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ScienceDirect
Procedia Engineering 151 (2016) 284 – 291
Procedia Engineering
www.elsevier.com/locate/procedia

International Conference on Ecology and new Building materials and products, ICEBMP 2016

Material solutions for passive fire protection of buildings and structures and their performances testing

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Abstract

In buildings and in civil engineering structures, both active and passive fire protection are used. Active fire protection includes automatic fire detection and fire suppression systems while the passive fire protection's main purpose is to attempt to contain fires or slower their spread. The aim of fire protection system's usage is to maintain the temperature of the building component (structural steel element, electrical installation) bellow the critical temperature during fire but also is intended to contain a fire in the origin fire compartment for a limited period of time. In this paper the passive fire protection material solutions were described and their action mode explained. Starting with thermal insulation barrier, endothermic building materials including concrete and gypsum and also novel solution based on alkali activated binders. Concrete is considered to be fire protective, however, in some specific cases, dense and low permeable concrete (i.e. high performance concrete) has a tendency to spall in explosive way under fire. Several fires in structures have caused the spalling of concrete elements that jeopardized the structure stability. In this specific case polypropylene fibres (PP) added to the concrete mix act as a passive protection system. Another group of passive fire protection materials, described in this document, are the intumescent and ablative materials for steel structure protection. The present manuscript describes also the techniques of passive fire protection testing in fire conditions.

Peer-review under responsibility of the organizing committee of ICEBMP 2016

Keywords: Passive fire protection; fire; building materials; concrete spalling

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1877-7058
Peer-review under responsibility of the organizing committee of ICEBMP 2016
doi:10.1016/j.proeng.2016.07.388

1. Introduction

In buildings and in civil engineering structures like tunnels, both active and passive fire protection are used. Active fire protection includes automatic fire detection and fire suppression systems while the passive fire protection main purpose is to attempt to contain fires or slower their spread. The aim of fire protection system's usage is to maintain the temperature of the building component (structural steel element, electrical installation) bellow the critical temperature during fire but also are intended to contain a fire in the origin fire compartment for a limited period of time.

Passive fire protection material solutions used for this purpose are as follows i) Thermal insulation barrier, ii) endothermic building materials including concrete and gypsum and also ii) novel solution based on alkali activated binders. In this listing of materials, a concrete is considered as the fire protective, however, in some specific cases, when dense and low permeable concrete (i.e. high performance concrete) is heated it has the tendency to spall in explosive way. Several fires in buildings and tunnels have caused the spalling of concrete elements that jeopardized the structure's stability. In this specific case polypropylene fibres (PP) added to the concrete mix act as a passive protection system. As the name suggests, passive fire protection remains inactive in the system until a fire occurs, as so does PP fibres in a concrete.

Another group of passive fire protection materials, described in this document, are the intumescent and ablative materials for steel structure protection. Steel is very sensitive to the temperature increase and 550 °C is considered as the critical temperature for structural steel because it induces an important strength loss. So the measures, like passive protection system, have to be taken to delay steel structure overheating by creating a layer of char between the steel and fire. The present manuscript describes also the techniques of passive fire protection systems effectiveness' testing in fire conditions.

2. Passive fire protection material solutions

2.1. Thermal insulation barrier

There is a wide variety of the thermal insulation materials that can be used for a basic purpose of insulation from heat transfer. However, while testing a fireproofing of thermal insulators, one can find only few materials that can resist a real fire conditions. Mineral wool, expanded aggregate and cellulose are representatives of fireproof material for thermal insulation.

Mineral wool, also known as rock wool or slag wool is one of the oldest types of insulation composed of non-combustible, naturally fire resistant stone wool. It can withstand temperature up to 1000 °C and does not burn. Over 1000 °C a mineral fibres start to melt. Mineral wool can be used as: the thermal and fire insulation between living area and non-heated roof spaces, a fire-resistant core for sandwich panels, a fireproof barrier for structural members in steel structures (Fig.1 a), and as the fireproof cover for industrial pipes and ducts as well. Well designed and tightly built-in insulation barrier can be therefore an efficient passive thermal and fire protection.

Other mineral materials are expanded perlite, shale, clay, slate and vermiculite. Those are recognized aggregate for fireproof cover manufacturing which offers the effective solution for life safety for both occupants and firefighting personnel. The non-combustible nature combined with high thermal insulation offers inherent structural integrity following exposure to fire what makes it the obvious choice for passive protection of building construction. Aggregate types affect fire ratings of cementitious composite material on the basis of heat transfer and on the basis of aggregate moisture absorption. Highly porous aggregates absorb moisture in varying degrees depending upon its type. The presence of moisture in the aggregate during a fire test extends the fire duration by the time when moisture is turned to steam and evaporated from the material.

