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An experimental study of the thermal performance of a novel intumescent fire protection coating

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ABSTRACT

The thermal performance of a novel intumescent coating was investigated at a laboratory scale. A combination of small and large-scale tests was performed in order to fully understand the behavior of the coating. For small-scale testing, experiments were conducted using thermogravimetric analyses. These experiments were run at several heating rates in a nitrogen atmosphere. The results showed that the thermal degradation of the coating occurred in different stages, and, the main mass loss took place around 300 °C. Furthermore, the current work showed that oxygen doesn't exert any significant effect during the early stages of degradation of the materials; however, its interference can be noted past the attainment of the peak value for mass loss rate curve.

For large-scale testing, the experiments were carried out in a cone calorimeter using a stainless steel plate as a platform to support the test specimen. The back surface temperature and expansion height of the intumescent coating were measured as a function of time. Several factors such as heat flux, distance to cone heater and coating thickness were also investigated. The results showed that the normalized expansion height of intumescent coating was consistent at different heat flux levels. Hence the expansion of the coating can be considered to be dependent only on the mass loss rates and not the value of the external heat flux.

Also, results from the cone tests, permit the formulation of an experimental protocol for evaluating of the thermal shielding efficiency of the intumescent coatings. The results showed that the data obtained using a cone calorimeter with 2.5 cm of distance cannot be compared with other distances, such as 4 or 6 cm. The present work also showed that the values of the relevant parameters did not differ significantly at distances to the cone heater above 4 cm.

In a second evaluation, the new intumescent coating was applied to polyurethane and Gypsum boards, for study using cone calorimetry. The use of the coating led to a decrease in the peak of heat release rate for combustion of polyurethane. The application of a coating layer can be used to decrease the overall requirement of thickness of the Gypsum board without compromising its thermal insulation performance.

1. Introduction

The protection of construction materials against fire is an important issue in the construction industry, especially when newer materials for construction are being introduced into the sector [1]. Some building materials, such as steel, are non-combustible. However, the structural properties of steel change at sufficiently high temperatures, induced by being heated in a fire, which can be lead to the failure of building structures where steel is used as the primary load-bearing component [2].

There are several methods to reduce the detrimental effects of fire on the structural components, such as the application of thermal shielding coatings, cement-based sprays and use of batten materials [3]. One of the most efficient ways to increase the fire resistance of construction materials is through the application of an appropriate intumescent coating. This technique can be applied to different backing materials, such as metals, polymers, steel, textiles, wood, etc. [3,4]. Intumescent coatings generally form a carbonaceous char layer during the degradation and expansion. This char layer can often act as an efficient thermal shield between the heat source and the materials [5]. However, the ultimate structural stability of the char layer depends on the temperature profiles and the amount of oxygen present in the system. Typically, intumescent coatings are expected to maintain the integrity of structural materials

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Nomenclature

h	expansion height (m)
h_{max}	maximum height (m)
T	Temperature (K)
$\dot{q}_e''$	External heat flux received by the intumescent coating (kW/m^2)
ε	Emissivity (−)
TGA	thermo-gravimetric analysis
HR	Heating rate (K/min)
t_{ig}	Time to ignition (s)
HRR	heat release rate (kW/m^2)
Y_{CO2}	Carbon dioxide yield (g/g)
Y_s	Smoke yield (g/g)
Δm	mass loss (g)
m_0	initial mass (g)
q	Heat Flux (kW/m^2)
$\dot{q}_{sub}''$	Heat flux received by material (kW/m^2)
σ	Stefan–Boltzmann constant ($W/m^2\ k^4$)
CC	Cone calorimeter
WB	Water-borne
PHRR	Peak of heat release rate (kW/m^2)
Y_{CO}	Carbon monoxide yield
HoC	Heat of combustion (MJ/kg)
PU	Polyurethane

(such as steel) for one to 3 h, during which the surrounding temperature exceeds 1100 °C and O_2 concentration drops to a very low level. Therefore, the thermal shielding efficiency of intumescent coatings is of great importance [1]. However, there is an influence of heating rate. If too fast, the heat wave could reach the materials before any development of intumescence.

