TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 667:620.199
https://doi.org/10.23947/2541-9129-2023-7-2-38-46

Original article

Fire Resistance of a Building Element with Intumescent Fire Protection: Standard Assessment and Express Analysis

Aleksey V Martynov[1], **Vasiliy V Grekov**[1], **Olga V Popova**[2]
[2] Stroitel'stvo Kachestvo Bezopasnost' OOO, 68, 69 office, 37, Kosmonavtov Avenue, Rostov-on-Don, Russian Federation
[1] Don State Technical University, 1, Gagarin Square, Rostov-on-Don, Russian Federation
✉ olvp2808@rambler.ru

Abstract
Introduction. The paper considers the problem of fire resistance assessment of building structures with intumescent fire protection. For the results reliability, a fire test should be carried out only when the intumescent coating at the facility is ready, which will make it possible to detect hidden factors of violation of its quality and prevent collapse in case of a possible fire. The work objective is to test the express analysis of intumescent coatings in comparison with standard methods for fire resistance assessment.

Materials and Methods. The elements of building structures covered with fire-resistant intumescent paint Defender M Solvent with different diluent content were studied. The fire resistance of the coatings was determined by two methods. The first one is an express analysis. The following indicators were recorded:
– general appearance of the coked cellular material (CCM);
– swelling coefficient;
– CCM compressive and shear-tear strength of the boundary layer.
The second one is a standard approach according to the requirements of ISO 834-75 (GOST 30247.0-94). The indicators were:
– time to reach the critical temperature;
– critical deflection during heating.

Results. In addition to the above indicators, testing also took into account the amount of diluent. The CCM swelling coefficient, CCM compression force, tensile strength and density were considered. The revealed patterns are systematized in a table. The obtained indicators were compared with the technical requirements for the material. The period during which the steel substrate of the sample reaches a critical temperature is recorded. It is established that with an increase in this time, the coefficient of swelling of the protective layer (CCM) and its shear-tear strength increases. At the same time, the values of compressive strength and CCM density decrease. When the intumescent paint is diluted beyond the norm, the fire protection parameters deteriorate and the fire resistance limit R45 is not reached. The research results are visualized in the form of diagrams. They confirm that the express analysis makes it possible to reasonably judge the suitability or unsuitability of the paint for fire protection, if the required fire resistance limit is R45.

Discussion and Conclusions. In comparison with the results of the application of standard techniques, the effectiveness of the express analysis technique and the correctness of the results of the assessment of intumescent fire protection were confirmed. In construction conditions, an express CCM analysis will be sufficient to determine the quality of an intumescent fire retardant coating.

Keywords: fire resistance, intumescent coating, coked cellular material, express analysis method, tensile strength, critical temperature, swelling coefficient, fireproof structures.

Acknowledgments. The authors express their gratitude to the editorial board of the journal and the reviewer for their professional analysis and recommendations for correcting the article.

For citation. Martynov AV, Grekov VV, Popova OV. Fire Resistance of a Building Element with Intumescent Fire Protection: Standard Assessment and Express Analysis. *Safety of Technogenic and Natural Systems.* 2023;7(2): 38–46. https://doi.org/10.23947/2541-9129-2023-7-2-38-46

Научная статья

Огнестойкость строительного элемента с интумесцентной огнезащитой: стандартная оценка и экспресс-анализ

А.В. Мартынов[1], В.В. Греков[1], О.В. Попова[2] ✉

[1] ООО «Строительство Качество Безопасность», Российская Федерация, г. Ростов-на-Дону, пр. Космонавтов, 37, оф. 68, 69

[2] Донской государственный технический университет, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1

✉ olvp2808@rambler.ru

Аннотация

Введение. Рассматривается проблема оценки огнестойкости строительных конструкций с интумесцентной огнезащитой. Для получения достоверных результатов нужно проводить огневое испытание только после полной готовности интумесцентного покрытия на объекте. Такой подход позволит выявить низкое качество материала и предотвратить обрушение при возможном пожаре. Цель исследования — испытание экспресс-анализа интумесцентных покрытий в сравнении со стандартными методами оценки огнестойкости.