Finally, the cellulose insulation is made in a loose form from a recycled paper, newspaper, cardboard or other similar materials, it is considered as one of the eco-friendliest thermal insulation materials. Although the composition of the material is associated with the high flammability, the chemical treatment with ammonium sulfate and borate provide its incombustibility. What is more, because of a high compactness of the cellulosic fibres, the material contains almost no oxygen and effectively chokes wall cavities of combustion air and thus can minimize the spread of fire. As cellulose insulation is a loose material, it can only be used as filling of roof, floor and wall space, so the external part of structure is directly subjected to fire.

a) b)

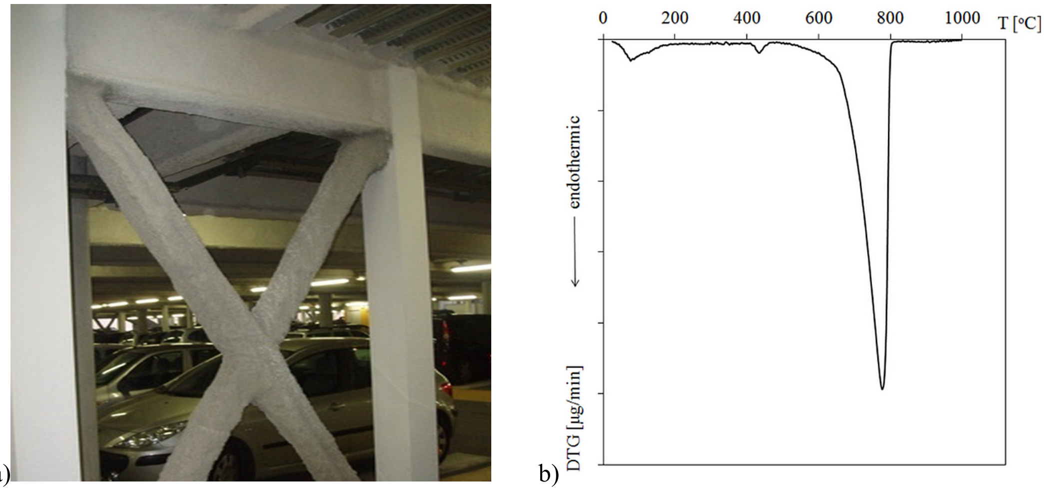

Fig 1. (a) Passive fire protection of steel structure, a fireproofing material sprayed onto steel structure elements; (b) endothermic reaction of concrete with dolomite aggregates, (Differential Thermal Gravimetry - DTG, sample weight 20 mg, heating rate 20°C/min).

2.2. Endothermic building materials including concrete and gypsum

Concrete is commonly known as fire resistant and incombustible material, so it has been used as a basic material for fire resistant structures for last decades. It protects a structure from fire in two ways. Concrete itself contains free water but also cement paste is made of significant quantity of hydrated crystals, so it contains a large amount of bound water. In case of fire, free water evaporates from a heat exposed surface and in this way it absorbs a great part of heat, leading to minimizing of temperature in internal part of structural member. In the next step, the dehydration process of CSH gel takes place, as well as portlandite decomposition when concrete is heated to temperature of 500–550 °C. Those processes also absorb heat. The endothermic reaction can be even higher if the calcareous aggregates are used (Fig. 1 b). Due to its low thermal conductivity, concrete protects underlying part of structure for a sufficient period enabling to take a preventive action in case of fire.

However, recent technological development and the increasing demand for high-strength structures caused also the development of concrete technology. As a result of increased density and better compaction of microstructure in high performance concrete, it is particularly more susceptible to fire spalling, whereas in normal concrete, in most cases, this phenomenon is not observed. Therefore, as far as normal concrete is used to protect steel in reinforced concrete (RC) structures, it provides its expected fire resistance. On the other hand, the cementitious coatings, ex. shotcrete, used as fire protection of steel structural members (beams, columns) are not recommended because of the risk of spalling, cracking or delamination in the contact layer between concrete and steel. Moreover, concrete-based coatings, as dense and massive materials, add a significant component of load to a load-bearing capacity design of steel structure.

