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Assessment of the effect of the applied hydroxide additives on the fire properties of varnish coating systems with a damping mass

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Abstract
The article addresses the very important issue of enriching the products with additives improving the fire resistance properties. For this purpose, hydroxide additives (aluminium and magnesium) were used, which decompose at increased temperature to form water. When designing the experiments, one of the Experimental Design Methods (DOE) was used: 2k factorial design for two independent variables. The enriched coatings were tested in accordance with the requirements of PN-EN 45545-2, incl. Intensity of heat release, lateral propagation of flame on products in vertical configuration, or testing of generated fumes and gases. Mechanical properties such as cohesion and impact toughness were also tested. The effectiveness of this type of additives was assessed, as well as their synergistic effect (due to the different decomposition temperature).

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1. Introduction

High functional properties of elements of modern devices are obtained, among others, through the use of new construction materials, as well as the use of protective layers, ensuring the best possible resistance to corrosion, abrasive and erosive wear, high fatigue strength, etc. (Dudek and Włodarczyk, 2010).

The use of new construction materials (mainly alloy steels) is expensive, which significantly increases the cost of the product, but it is used when there are high loads in the entire element (Ulewicz, et al., 2014).

The production of protective layers on machine parts is economically justified in the case of wear of their fragments or the surface layer, and when other features than the core are required from the surface layer.

The development of modern technologies is inextricably linked with Industry 4.0 (Pietraszek, et al., 2020). Currently, a dynamic development of coatings production with various surface engineering technologies is observed (Radek, 2009; Żurawski, et al., 2008; Radek, et al., 2014; Burakowski, 2013).

The paint coating systems account for approximately 50% of all coating systems. It is estimated that approx. 95% of steel structures are protected against corrosion by means of protective coatings, including as much as 90% by means of paint coatings (Burakowski, 2013). Service life of varnish coating systems ranges from several months to several years (Kozłowska, 1987).

The varnish coatings intended for the rolling stock must meet a number of mechanical and quality properties that translate into the longest possible preservation of protective and decorative properties. These requirements include: adhesion, resistance to changing weather conditions (humidity, UV, corrosion) as well as hardness and more and more often specialist properties such as anti-graffiti. Coating systems intended for rolling stock, in addition to meeting the above-mentioned requirements, as well as ease of application and operation, must also have appropriate fire properties (Pasieczyński, et al., 2018; Radziszewska-Wolińska, et al., 2018). Currently, fire-protective coatings made of various materials are used (He, et al., 2022; Hong, et al., 2015; Liu, et al., 2019; Weil, et al., 2011).

Obtaining modern fire protection in rolling stock is a multi-level process that begins at the time of construction and selection of materials for the production of a safe rail vehicle and does not end throughout its lifetime. In this work, the emphasis was placed on the selection of varnish materials, their enrichment with appropriate additives improving their fire-retardant properties and the influence of such modifications on the mechanical properties of the produced varnish coating. As an example of the varnish material to be modified, a damping mass was chosen in a system with an anti-corrosion primer and a topcoat, due to the fact that it is common in every vehicle, and the large layer thicknesses necessary for effective stunning.

In the European Union, the fire protection requirements for rolling stock are defined in the EN-45545 series of standards. For the materials of which the rolling stock is made, part 2 of this standard is appropriate, which indicates the methods, conditions and requirements for materials and products used in the rolling stock depending on the risk level. Hazard levels are defined as a three-point HL scale, with HL1 being the lowest and HL3 the highest. The grades are assigned depending on the design and operational category of a given vehicle, as shown in Table 1. The classification method is described in the PN-EN 45545-2 standard.

Table 1. Classification of the level of threats (PN-EN 45545-2)

Operation category	Design category			
	N: Standard vehicles	A: Vehicles forming part of an automatic train having no emergency trained staff on board	D: Double decked vehicle	S: Sleeping and couchette vehicles
1	HL1	HL1	HL1	HL2
2	HL2	HL2	HL2	HL2
3	HL2	HL2	HL2	HL3
4	HL3	HL3	HL3	HL3

To determine the types of tests, use the PN-EN 45545-2 standard, specify the application of the coating, inside, outside and the exact place of occurrence. Depending on these parameters, the standard gives the product a classification number. Then, depending on the number, the necessary criteria for fulfilment. In rolling stock, damping masses are used both inside and outside the vehicle. In the case of exterior applications, we are talking primarily about the chassis, while inside, the largest surfaces are the walls and the ceiling of the vehicle. The PN-EN 45545-2 standard assigns the numbers IN1A, IN1B and EX3 to the paint coatings used in this way, which results in the criteria R1 and R7. These criteria impose the obligation to meet the requirements of **Błąd! Nie można odnaleźć źródła odwołania.**and **Błąd! Nie można odnaleźć źródła odwołania.** Finally, it is necessary to perform lateral fire spreading, heat and smoke release, optical smoke density and analysis of gases released during combustion.

