test methods can be distinguished in which the material's behavior is studied in stressed, and unstressed conditions. The stressed test method corresponds to conditions in which the specimen is uniaxially loaded during heating. A compressive load of 10–50 % of ultimate stress is applied to the specimen at room temperature, which remains constant during heating to the target temperature level (T). All spalling events are recorded as well as the temperature at its occurrence. Although these methods were mainly used to determine the material properties at the hot stage, the concrete's susceptibility to spalling can be also assessed using these procedures.

The testing set developed by Connolly [1] employs cylindrical specimens of Ø 150 mm, H 100 mm. The specimen is mounted in steel ring and is loaded peripherally by hydraulic arms in both vertical and horizontal directions. The loading arms are also designed to restrain thermal expansion. Both the load and thermal expansion are recorded within the event by a load cell. Structural stability is obtained by the stiff restraint frame, which provides support for hydraulic jacks. Heating is delivered by electrical radiative heating elements by Kanthal Electrical Ltd., producing a heat flux level of 150 $kW/m^2$. The temperature was measured with the use of thermocouples cast at different depths of the specimen, which was also equipped with a ceramic pipe connected to pore pressure transducers capable of reading the pressure within concrete up to 10 $N/mm^2$. The assessment of spalling, if such occurred, was determined by counting the number of steel grid squares (10 x 10 mm) placed over the concrete surface which were damaged more than 50%. By this procedure the authors obtained the extent of spalling expressed in a percentage of the total surface area.

The PTM test developed by Kalifa [8] is so far one of the most referenced and cited test methods. The examination of specimens – recording prisms done with additional pressure (P), temperature (T) and mass loss (M). These specimens can be instrumented with six gauges made of a sintered metal round plate, which are placed at casting. The last one is brazed to a thin metal tube (inner diameter 1.6 mm), which comes out of the rear face of the specimen. At the time of testing, a tight connector is placed at the free end of the tube. Firstly, it connects the gauge to a piezoelectric pressure transducer by means of a flexible tube filled with silicone oil. Secondly, a thermocouple is inserted in the tube through the connector down to the metal plate. The free volume of the gauge is around 250 $mm^3$. The specimen, a prism (300 mm x 300 mm x 120 mm), is positioned horizontally. Its upper