Gypsum (calcium sulfate dihydrate) is a crystalline formed mineral found in sedimentary rock, but can also be a synthetic gypsum (Flue Gas Desulphurization gypsum or desulphurised gypsum) that is derived from coal-fired electrical utilities which are able to remove sulfur dioxide from flue gasses. Gypsum wallboards are an effective passive fire protection. As gypsum contains ca. 20% of chemically bounded water, it can be evaporated in case of fire and help to minimize the temperature in the interior of protected structure and spread of fire, as described before. Moreover, gypsum boards are completely incombustible material and even after evaporation of entire amount of water, it remains a thermal insulation barrier.

Producers of gypsum boards offer a wide variety of products for range of applications, including: wallboards for surface assembling on walls and ceilings, as well as in the interior of elevators or similar kind of shafts. Gypsum board can also be used to construct a fire separator between two areas or can be mounted directly of structural members, ex. steel beams, to provide a fire-resistant layer. However, in case of gypsum fireboard, tightness of coating is at highest importance.

2.3. Novel solution based on alkali activated binders

As mentioned before, Portland cement based concrete is incombustible and it is endothermic, however some concretes, especially those with low water cement ratio like Reactive Powder Concretes, due to their high density and low permeability are particularly susceptible to fire spalling. Alternative binders for Portland cement are the recently developed alkali-activated binders (geopolymers). They are inorganic, ecofriendly binders and provide a better behaviour in fire.

According to tests performed by [1] a cement made with (Na, Ca)-Poly(sialate) and (K, Ca) Poly(sialate-siloxo) does characterize a similar initial structural properties as high performance Portland cement. The initial compressive strength for those materials were 90 MPa and 100 MPa, respectively. In contact with fire load, the alkali-activated binder remains its mechanical properties up to temperature of 1200 °C, while Portland binder presents a degradation of properties at ca. 400 °C, Fig. 2.

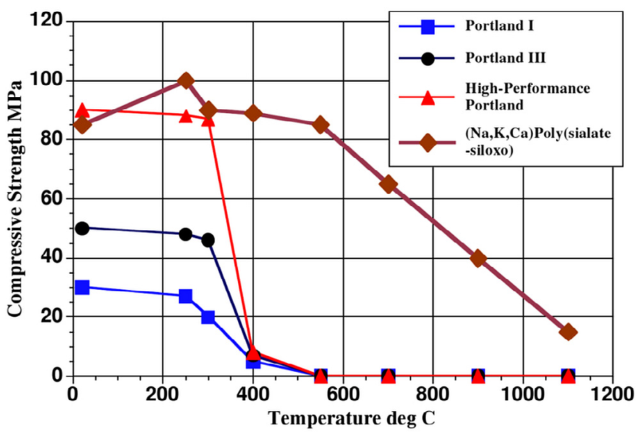

Fig. 2. Fire scenarios used in laboratory testing [1].

It can be seen that alkali activated binder material gains strength after exposure to high temperature. This behaviour of the geopolymer appears to be related to two processes in action at high temperature exposures. That is, sintering and further geopolymerisation process that occurs when the temperature increases. As we can conclude from the results presented for geopolymer material, the loss of strength due to heating is much lower than for Portland cement concrete.

As a passive fire protection, alkali-activated binders act similarly to endothermic building materials. Chemically bonded water evaporates from a heat exposed surface and in this way it absorbs a great part of heat, leading to minimizing of temperature in internal part of structural member.

While comparing them to concrete as passive protection, alkali-activated binders characterize a long-term load bearing capacity in terms of fire duration, do not experience fire spalling (spalling was not reported) and may obtain higher mechanical properties. Moreover, geopolymers can provide an excellent burn-through fire resistance, are not ignitable, nonflammable, do not produce neither combustion gases, toxic gases nor smoke, so they are eco-friendly and safe for both daily exploitation and in case of fire.

3. Polypropylene fibres as the passive protection of concrete

There exists an effective and well-known technique to prevent and reduce Portland cement concrete spalling that consists in use of polypropylene (PP) fibres. Even in standards one can find the recommendation concerning polypropylene fiber's dosage that enable to prevent and reduce the spalling occurrence.

At a temperature of about 170 ºC, PP fibres begin to melt [2] and polymer blends into the concrete matrix. It produces a network of ducts in places previously occupied by fibres. Additionally, thermal expansion of the PP fiber is 8.5 times higher in comparison to concrete thermal strains [3]. This feature leads to rising of tensile stresses, which provides to creating numerous of microcracks in concrete structure. Both mechanisms lead to increase of permeability of concrete, which reduces the water vapour pressure in material pores.