Table 1. Requirements for the R1 criteria (PN-EN 45545-2)

Requirement set	Test method reference	Parameter and unit	Max or min	HL1	Hl2	HL3
R1	T02 ISO 5658-2	CFE kWm^{-2}	Min	20 a	20 a	20 a
	T03.01 ISO 5660-1 50 kWm^{-2}	MARHE kWm^{-2}	Max	-	90	60
	T10.01 ISO 5659-2 50 kWm^{-2}	$D_s(4)$ Dimensionless	Max	600	300	150
	T10.02 ISO 5659-2 50 kWm^{-2}	VOF4 min	Max	1200	600	300
	T11.01 EN 17084 Method 1 50 kWm^{-2}	CIT_G Dimensionless	Max	1.2	0.9	0.75

Table 2. Requirements for the R7 criteria (PN-EN 45545-2)

Requirement set	Test method reference	Parameter and unit	Max or min	HL1	Hl2	HL3
R7	T02 ISO 5658-2	CFE kWm^{-2}	Min	20 a	20 a	20 a
	T03.01 ISO 5660-1 50 kWm^{-2}	MARHE kWm^{-2}	Max	-	90	60
	T10.04 ISO 5659-2 50 kWm^{-2}	$D_s$max Dimensionless	Max	-	600	300
	T11.01 EN 17084 Method 1 50 kWm^{-2}	CIT_G Dimensionless	Max	-	1.8	1.5

Except for fire properties compliant with European standards, several mechanical properties were selected for testing. In addition to the standard measurement of the thickness of particular coating layers, it was decided to test the adhesion using the pull-off test, falling-weight with a large-area indenter test of rapid-deformation and gritting according to the requirements for railway axles. These tests were selected due to the expected high impact of high filling of the damping mass with additives improving fire protection.

There are many compounds that can potentially be considered fire retardant fillers. To choose the most appropriate one, we should consider what requirements should be met, e.g. what compounds are formed during thermal decomposition. After decomposition, the group of metal hydroxides leaves mainly metal oxide and water. In order to inhibit combustion, they can show significant endothermic decomposition at a temperature exceeding the melting point of the protected polymer, usually between 180°C and 300°C. The flame- retardant additives used should have a small particle size and surface area to be used at high filler saturation values of the flame retardant product . The additive should not affect the application properties of the product and its final physical and mechanical properties.

2. Experimental

In order to improve the fire-retardant properties, it was decided to use the two most popular hydroxides: aluminium (ATH) and magnesium (MDH). They improve the combustibility properties in several ways. First, they replace some of the available fuel - the resin that supports the fire. Second, ATH contains 34.6% and MDH 30.9% of bound water that is released when exposed to high temperature (depending on the source, starting from 180°C - 230°C for ATH, and 300°C - 340°C for MDH), providing a protective effect by limiting the access of oxygen needed for combustion. Additionally, after decomposition, hydroxides produce metal oxides: aluminium (Al_2O_3) and magnesium (MgO), which have a relatively high heat capacity. This helps to reduce energy that would otherwise be used to maintain the flame on the protected components. A further advantage is that a "charred" layer is formed during a fire, which will result in further flame protection and less smoke production (Yang, 2017; Hornsby, 2001).

ATH is most popular for several reasons, in particular its low cost, good flame retardant properties and non-toxic smoke.

The schematical equations of thermal disintegration of used flame retardants:

$$Mg(OH)_2 \xrightarrow{\Delta T} MgO + H_2O \quad (1)$$

$$2Al(OH)_3 \xrightarrow{\Delta T} Al_2O_3 + 3H_2O \quad (2)$$

The experiment was designed using a 2^k factorial design for two independent variables. This gives four paint systems: the basic system without modifications - 0, the system with the maximum content of aluminium hydroxide - 1, the system with the maximum content of magnesium hydroxide - 2 and the system with the combination of these compounds - 3. A full set of tests was performed on all systems.

The schematically made systems are presented in the matrix below with the use of coded variables where (-1) - No addition; (+1) - an allowance in the maximum amount (Jańczewski, et al., 2010).

Table 1. Matrix of experiment

System	ATH	MDH
0	-1	-1
1	+1	-1
2	-1	+1
3	+1	+1

The tested systems were made on 1.5 mm thick steel substrates, sanded with P80 grit sandpaper. An anti-corrosive epoxy primer, a damping mass (the layer undergoing modification) and a polyurethane topcoat were applied to the substrate.

Mass modifications were as follows - volume share in%:

Table 2. Modifications mass damping

System	The damping mass	ATH	MDH
0	100%	0%	0%
1	91.40%	8.60%	0%
2	95.10%	0%	4.90%
3	93.30%	4.60%	2.10%

In order for the additives to fulfil their functions, they must be introduced into the system in an appropriate manner ensuring their proper fineness and pigment volume concentration (PVC) that will not exceed the critical value (CPVC). The pigment volume concentration is a reference value expressing the volume ratio of pigments and fillers to the resin in the cured coating. It is counted using the formula (Hyrynkiewicz, 1999):

$$PVC = \frac{V_p + V_w}{V_p + V_w + V_{sb}} \cdot 100\% \quad (3)$$

Where: V_p - Pigment volume;
V_w - The volume of the filler;
V_{sb} - Volume of the film-forming substance (resin).