Материалы и методы. Исследовались элементы строительных конструкций, покрытые огнезащитной интумесцентной краской Defender M Solvent с различным содержанием разбавителя. Огнестойкость покрытий определяли двумя методами. Первый — экспресс-анализ. Фиксировались следующие показатели:

– общий вид пенококса (ПК);

– коэффициент вспучивания;

– прочность ПК на сжатие и на сдвиг-отрыв приграничного слоя.

Второй — стандартный подход согласно требованиям ISO 834–75 (ГОСТ 30247.0–94). Показатели:

– время достижения критической температуры;

– критический прогиб при нагревании.

Результаты исследования. Кроме заявленных выше показателей тестирование учитывало также количество разбавителя. Рассматривались коэффициент вспучивания ПК, сила сжатия ПК, предел прочности и плотность. Выявленные закономерности систематизированы в табличном виде. Полученные показатели сопоставлялись с техническими требованиями к материалу. Зафиксирован период, в течение которого стальная подложка образца достигает критической температуры. Установлено, что с увеличением этого времени повышается коэффициент вспучивания защитного слоя (ПК) и его прочности на сдвиг-отрыв. Одновременно уменьшаются значения прочности на сжатие и плотности ПК. При разбавлении интумесцентной краски сверх нормы ухудшаются параметры огнезащиты и не достигается предел огнестойкости R45. Итоги изысканий визуализированы в виде диаграмм. Они подтверждают, что экспресс-анализ позволяет обоснованно судить о пригодности или непригодности краски для огнезащиты, если требуемый предел огнестойкости — R45.

Обсуждение и заключения. В сопоставлении с результатами применения стандартных методик подтверждена эффективность методики экспресс-анализа и корректность результатов оценки интумесцентной огнезащиты. В условиях стройки экспресс-анализа ПК будет достаточно для определения качества интумесцентного огнезащитного покрытия.

Ключевые слова: огнестойкость, интумесцентное покрытие, пенококс, метод экспресс-анализа, предел прочности, критическая температура, коэффициент вспучивания, пожаробезопасные конструкции.

Благодарности. Авторы выражают благодарность редакционной коллегии журнала и рецензенту за профессиональный анализ и рекомендации для корректировки статьи.

Для цитирования. Мартынов А.В., Греков В.В., Попова О.В. Огнестойкость строительного элемента с интумесцентной огнезащитой: стандартная оценка и экспресс-анализ. *Безопасность техногенных и природных систем*. 2023;7(2):38–46. https://doi.org/10.23947/2541-9129-2023-7-2-38-46

Introduction. Intumescent coatings are widely used in the design of relatively fireproof reinforced concrete and steel structures. This explains the interest of researchers in assessing the fire retardant effectiveness of such materials [1–3]. The publications criticize uninformative methods based on standard fire resistance tests. To solve the problem, comprehensive approaches are proposed to study the effectiveness of intumescent coatings that swell under the action of fire [1, 2]. They must meet certain standards. In academic research, it is difficult to establish the compliance of the material with industrial standards. There are two main reasons for this:

– the necessary stationary equipment is usually not available;

– the experiments require a long time and significant resources (in particular, energy).

However, the authors of [4, 5] use some industrial standards — curves of nominal temperature and time. Let us note that the parameters of a real fire in a modern building may differ significantly from the nominal curves defined in industrial standards [6–8]. Nevertheless, industrial standards remain the main guideline. The international standard for fire resistance testing of building structures ISO 834-75 (GOST 30247.0-94)[1] defines general requirements for methods of fire exposure to establish limit conditions.

