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Effect of temperature on thermal properties of spray applied fire resistive materials

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ABSTRACT

Thermal properties of fire insulation namely thermal conductivity, specific heat, thermal strain and mass loss play a critical role in determining the effectiveness of these materials to improve fire resistance of steel structural members. These properties vary with temperature and are predominantly governed by moisture content and chemical constituents. This paper presents the effect of temperature on thermal properties of different types of spray applied fire resistive materials (SFRM). High temperature property tests were carried out on three types of commercially available SFRM to measure thermal conductivity, specific heat, mass loss and thermal strain in the range of 20–1000 °C. Data from these tests show that temperature has significant influence on thermal conductivity, thermal expansion and mass loss of fire insulation. The measured test data are utilized to develop thermal property relationships for fire insulation in terms of temperature. The proposed relations can be used as input data in thermo-mechanical analysis for evaluating fire resistance of steel structures.

1. Introduction

Steel structural members exhibit lower fire resistance and this is mainly attributed to high thermal conductivity, low specific heat, and faster degradation of strength and elastic modulus of steel with temperature [1]. To overcome this drawback steel structural members are often applied with spray applied fire resistive materials (SFRM) to delay temperature rise in steel. Thus, fire resistance of steel structures is mainly dictated by the thickness and the thermal properties of SFRM. The evaluation of fire response of a steel structural member requires information on thermal properties of fire insulation, namely thermal conductivity, specific heat, mass loss and thermal strain. There is limited information in the literature on the effect of temperature on thermal properties of SFRM.

SFRM offers several advantages over other types of fire insulation such as cost effectiveness, ease of application, and light weight, and therefore is widely used as fire proofing material for steel structures. SFRM is generally composed of gypsum, cementitious and mineral fiber based materials. Apart from these base materials, another constituent namely vermiculite, an intumescent mineral, is added to counteract the shrinkage phenomenon which occurs at high temperature in compounds like gypsum [2]. Table 1 presents the main composition of three different SFRMs taken from material safety data sheets. In these SFRMs namely CAFCO 300, Carboline Type-5MD, Tyfo WR-AFP, the main ingredient is gypsum and thus, thermal properties of SFRMs are expected to be highly influenced by the properties of gypsum. Carboline and CAFCO are the most widely used commercially available SFRMs, while, Tyfo WR-AFP is a new SFRM that is finding numerous applications.

Thermal properties of fire insulation vary with temperature and also with its composition. However, in practice fire resistance of structural members is evaluated by considering only room temperature thermal properties, without any consideration to variation of properties with temperature. This is mainly due to lack of data on the effect of temperature in thermal properties of SFRM. Such a design consideration can lead to inaccurate fire resistance ratings. To better understand the realistic fire performance of SFRMs, data on temperature dependent thermal properties is critical. Further, there is lack of data on relative thermal performance of different insulation materials even at room temperature. To overcome some of these knowledge gaps, thermal properties of three different SFRMs are evaluated at elevated temperatures. The property tests were conducted following the procedures outlined in test standards. Thermal conductivity and specific heat were measured in the temperature range of 20–700 °C, thermal strain was measured in the range of 20–1000 °C and mass loss was measured in the temperature range of 20–775 °C. These tests are conducted under bench scale conditions. However, correlation with a full-scale fire tests can be made by undertaking full-scale fire tests on SFRM insulated structural members. Such

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Table 1
Chemical composition of prevalent commercial SFRMs.

CAFCO 300		Carboline type-5MD		Tyfo WR-AFP	
Composition	Wt% (Max.)	Composition	Wt% (less than)	Composition	Wt% (Max.)
Gypsum (Calcium sulfate hemi hydrate)	50–75	Gypsum	70	Gypsum (Calcium sulfate hemi hydrate)	30–40
Vermiculite	15–35	Vermiculite	30	Vermiculite (refined and exfoliated)	25–35
Cellulose	1–10	Cellulose	5	Cellulose and additives	>10
Calcium-carbonate	1–10	Limestone	5	Portland cement	30–40
Quartz	0–5	Microcrystalline silica	0.7	Ceramic fibers	10

correlation is being planned in ongoing test programs at Michigan State University.

2. Experimental program

An experimental program was designed to measure thermal properties of three commercially available SFRM namely CAFCO 300, Carboline Type-5MD, and Tyfo WR-AFP. The measured properties are density, thermal conductivity, specific heat, thermal strain and mass loss at various temperatures.