The critical pigment volume concentration (CPVC) value is the value at which the pigments and fillers are still wetted by the resin. Above this value, the surfaces are not fully covered with resin, which begins to affect the properties of the cured coating, e.g. the coating loses its gloss, mechanical resistance such as cohesion and elasticity decrease, the permeability of the coating increases - loss of barrier properties. The CPVC value varies depending on the type of pigments and the binder used in the system. Most often it is determined experimentally, which was also done during the preparation of test mixtures.

Additives improving the fire-smoke properties were added in the determined limit amount, which did not adversely affect the application properties of the modified product, and theoretically should not have a significant impact on the properties of the cured coating. A number of studies have been carried out to analyse the effect of these additives on the systems tested.

3. Results and discussion

3.1. Tests physics - mechanical

In order to evaluate the mechanical properties of the paint system with a damping mass, the following were selected:

- determination of the coating thickness according to ISO 2808, method 7B.2 of magnetic induction
- Pull-off test for adhesion evaluation according to ISO 4624
- rapid-deformation (impact resistance) test according to ISO 6272-1
- gritting resistance according to PN-EN 13261 Annex H

Physics-mechanical tests were carried out in the FH Barwa Adhesive Coating Laboratory.

3.1.1. Thickness measurement

The thickness of the paint coating was measured in accordance with the PN-EN ISO 2808 standard using the magnetic induction method 7B.2. The measurement was performed after each layer of the varnish system. On each sample number of measurements depended on the size of the sample. The average values for individual systems are given in Table 6, the total average thickness of the system is 1486.6 μm.

Table 3. Comparison of thickness measurements

System	Average thickness, μm		
	Anti-corrosion primer	Damping mass	Topcoat
0	42.8	1429.1	48.4
1	47.3	1396.8	46.1
2	45.3	1389.7	45.5
3	45.5	1365.8	44.3
Average :	45.2	1395.3	46.1

3.1.2. Cohesion test

The cohesion of the damping mass was tested using method B of the PN-EN ISO 4624 standard and useing dollies with a diameter of 50 mm. The dollies were glued to the sanded surface of the topcoat with 2K epoxy glue, after the seasoning period, the coating around the stamp was cut and then torn off using the hand-held PosiTest device. Fig. 1shows place and nature of fracture after test. Top photos presents dolly, bottom photos shows test area at the samples.

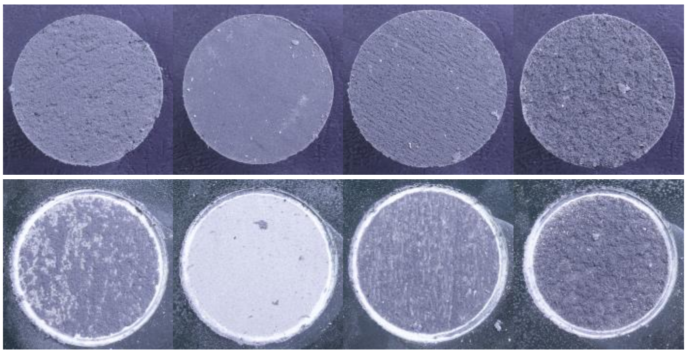


Fig. 1. From left to right : System 0 average value 0.82 MPa; System 1 average value 1.01 MPa; System 2 average value 0.61 MPa; System 3 average value 0.80 MPa

The presented photos expressively indicate the differences between the individual systems. The highest value for breaking was achieved by System 1 and the lowest by System 2, but in all cases the values are low mostly because of the substrate thickness, which indicates the need to repeat the tests with changed parameters or change the measurement method.

The nature of the break, however, shows differences. Although all tests were assessed as breaking in the layer of damping mass, the appearance of the surface is completely different for each system. System 0 is the reference. System 1, in terms of appearance, differs the most. The break was very close to the primer, but you can clearly see the grey "haze" that remained on the primer. System 2, gained a finer fracture structure. System 3 is clearly fractured in the middle of the damping mass.

The above results indicate a different arrangement of the flame retardant pigments in the damping mass and a certain influence on the fracture value. Further research is needed in this regard, with a change in the measurement method.

3.1.3. Impact resistance test

Rapid-deformation test was performed according to PN-EN ISO 6272 standard - Test with a large-area indenter. The test consists in lowering a weight of a standardized mass onto the coating from a height that causes the deformation of the coating and the substrate. The height increases until the coating is damaged. The measurement can be performed from the side of the coating or from the substrate. The result is the mass of the indenter and the height it was dropped from to deal a damage to coat. The photos of the coating after testing are summarized in Fig. 2.