Research and development of intumescent coatings take place in different conditions. Different test equipment is involved. This allows you to quickly check new formulations of coatings [4, 5, 9, 10], conduct tests in non-standard fire conditions [11, 12] and measure additional parameters [13, 14]. Most authors pay attention to the strength and adhesion of the paint itself, not paying attention to the mechanical properties of coked cellular material (CCM). However, the finished paint layer is not fire protective. It is more correct to present it as a stock of materials for the formation of such protection, i.e. for transformation into another material — coked cellular material. The authors of publications [15–17] investigated the strength of coked cellular material on stationary laboratory equipment.

The effectiveness of the coating is determined mainly by the thickness of the intumescent layer and the degree of dilution of the finished paint immediately before application. All this affects the quality of the CCM — the thickness of the layer and the density. Modern standards do not allow establishing these indicators during external examination of the paint layer, measuring its thickness and fixing conditional adhesion [18].

The authors of the presented work have developed an express analysis method that allows you to quickly identify the actual suitability of fire protection. At the same time, simple and inexpensive equipment is used, there is no need for special laboratory conditions and high energy costs. The quality of fire protection can be determined directly on the building structure [19, 20].

The work objective is to substantiate the effectiveness of the express method developed by the authors for evaluating the effectiveness of intumescent coatings of building structures. The proposed approach is tested and compared with standard methods for fire resistance assessment.

Materials and Methods. When testing fire retardant properties of elements of a metal building structure, three different variants of intumescent (swelling) material were used:

– mid-priced paint Defender M Solvent OOO "Laboratoriya "Evrostil" with the parameters stated in the technical documentation (composition 1);

[1] *GOST 30247.0-94 (ISO 834-75). Elements of building constructions. Fire-resistance test methods. General requirements*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/9055248 (accessed 10.04.2023). (In Russ.).

– the same paint, diluted by orthoxylene (6 % of weight), which slightly exceeds the maximum stated in the technical documentation (composition 2);

– the same paint, excessively diluted with orthoxylene — 10 % of weight. (composition 3).

Let us note that excessive dilution is often found in practice. We are talking about cases when the viscosity of the paint is corrected using unsuitable, cheap coating equipment or it is excessively diluted in order to save paint [18]. According to the instructions, the dilution should not exceed 5 %.

As part of the work, two types of structures were protected.

1. Hot-rolled I-beams with parallel flanges No. 12 (GOST R 57837-2017). The thickness of the finished paint coating layer after drying is 1–1.2 mm. The vertically oriented structure (column) in the furnace was tested for fire retardant efficiency according to the parameter "time to reach the critical temperature".

2. Beams of the 35SH1 grade with a length of 4.2 m with a thin-layer fire retardant coating of 0.87 mm. The loaded beam horizontally oriented in the furnace was tested for fire resistance of the structure according to the parameter "critical deflection during heating".

The coatings after application to the structures were dried until the diluent was completely removed — 10–14 days at a temperature of +20 °C and a humidity of no more than 80 %. The tests were carried out for each sample according to the developed method of express analysis [19], after which the coatings were restored at the test sites. Further, the tests were carried out for each sample in a flare furnace according to GOST R 53295-2009[2] and GOST 30247.1-94[3].

The test results using the express analysis method were evaluated according to the following indicators:

– CCM general appearance;

– swelling coefficient;

– CCM compressive strength;

– CCM shear-tear strength of the boundary layer with a thickness of 1 mm from the substrate (according to the method described in [19]).

Additionally, the CCM density was measured in the laboratory.

The time of reaching the critical temperature of the protected material according to GOST R 53295-2009 was estimated. For this purpose, a temperature curve was constructed — the dependence of the critical temperature of the steel substrate on the time of the fire test. Test conditions:

– ambient temperature — +18° C;

– relative humidity — 30 %;

– air velocity — less than 0.5 m/s.

The average temperatures in the fire chamber of the furnace did not exceed the permissible deviations. Fire resistance of the structure before reaching the maximum permissible deformation of the beams under fire exposure was determined in a special horizontal furnace. Beams with coatings were tested under a point load of 16 tons every 1/3 span. During the tests, the time of occurrence of the limiting states and their type, the temperature in the furnace, the temperature on the unheated surface of the sample, the deformation of the beam, and the temperature regime in the chamber were recorded.