There are a number of studies relating to effective amount and type of PP fibres that affects positively on spalling behaviour of concrete. The different amounts [4], diameters [5,6], lengths [4] and types were employed to find the one universal one recipe. The [7] found that in concrete with w/c of 0.4 the addition of 0.05% (by weight) completely eliminates the occurrence of spalling. Similar conclusions have been reached by [8]. When the mixture contained PP fiber above 0.05% by volume, no spalling occurred, so that spalling resistance was significantly improved. The [9] performed tests on RPC with different amount of PP fibres (1 kg/m^3 and 2 kg/m^3) and different heating rate (0.5, 1, 2, 4 and 8 ºC/min). The addition of PP fibres added in the amount of 2.0 kg/m^3 PP fibres allows limiting the spalling risk of RPC cement material. Spalling was efficiently limited even when the relatively high heating rate (8 °C/min) was applied.

In scientific community, however, it is known that PP fibres can limit spalling risk only to some extent. In case of HPC (High Performance Concrete) and very severe fire scenario, spalling can be observed, regardless of PP fiber dosage. Therefore, the further research aimed at understanding the key factors influencing spalling are highly needed.

4. Intumescent and ablative materials

Fire protection barriers enable to create fire resistant compartments preventing fire spread. Separation of larger buildings into smaller fire resistant compartments, increases the safety of the building occupants. Effective fire compartment barriers seal all openings like electrical services. Electrical services transmit power by cables placed either in cables trays or in cables trunking. In case of transmission lines, the fire protection of opening and cables itself is at highest value. In order to separate occupancies from fire, the openings are often sealed with intumescent material while ablative materials are used commonly as protective paint like coating for cables protection.

When considering steel structure and its susceptibility to damage under fire, intumescent and ablative materials may be applied successfully as well.

4.1. Intumescent materials

An intumescent is a water-, solvent-, or epoxy-based paint like coating material. It experiences complex chemical reactions at temperature range of 200 °C to 250 °C that provide a significant expansion in its volume, decrease its density and result in low thermal conductivity of intumescent layer. Two main types of intumescent materials can be distinguished: thin film and thick film coating.

Thin film intumescent materials - the fire-resistant thin film intumescent coating consist in a water- or solvent-based painting layer of approximately 1 – 3 mm thickness. The complex layer is usually made of three separate components: a primer layer, a base layer that reacts with fire and a sealer that provides a tightness of coating. A base layer, as a responsible for fire protection is made of a number of ingredients influencing proper behaviour during fire action. Among them, the following should be mentioned: an acrylic resin that softens at specific temperature, and a spumific agent that decomposes simultaneously with melting of acrylic resin and produce a large amount of nonflammable gases. These gases include carbon dioxide, ammonia and water vapour. As a result of presence of a great amount of free gases and melted raisin, the initial material expands in its volume by 20 – 50 times. Such expanded layer can withstand a fire load for even 120 minutes. This kind of coating can be applied to steel structural elements either on-site by specialized technicians or off-side in dedicated industrial hall. Off-side application is more expensive, but more accurate in terms of both the tightness of the coating and appearance, which is especially important for components being exposed. Thin film coatings are usually used for protection from cellulosic type fires that occur in industrial and commercial buildings.

Thick film intumescent materials - in the risk of hydrocarbon fires, that are more severe than cellulosic ones and occur mostly in high rise buildings and tunnels, the application of thick film intumescent material is recommended. It is epoxy-based instead of water or solvent in order to provide additional protection from corrosion of steel members in contact with water. Thick film coating can be applied in form of spray, by trowel or by the use of casting, which provide a high quality, hard and smooth finishing surface. This kind of coatings characterize of higher film thickness than thin film ones, and the thickness is dependent on particular purposes of a structural element being protected. However, the operating principles in fire conditions are the same as those described for thin film coatings, but expansion ratio in this case is reaches 5 times of initial value. Due to higher resistance to water environment, those coatings are often used in off-shore structures to protect steel elements from corrosion and aggressive marine environment.