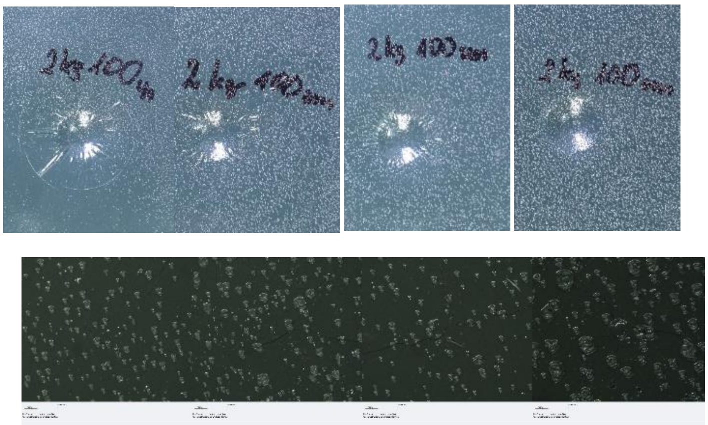


Fig. 2. The top row shows the front shots 2kg 100cm and the bottom row the back shots 1kg 10cm. From left to right: System 0; System 1; System 2; System 3

There was no significant difference between the different systems. For the test from the coating side, no cracks appear at the point of impact, the damping mass, regardless of the flame- retardant additive used, absorbs the weight energy well. In order to obtain higher energies and to observe possible differences, it is necessary to change the method. For the test from the substrate side, the coating cracks even with a small load, this is due to the high thickness of the coating.

3.1.4. Gritting test

To test the gritting, the method indicated in the standard for railway axles PN-EN 13261 Annex H was selected. In this method, we use a stand consisting of a five-meter pipe with a diameter of 38 mm set vertically, we place the test object 30 mm below the pipe outlet at an angle of 45°. From the top, through the pipe, we drop 1 kg of standardized nuts. Then we evaluate the degree of chipped coating from the substrate.

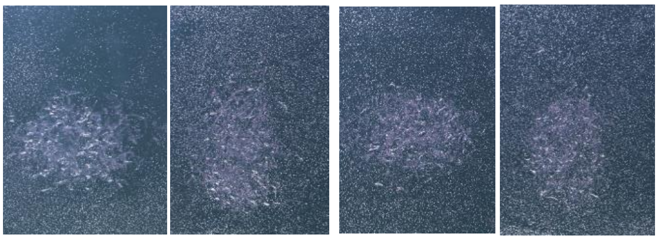


Fig. 3. From the left : System 0; System 1; System 2; System 3

There were no differences between the systems. The damping mass absorbs the energy accumulated in the nuts, which prevents the coating from chipping, thanks to which the paint system achieves the highest abrasion class in accordance with the requirements of the standard.

3.2. Fire tests

A significant effect of the fire (which is fatal to passengers and hinders evacuation) is the lateral flame on the surface, the rate of heat emission, and the density and toxicity of the smoke produced as a result of burning materials that constitute the lining of walls and ceilings of rail vehicles.

In order to assess the fire resistance resulting from the application of a paint system with a damping mass, the fire parameters were selected, as required, that characterize the material resistance to external fire sources, i.e.:

- critical flux at extinguishment- CFE (the lower its value, the greater the fire hazard of the material) according to ISO 5658-2
- maximum average rate of heat emission - MARHE (the higher its value, the greater the fire hazard of the material) according to ISO 5660-1
- intensity of emitted smoke (optical density of the air in the vicinity of the burning sample - $D_s(4)$, $D_s max$, VOF(4) according to PN-EN ISO 5659-2
- emission of toxic gases (standard CITG toxicity index in 4 and 8 min.

The fire tests were carried out in the Materials and Structural Elements Test Laboratory of the Railway Institute. This unit is recognized by CERTIFER (Railway Certification Agency) in the field of fire tests and is accredited by the PCA (Polish Centre for Accreditation, AB 369)

3.2.1. Lateral flame propagation on products in a vertical configuration

The test method included in the ISO 5658-2 standard was used to measure the lateral spread of the flame along the surface of the product oriented in a vertical position. This test consists in exposing conditioned samples in a well-defined field of radiating heat flux and measuring the ignition time, lateral spread of the flame and its final extinction, which is the main parameter of this test and is a characteristic of the material i.e. CFE (CFE - critical heat flux at extinguishment, i.e. the smallest value of the heat radiation intensity of the sample surface at which flame combustion still takes place). The lower the CFE value, the greater the fire hazard the material presents (Radziszewska-Wolińska and Milczarek, 2018).

The test specimen is placed vertically adjacent to the angled propane fired radiation panel with heat flux standardization along the calibration plate. Fig. 4 shows a sample of the material during the test. On the other hand, Fig. 5 and 6 show an example of a paint system before and after the test.

Fig. 3. Material sample during CFE determination (source: Railway Institute)

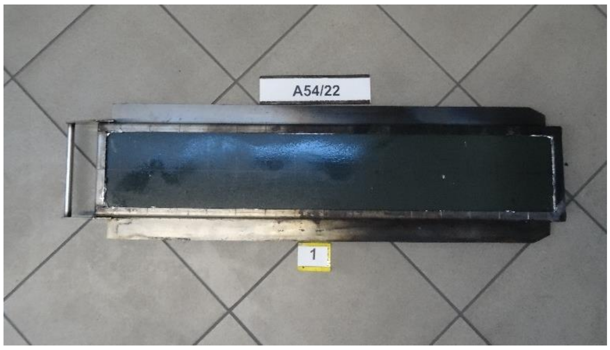


Fig. 4. Paint system sample before testing

Fig. 5. A sample of the painting system after the test

The results of the tests for determining the flame spread over the surface for paint systems with a damping mass (according to Table 6) are presented in Table 7.