Results. After conducting fire tests according to the standard methodology and express analysis methodology [19], the samples were examined and their physical and mechanical parameters were measured. The results are summarized

[2] *GOST R 53295-2009. Fire retardant compositions for steel constructions. General requirement. Method for determining fire retardant efficiency*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200071913 (accessed 10.04.2023). (In Russ.).

[3] *GOST 30247.1-94. Elements of building constructions. Fire-resistance test methods. Loadbearing and separating constructions*. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/9055247 (accessed 10.04.2023). (In Russ.).

in Table 1. The results of CCM density measurements not provided for by the express analysis methodology are also presented [19].

Table 1

Test results of intumescent fire protection by express analysis and according to GOST R 53295-2009

Parameter	Composition 1	Composition 2	Composition 3
Amount of diluent in IP, % wt.	0	5	10
Time to reach the critical temperature of the substrate (+500 °C), min	47	34	27
CCM swelling coefficient	36	17	11
CCM compression force outside gas bubbles, with an indenter with a diameter of 3 mm, g.wt	6	14	27
CCM compressive strength, g.wt/cm^2	86	200	360
CCM shear-tear strength of the boundary layer from the substrate, g.wt/cm	78	56	42
CCM density outside large gas bubbles, g.wt/cm^3	0.28	0.44	0.51
CCM density taking into account large gas bubbles, g.wt/cm^3	0.28	0.14	0.45

Fig. 1 shows the fire resistance test in a standard furnace and the formation of coked cellular material from intumescent paint compositions 1-3 on a metal column of I-section.

a) *b*)

Fig. 1. Fire test result in a standard furnace of I-beam column with an intumescent coating of composition 1:
a — 10 minutes after the start of firing; *b* — after 30 minutes

Let us consider the test results by the standard method. When the sample coated with composition 1 is heated, after 47 minutes, the limit state is fixed according to the parameters "time to reach the critical temperature" (Fig. 2) and "critical deflection during heating" (Fig. 3). This confirms the compliance of composition 1 with the time stated in the technical documentation for reaching the critical temperature (45 min).

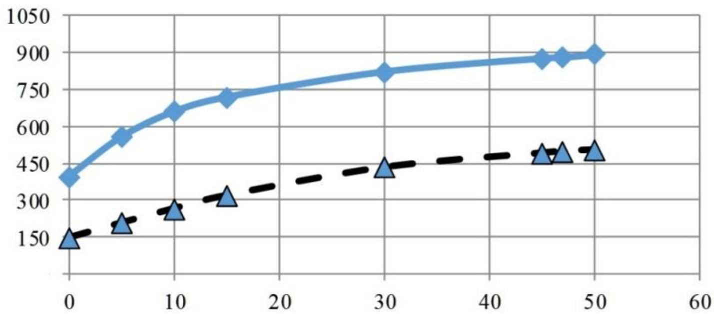

Fig. 2. Time to reach the critical temperature of the sample coated with composition 1 (without dilution). The solid line is the heating temperature; the dotted line is the surface temperature under the CCM layer. The vertical axis shows the temperature (°C), the horizontal axis shows the time (min)

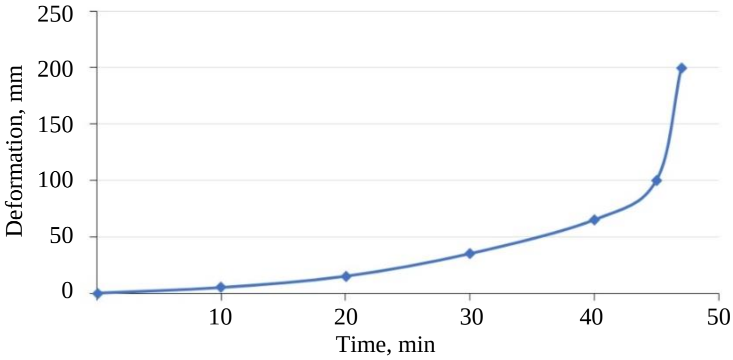

Fig. 3. Dependence of sample deflection with a fire retardant coating of composition 1 (without diluent) on the time of thermal exposure in the furnace fire chamber

The express analysis results regarding the compliance of the fire retardant composition with the technical documentation (CCM swelling coefficient, see Table 1) indicate the correctness of the proposed methodology.