2.1. Test specimens

To prepare necessary test specimens, three insulation blocks of $100 \times 100 \times 350\ mm^3$ were cast by mixing powdered SFRM insulation with water as per the instructions specified by each manufacturer. The SFRM mix was cast in layers in fabrication molds and caution was taken not to over compact the mix. After curing, test specimens were cut to required size from casted insulation block using power saw. The size of the test specimens was different for different property tests. For thermal conductivity, specific heat and density measurements a specimen size of $50 \times 50 \times 25\ mm^3$ was used. For thermal expansion measurements, the insulation specimen was cut to $10 \times 10 \times 18\ mm^3$ size and was perfectly ground at ends. For mass loss tests, specimen of approximately $3 \times 3 \times 3\ mm^3$ size and 50 mg weight was used.

2.2. Test apparatus

Thermal conductivity and specific heat of insulation was measured using Hot Disk TPS 2500S equipment (see Fig. 1). Hot Disk utilizes transient plane source technique to measure thermal conductivity and specific heat of the specimen. A flat source or sensor is placed between the two specimens. The sensor acts both as a heater as well as a detector of the temperature rise [3]. The sensor is a spiral nickel wire probe insulated between two layers of either Kapton or Mica. The Kapton sensor is suitable only for temperatures up to 200 °C and the Mica sensor can be used for higher temperatures up to 700 °C. Uniform temperature is to be maintained in the specimen before the measurements are made [3].

Density was evaluated by measuring weight and dimensions. The specimens used for Hot Disk tests were utilized for evaluating the densities at ambient temperature and after exposure to 700 °C. For weight measurements, digital weighing machine with a least count of 0.1 g was used, and for measuring dimensions, a linear caliper with a least count of 0.01 mm was used.

For thermal expansion measurements, Thermo-Mechanical Analyzer (TMA) equipment was used (see Fig. 2). TMA comprises of a movable-core linear variable differential transducer (LVDT), which generates an electric signal corresponding to dimension change. TMA is capable of measuring thermal expansion in the temperature range of 20–1000 °C. A flat tip probe, also known as macro-expansion probe, is utilized for evaluating dimension change in the specimen at elevated temperatures. The flat tip of the probe is to be kept in perfect contact with the specimen during the test. TMA records linear change in dimension at any specified temperature [4].

The mass loss of insulation is measured using TGA (Thermo-Gravimetric Analyzer) equipment (see Fig. 3), which comprises of three major components namely, a thermal balance, a temperature controller and a recording device. The thermal balance incorporates a furnace to provide uniform controlled heating at a constant rate in 20–1000 °C range, a temperature sensor continuously measures the furnace temperature and an electric balance continuously measures the mass. The temperature controller allows operation of the furnace following an user defined temperature regime and the recording device records and displays change of mass with temperature in real time.

All three equipments, TPS2500, TMA and TGA, are connected to computer console to define test parameters as per test standards. Parameters such as temperature regime, power, measuring time etc. are defined in the dedicated software which controls the test equipment.

2.3. Test procedure

For thermal conductivity and specific heat measurements, specimens of $50 \times 50 \times 25$ mm size were dry sliced from casted insulation blocks using a power saw. Caution was taken to produce smooth surfaces while sawing, which avoided the necessity for further grinding the specimen surface. Smooth surface is critical for good contact with the Hot Disk sensor. Hot Disk test regime was set-up to record property measurements at eight different target temperatures of 20, 100, 200, 300, 400, 500, 600 and 700 °C. The maximum target temperature was kept at 700 °C, not to exceed the operating temperature range of the Hot Disk furnace.

At a given temperature, Hot Disk equipment measures thermal conductivity (k) and thermal diffusivity (α), and then computes (internally) specific heat (c_p) at that temperature. When a constant heat source is applied, the temperature in the sensor raises allowing heat flow in the test specimen. Hot Disk equipment maintains an uniform temperature distribution throughout the specimen at the time of measurement [4]. Due to high cost involved (sensors gets damaged at high temperatures and new sensors are required for each test), thermal conductivity test was conducted on one specimen.

Thermal expansion measurements were carried out as per ASTM E381-06 standard procedure [5]. The macro-expansion probe was positioned on the specimen placed in an upright position. A small static force was specified in the software so as to keep the expansion probe in contact with the specimen at all times. The specimen was subjected to an user defined temperature regime, and the change in linear dimension of the specimen (expansion or contraction) was recorded by the movement of the probe [4]. As per test standard, heating rate was set to 5 °C/min, and these property tests were carried out on two identical specimens.