Table 4. Fire properties of paint systems with a damping mass in the range of the CFE

System	Mean thickness*, mm	The ignition time is, s	Time extinction the flame tk, p	Time smoking t, s	CFE, kW/m²
0	2.99	47	666	619	21.3
1	2.70	56	639	583	21.9
2	2.71	60	602	542	27.1
3	2.89	71	530	459	24.7

* thickness of the mass with a steel substrate

During the test, it was observed that the type of flame retardant used to make the damping mass flame-retardant influenced the burning time of the sample and the spread of the flame over the sample surface. These dependencies are presented in Fig 7.

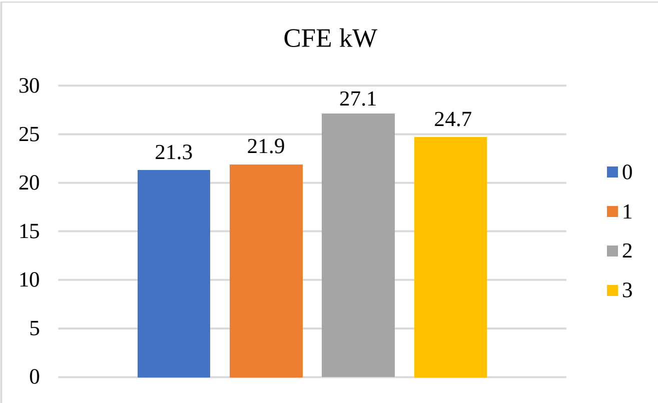


Fig. 7. Influence of the type of anti- pyrene used to fire the damping mass on the size of the critical heat flux CFE

The most effective value of energy, measured at the surface of the samples, at which flame combustion still occurs, is increased by the addition of magnesium hydroxide (MDH). The oxide layer produced after its dehydration process most effectively reduces the decomposition of the polymer and creates a tight barrier coating. Magnesium hydroxide additionally absorbs more heat from the environment on decomposition than aluminium hydroxide. It was also observed that hydroxide additives, in each case - applied alone or together, prolong the ignition time of the samples and shorten the burning time of the material. Taking into account all these parameters, the combined use of ATH and MDH seems to be optimal due to the simultaneous increase of the CFE parameter with a simultaneous significant reduction of the burning time of the modified coating.

3.2.2. The intensity of heat release

The intensity of heat release was measured with the use of a cone calorimeter according to the methodology contained in the ISO 5660-1 standard. It specifies a method for assessing the rate of heat release of a sample exposed in a horizontal orientation to controlled levels of irradiation using an external ignition. The rate of heat release is determined by measuring the oxygen consumption from the measurement of the oxygen concentration and the flow rate of the combustion stream products. In general, the net heat of combustion is proportional to the amount of oxygen used to burn the sample. This is approximately 13.1x103 kJ of heat released per kilogram of oxygen consumed.

The radiation source is a cone-shaped electric radiator. The irradiation of the sample can be set between 0 and 75 kW/m², but the most common are 25 kW/m² and 50 kW/m². This test also measures the rate of weight loss, the production of smoke, and the time to ignition (flame retention). Fig. 7 shows the ISO 5660-1 stand and the sample under test.

Fig. 8. Test stand according to ISO 5660-1 and a sample during the test (source: Railway Institute)

An oxygen analyser is used to measure oxygen depletion, which measures the baseline oxygen before the test and the oxygen concentration during the test. Based on these measurements, the maximum average rate of heat emission (MARHE) is calculated, which is the main practical parameter of this test method. Fig. 9 shows an exemplary sample of the paint system before and after testing.

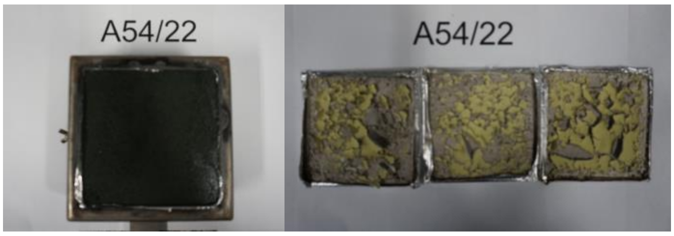


Fig. 9. Sample of the paint system before and after testing

The results of tests to determine the heat release rate during combustion for paint systems with a damping mass (according to Table 6) are presented in Table 8.

Table 5. Fire properties of paint systems with a damping mass in terms of the MARHE

Where: HRR_{180} - Average heat release rate after 180s, kW/m^2
HRR_{max} - Maximum heat release rate, kW/m^2
MARHE - Maximum average heat release rate, kW/m^2

System	Mean thickness*, mm	HRR_{180}, kW/m^2	HRR_{max}, kW/m^2	MARHE, kW/m^2
0	3.00	73.10	88.24	62.7
1	2.91	55.04	171.91	42.7
2	2.98	54.89	173.10	42.7
3	2.87	48.65	126.69	40.5