When testing a sample coated with composition 2 according to the standard procedure, the time to reach the limit states was 34 minutes (Fig. 4). That is, the tested material does not comply with the technical documentation. The composition cannot be used for fire protection if the required fire resistance limit is R45.

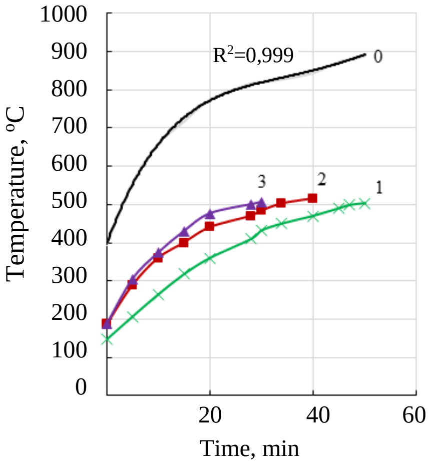

Fig. 4. Dynamics of temperature changes in the fire chamber (curve 0) and the temperature of the protected surface during the testing of samples 1-3 (curves 1-3)

The results of the tests using the express analysis method confirm the unsuitability of the paint, despite the fact that the coefficient of swelling of the coating exceeds the minimum value specified in the regulatory documentation. The resulting CCM is externally heterogeneous, large gas cavities are noticeable. The CCM layers outside of these defects have increased strength and density, as well as relatively low adhesion to the protected material.

Tests of sample 3 gave the following results. The steel substrate reaches its limit state after 27 minutes when tested according to the standard procedure (Fig. 4). This indicates the unsuitability of composition 3 according to the indicator "time to reach the critical temperature" (45 min). This fact was confirmed by the results of tests by the express method. The CCM is heterogeneous, there are large gas cavities. The strength and density of the CCM layer outside these defects is increased, the adhesion to the protected material is low.

The express analysis allowed us to establish that at a given critical deflection value of 200 mm, the loss of bearing capacity in sample 1 was observed after 47 minutes, in sample 2 — after 42 minutes, in sample 3 — after 35 minutes.

Therefore, the longer the heating time of the steel substrate of the sample to the critical temperature, the higher the coefficient of swelling of the CCM protective layer and the lower the index of the CCM compressive strength (Table 1, Fig. 5).

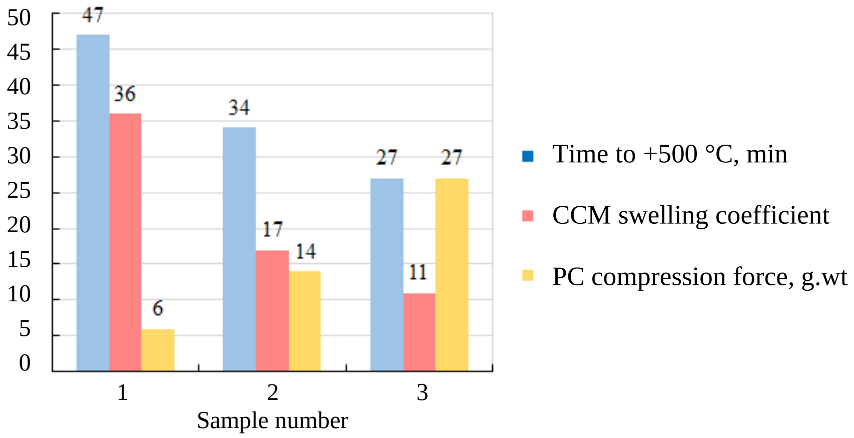

Fig. 5. Results of fire resistance tests according to GOST 30247.0-94 (time to reach the critical temperature of the substrate) and by express analysis (CCM swelling coefficient, CCM strength)