4.2. Ablative materials

Another solution for paint like coating material is the use of ablative painting. Fire triggers in ablative materials the endothermic reactions, which absorb a thermal energy in a great extent and minimize the increasing of temperature in underlying layers. In addition, while using energy, the reactions cause production of a steam which helps to retard and reduce the flames formation. Ablative coating can be applied either in form of spray or by trowel and its thickness is directly dependent on the designed fire load and its duration. Those materials are made of elastomeric silicone so, if properly designed, they are elastic enough to remain tight on curved surface as well as are resistant to cracking in exploitation phase of structure. According to tests by [10], the 1–2 mm thickness of ablative coatings can resist fire load for 20 minutes and thus preferred coating thicknesses are approximately applied in range between 1 mm and 7 mm to provide fire resistance between 30 minutes and 120 minutes. In order to protect the ablative layer from water and mechanical damage, the non-structural top layer of resin is commonly applied.

5. Testing of passive protection

Generally, testing of passive protection is performed according to specific guidelines and procedure described in standards. For Europe, the basic standard for fire testing is EN 1363-1: Fire resistance tests - Part 1: General Requirements [11], while in United Stated, the principal fire standard is ASTM E119: Standard Test Methods for Fire Tests of Building Construction and Materials [12]. There exists also a range of national and international guidelines and technical reports [13,14,15] providing detailed instructions for testing passive protection for particular purposes, ex. tunnel linings.

While testing the passive protection in fire, the basic requirement of insulation shall be proven, in particular: material shall be classified as incombustible or combustible. Additionally, most standards and guidelines require to report a measurement for heat transfer through material and flame propagation by material within fire duration. Also the information about production of smoke and toxic gases shall be noted in a test report.

The fire test does not take into consideration materials individually, but investigate an entire system, ex. a sandwich wall with insulation, a tunnel ring with lining, or even complex structural system, if necessary. Regardless of standard being used, it defines heating regimes, pressure conditions, testing methods, criteria for determining fire resistance and instrumentation of testing setup.

In general, in fire testing we can distinguish few types of time-temperature curves that are followed by researchers in order to reflect expected fire conditions (Fig. 3). While testing the passive protection for industrial or commercial area, the cellulosic fire of ISO 834-1 curve is used. It reflects the burning rate of the general building materials and contents. In buildings of risk of burning the car fuel tankers, petrol or other chemical tanker, the development of fire is faster and the temperature in such case exceed the ISO 834-1 curve. In that case the Hydrocarbon (HC) curve shall be used. Sometimes in laboratory testing of passive protection for tunnels another curve, RWS, is used, as a result of studies carried out in Netherlands and Norway. In some research one can find also reference to RABT curve that was developed on the basis of series of research program performed in Germany.

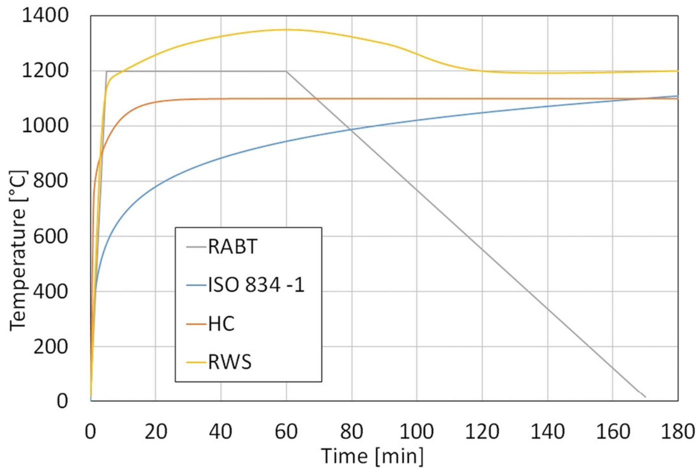

Fig. 3. Fire scenarios used in laboratory testing.

During the test, a temperature development in testing element is measured with the use of a type K thermocouples that are moulded inside concrete specimen, as well as plate thermocouples placed near the fire exposed surface. The high temperature conditions are provided mostly by propane or oil burners.

In case of testing of passive protection, there is no need to continue tests longer, if the criteria of insulation are no longer met. Moreover, to determine the effectiveness of passive protection, the test should last as long as it is required by designed purposes. The duration of the test is dependent on considered resistance R, which is defined in standard [11]: R15, R20, R30, R45, R60, R90, R120, R180, R240, where the number means a minimum period of time in minutes, which structure should withstand under fire load.

The passive protection is considered to be effective if after defined period of time, the structure being protected is not exposed to fire, or the load bearing properties of structural component of testing system is not decreased in undesirable extent.

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