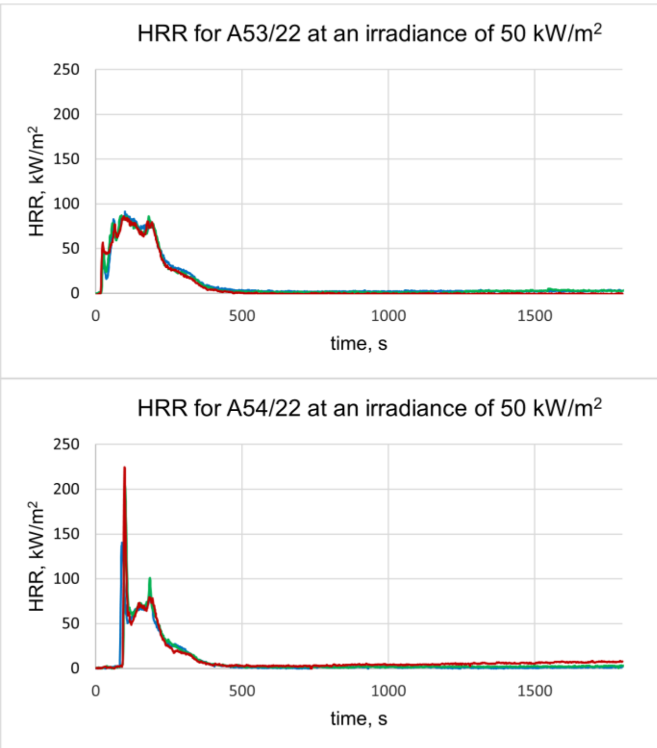
* thickness of the mass with a steel substrate

Table 9. Fire properties of paint systems with a damping mass in terms depending on the burning time

Sys-tem	Mean thickness*, mm	The igni-tion time is, s	Time extinc-tion the flame t_k, s	Time smo-king t, s	MARHE, kW/m^2
0	3.00	40	362	322	62.7
1	2.91	97	322	225	42.7
2	2.98	92	323	231	42.7
3	2.87	88	299	211	40.5

* thickness of the mass with a steel substrate

During the test, it was observed that the type of flame retardant used to inhibit the fire of the damping mass had an effect on the rate of heat release (HRR_{180} and HRR_{max}). These dependencies are presented in Figs. 10, 11, 12 and 13.



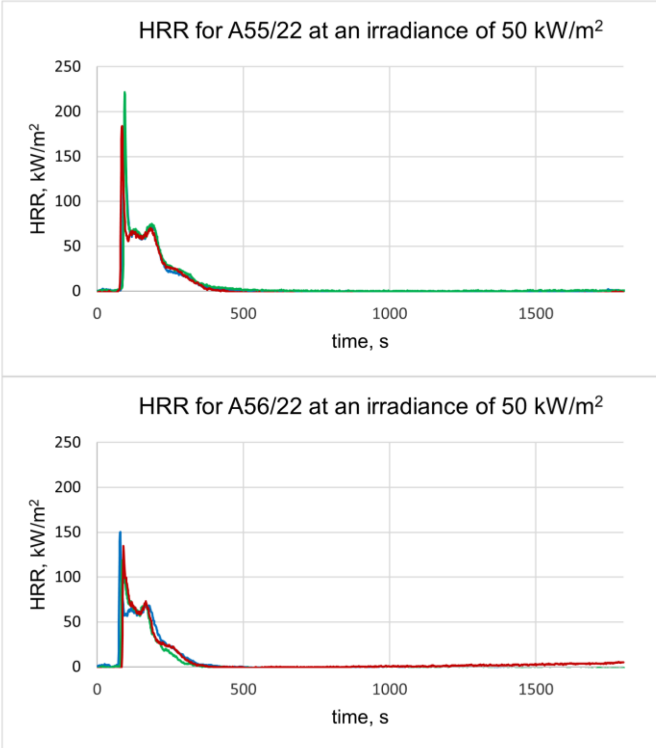


Fig. 10. Influence of the type of flame retardant used on the heat release rate (HRR) during the combustion of individual paint systems with a damping mass

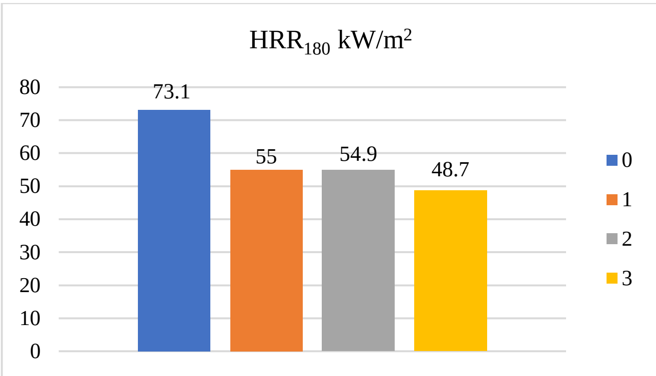


Fig. 11. Average HRR_{180} values for individual paint systems with a damping mass

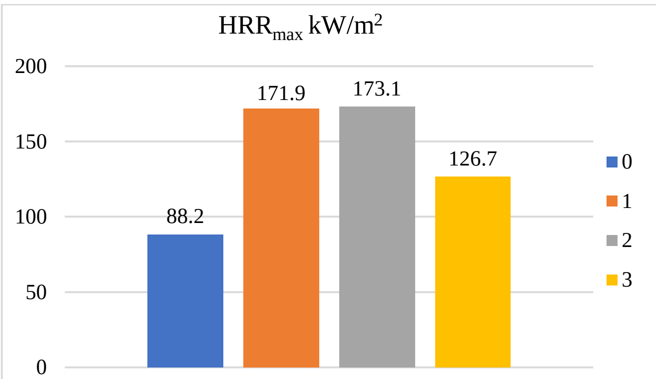


Fig. 12. Average HRR_{max} values for individual paint systems with a damping mass