The relatively high compressive strength of CCM, established by the express analysis method for sample 3, assumes a high density of CCM (Table 1) and an increase in the thermal conductivity of the protective layer, which reduces the time to reach the critical temperature of the substrate and is confirmed by the test results according to GOST 30247.0-94.

Discussion and Conclusion. The express analysis of fire resistance of intumescent coatings proposed by the authors was tested on I-beam building structures. The results were compared with a similar test according to GOST 30247.0-94. The comparison demonstrated the correctness of the authors' approach.

The results of the tests for both methods are divided into three groups. The first category includes the results obtained for coatings with high-quality undiluted fire retardant paint that meet the requirements of regulatory documentation in all respects. The second is the results of testing coatings that do not provide the specified fire retardant parameters. At the same time, the CCM coefficient of swelling and its adhesion to the substrate decreases, strength and density increase. The third group is characterized by significant deviations from the required parameters. Based on the results obtained, it can be argued that the assessment of CCM parameters by the express analysis method in the conditions of a construction object is sufficient to decide if the intumescent coating is suitable or unsuitable for fire protection.

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About the Authors:

Aleksey V Martynov, general director, Stroitel'stvo Kachestvo Bezopasnost' OOO (68, 69 office, 37, Kosmonavtov Avenue, Rostov-on-Don, 344113, RF), ORCID, mail@fireguard.ru

Vasiliy V Grekov, technical adviser, Stroitel'stvo Kachestvo Bezopasnost' OOO (68, 69 office, 37, Kosmonavtov Avenue, Rostov-on-Don, 344113, RF), ORCID, Torobas@mail.ru

Olga V Popova, professor of the Life Safety and Environmental Protection Department, Don State Technical University (q, Gagarin Sq., Rostov-on-Don, 344003, RF), Dr. Sci. (Eng.), professor, ResearcherID, ScopusID, ORCID, olvp2808@rambler.ru

Claimed contributorship:

AV Martynov: formulation of the basic concept, goals and objectives of the study, calculations, preparation of the text, formulation of the conclusions. VV Grekov: conducting experiments, preparation of the text, formulation of the conclusions. OV Popova: academic advising, analysis of the research results, revision of the text, correction of the conclusions.

Received 03.04.2023.

Revised 18.04.2023.

Accepted 21.04.2023.

Conflict of interest statement

The authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Об авторах

Мартынов Алексей Владимирович, генеральный директор, ООО СКБ «Строительство Качество Безопасность» (344113, РФ, г. Ростов-на-Дону, пр. Космонавтов, 37, оф. 68, 69), ORCID, mail@fireguard.ru

Греков Василий Владимирович, технический консультант, ООО СКБ «Строительство Качество Безопасность» (344113, РФ, г. Ростов-на-Дону, пр. Космонавтов, 37, оф. 68, 69), ORCID, Torobas@mail.ru

Попова Ольга Васильевна, профессор кафедры «Безопасность жизнедеятельности и защита окружающей среды» Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), доктор технических наук, профессор, ResearcherID, ScopusID, ORCID, olvp2808@rambler.ru

Заявленный вклад соавторов:

А.В. Мартынов — формирование основной концепции, цели и задачи исследования, проведение расчетов, подготовка текста, формулирование выводов. В.В. Греков — проведение экспериментов, подготовка текста, формулирование выводов. О.В. Попова — научное руководство, анализ результатов исследований, доработка текста, корректировка выводов.

Поступила в редакцию 03.04.2023.

Поступила после рецензирования 18.04.2023.

Принята к публикации 21.04.2023.

Конфликт интересов

Авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.