There are several approaches for estimation of the thermo-protective properties of intumescent coatings, such as standard furnace and natural fire tests [5]. Nevertheless, the assessment of the thermal insulation performance of intumescent coatings is not an easy task given the cost and time required for a proper classification and approval rating of the materials. Standard testing regimes available for building construction materials often include full-scale experiments. However, it is a common practice to test the efficacy of intumescent coatings on stainless steel plate by employing laboratory-scale techniques. For example, apparatus such as a thermogravimetric analyzer and cone calorimeter have been extensively used in order to test the protective effectiveness of various intumescent coatings at a laboratory scale [1,6–10].

The results obtained from TGA tests may not be applied to real-life fire situations. However, the flexible heating regimes on milligram size samples of a solid material can help to elucidate the various thermal and thermo-oxidative processes that may occur as the materials is heated. Moreover, these tests can also be used to support computation of relevant kinetic parameters. On the other hand, the study of the evolution of mass loss, as a function of temperature, through TGA tests does not necessarily allow a complete and detailed evaluation of all the underpinning thermal reactions that occur [11]. Furthermore, given the relatively very small size of the test sample, it can be only considered behaving as a 'thermally thin' material, and thus cannot be considered as a representative test specimen. However, the thermograms obtained are useful as reliable indicators regarding the degradative behaviours of the test materials upon progressive heating from an external source. In contrast to a thermogravimetric analysis, a cone calorimeter will definitely yield better degradation and combustion profiles for materials, and therefore it is considered to be the standard laboratory-scale test apparatus [12]. It also measures the evolution of mass loss, as well as mass loss rate as a function of time. The other useful parameters from cone calorimetric runs include: time-to-ignition, heat release rates, total heat released, CO, CO_2, and smoke yields, etc. The conditions of thermal degradation are more realistic for both thermally 'thin' and 'thick' materials. Moreover, with larger scale heat fluxes, and heat and mass transfer phenomena, the behaviors of materials in a cone calorimeter can be considered as a better indicator of their corresponding behaviors in real fire scenarios. However, it should be noted here that the actual size and orientation of real fire loads, say in enclosure fires, cannot be realized during the cone measurements, and that convective mode of heat transfer and any heat losses, facilitated through the sample holder, are largely ignored.

Generally, the results from cone calorimetric investigations cannot be easily compared. This can be mainly attributed to the difference in the test configurations, such as the distance between sample and heater, thickness of the coating, nature of the backing materials (plate), heat flux, and to the actual nature of the parameters that are measured. For instance in one investigation, the profile of temperature at the interface between the intumescent coating and the metal plate at a constant value of heat flux (30 kW/m^2) with 1 mm thick of intumescent coating has been reported [7]. Here it should be also noted that the samples in the sample holder were insulated with four layers of 3 mm thick Cotronics ceramic paper. However, an attempt of compare results from a closely related study was not possible because the thickness of the coatings were quite different (in the range 5–15 mm) [8].

In the present work, the fire performance of a new intumescent coating was investigated using thermogravimetric analyses in order to determine the behavior of the intumescent coating, as a function of increasing temperature.

The mass and mas loss rate were quantified during cone calorimetry experiments. In addition, cone calorimetric data were obtained at different heat fluxes, and the intumescent height was continuously quantified during the runs. In parallel, the temperature of the back surface was measured using a k-type thermocouple.

In order to gauge the benefits of using the new intumescent coating, experiments were also conducted using different backing materials (polyurethane plaque: 240 kg/m^3, 25 mm thickness and Gypsum boards: with thicknesses of 15, 12 and 9 mm) at a pre-set value of heat flux of 50 kW/m^2. This value is widely used as standard in order to compare the behavior of materials in cone calorimetric experiments [13]. An experimental protocol for evaluating the fire protective properties of intumescent coatings, which accounts for the influence of many parameters which can affect the thermal performance of the coatings, has been developed based on results obtained in this study.

2. Experimental set-up

2.1. Materials

Steel plates (100 × 100 × 5 mm) were coated with an intumescent material. This was a new water-borne intumescent coating developed and supplied by FARBE SPA Company, Milan, Italy. The salient characteristics of the intumescent coatings are listed in Table 1. In order to improve the quality of the coating, potassium chloride, hydrogenated castor oil, potassium ferrocyanide and hydroxypropyl methylcellulose were added to the coating. These ingredients are incorporated, primarily, to improve the uniformity of the coating as well as the adhesion between the coated layer and the materials. All operations such as importation of the materials and the preparation of the coating were completed by FARBE SPA Company (Italy).

Polyurethane and gypsum boards were used as the base for the coatings in order to assess the benefits of using intumescent coating on different materials. The polyurethane samples (100 × 100 mm; 240 kg/