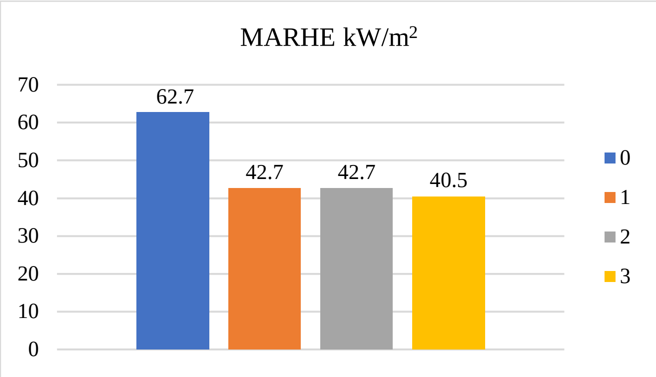


Fig. 13. Influence of the type of fire retardant used to fire the damping mass on the maximum average rate of heat release MARHE

On the basis of the conducted research (Table 8 and the dependencies presented in Figs. 10, 11, 12 and 13), it can be seen that the varnish coat with a damping mass to which no flame retardant additives have been added has the MARHE parameter exceeding 60 kW/m^2, which means that it does not meet the highest risk level HL3, the requirements for non-metallic materials intended for use in rolling stock. The purpose of introducing hydroxide flame retardants was to lower the MARHE value and achieve the HL3 hazard level. The MARHE parameter is the maximum value of the ARHE function, analysed during the first 20 minutes of the test, which is described by the formula:

$$ARHE(t_n) = \frac{\sum_2^n (t_n - t_{n-1}) \cdot \frac{\dot{q}_n + \dot{q}_{n-1}}{2}}{t_n - t_1} \quad (4)$$

The ARHE is calculated considering that the heat release rate data comprises pairs of data points, the first data point of which is the point (t_{1q}), where:

t – is time

q – is the rate of heat release.

As can be seen from the above dependence, the ARHE value and the related MARHE parameter depend on the amount of heat released and the time in which this emission occurs. The later the sample ignites and the maximum amount of heat is released, the smaller the MARHE is. During the tests, it was observed that the type of flame retardant used to make the damping mass flame-retardant influences the ignition time, the heat release rate recorded after three minutes of the test (HRR_{180}) and the burning time of the samples. Separately used hydroxide additives reduce the value of HRR_{180} to a very similar level. Also, an extension of the ignition time and a shortening of the burning time of the tested coatings were observed. Due to this effect, the MARHE parameter decreased to the value of 42.7 kW/m^2 in both cases. However, the best flame-retardant effect is seen when adding ATH and DTH simultaneously. Both HRR_{max} and HRR_{180} drop, and the burning time is further reduced while the extended ignition time is maintained. All this means that we obtain a reduction of the MARHE parameter at an even lower value of 40.5 kW/m^2. Thus, we can see that the modification of the varnish coating with a soundproofing layer with hydroxide flame retardants brought the assumed effect - the MARHE parameter was achieved at a level lower than 60 kW/m^2.

3.2.3. Optical smoke density

Smoke and the toxic products of combustion it contains are a particular threat to human life and health. Limited visibility in dense smoke conditions is often the reason for the efficient evacuation. Therefore, the determination of the optical density of the smoke resulting from the combustion of a material is an important parameter of its fire properties. The measurement was made using the method according to PN-EN ISO 5659-2 (Radziszewska-Wolińska and Tarka, 2018) and consists in measuring the production of smoke from the exposed surface of a material or composite sample. It is applicable to specimens not exceeding 25 mm in thickness, placed horizontally and subjected to thermal decomposition and combustion in a closed chamber under the following conditions:

- thermal radiation of 25 kW/m^2 in the presence of a flame from a pilot burner,
- thermal radiation of 25 kW/m^2 without the flame of the pilot burner,
- heat radiation of 50 kW/m^2 in the presence of a flame from a pilot burner,
- heat irradiation of 50 kW/m^2 without a pilot burner flame.

The test stand used to conduct the research is presented Figure 14.

Fig. 14. Test stand according to PN-EN ISO 5659-2 (source: Railway Institute)

The results of tests to determine the rate of heat release during combustion for paint systems with a damping mass (according to Table 6) are presented in Table 10.

Table 10. Fire properties of paint systems with a damping mass in the scope of optical smoke density

System	Mean thickness*, mm	$D_s(4)$	$D_s max$	VOF(4), min
0	2.96	176.53	250.62	210.45
1	3.01	141.69	196.61	176.98
2	3.04	125.01	153.65	153.78
3	2.86	134.55	153.22	180.07

* thickness of the mass with a steel substrate

During the test, it was observed that the type of flame retardant used to reduce the fire of the damping mass to the smoke intensity. These dependencies are presented in Figs. 15, 16 and 17.

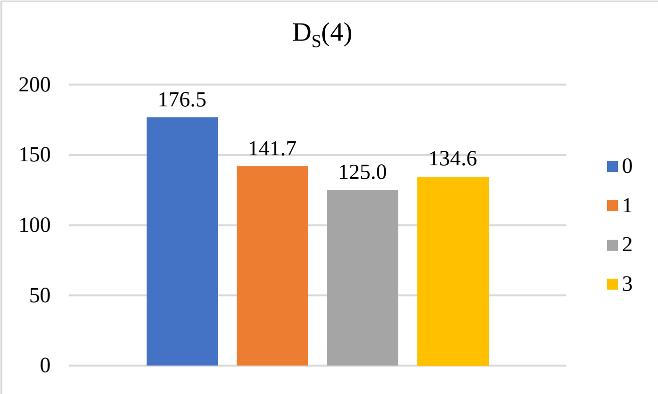


Fig. 15. Influence of the type of flame retardant used to fire the damping mass on the optical density of the smoke in the 4th minute of the test

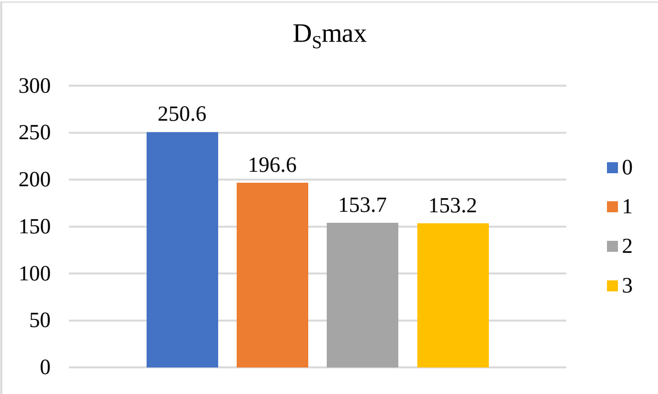


Fig. 16. Influence of the type of flame retardant used to flame - retard the damping mass on the maximum smoke optical density

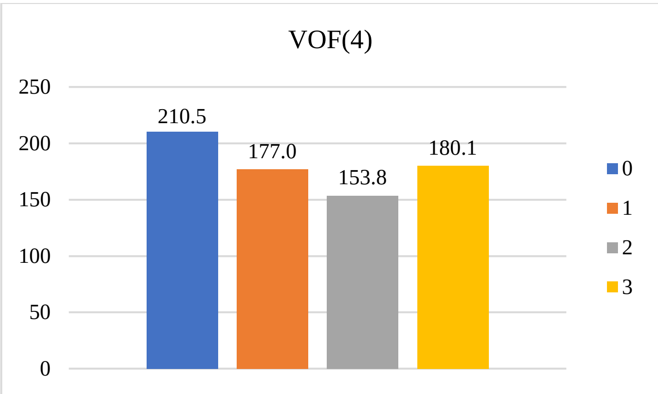


Fig. 17. Influence of the type of flame retardant used to fire the damping mass on the specific optical density of the smoke in the 4th minute of the test

All smoke parameters are most effectively reduced by the addition of magnesium hydroxide (system 2 according to Table 10). The greatest decrease in the $D_s$max value - a parameter that is required to be determined for paint coatings, occurred in the case of system 3, containing both hydroxide additives. This modification is therefore most effective in reducing the smoke intensity for paint systems.

4. Conclusion

On the basis of the obtained research results and their interpretation, the following conclusions can be drawn:

1. Aluminium and Magnesium hydroxides significantly improve the fire properties of the tested coatings, which will increase the safety of passengers in rail transport. The most effective in this respect, as shown by the research, is the combination of ATH and MDH additives, especially reducing the amount of heat (MARHE) and smoke ($D_s$max).
2. Critical Pigment Volume Concentration has not been reached, although with System 1 the pigment content is very close to this limit. This is indicated in particular by the cohesion test and the nature of the coating breaking.
3. The addition of flame retardants did not affect the mechanical properties of the coating, which was confirmed by impact resistance and gritting tests.
4. Further research is needed to make sure that other mechanical properties of the paint coatings, like impact resistance, have not been lowered.

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评估施加的氢氧化物添加剂对具有阻尼质量的清漆涂层系统的防火性能的影响

關鍵詞
火烟特性
机械性能
氢氧化铝
氢氧化镁
2k 因素计划

摘要
评估施加的氢氧化物添加剂对具有阻尼质量的清漆涂层系统的防火性能的影响 这篇文章解决了用添加剂丰富产品以提高耐火性能的非常重要的问题。为此，使用了氢氧化物添加剂（铝和镁，它们在升高的温度下分解形成水。在设计实验时，使用了一种实验设计方法 (DOE)：两个独立变量的 2k 因子设计。富集涂层根据 PN-EN 45545-2 的要求进行了测试，包括。放热强度、火焰在垂直配置产品上的横向传播或产生的烟雾和气体的测试。还测试了内聚力和冲击韧性等机械性能。评估了这类添加剂的有效性，以及它们的协同效应（由于不同的分解温度）