Chapter 5

Crack Resistance of Paint Coatings, Cement Concretes

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Additional information is available at the end of the chapter

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Abstract

Information on the method for assessing the crack resistance of paint and varnish coatings is given. A method is proposed, based on the ratio between the length of the crack, the Vickers indenter imprint, and the fracture toughness. Numerical values and stress intensity factor in coatings are given, depending on the type and duration of aging, porosity of the cement substrate, and the quality of the appearance of the coatings. It is established that with an increase in the roughness of the coating surface, the value of the stress intensity coefficient is increased. The increase in the moisture content of the substrate at the time of application of the paint composition leads to the appearance of a more defective structure of the contact layer "coating-substrate" and a greater propensity to cracking. It is revealed that there is a value of the optimum substrate moisture, for each particular coating in terms of its fracture toughness. It is shown that during the aging of protective and decorative coatings of the exterior walls of buildings, a mechanism of their destruction from elastic ductile to brittle changes occurs.

Keywords: coatings, crack resistance fracture intensity factor, failure mechanism

1. Introduction

Building and maintaining the working condition of buildings and structures require a large number of paint and varnish compositions. Growing competition in the market of finishing materials, increasing demands of consumers require manufacturers to obtain high-quality painted surfaces. However, the practice of finishing works shows that often the quality of the finish is bad. It leads to premature unscheduled repairs and additional costs.

Coatings for finishing facades of buildings must have a high-quality appearance. The conditions for obtaining and the quality of the appearance of cured inking coatings largely depend on the rheological properties of paint and are determined by the processes of wetting and application of paint. In literature, the quality of the appearance of coatings on metal substrates is studied. When selecting paint systems for concrete, the features of this material (strength, roughness, humidity, alkalinity, etc.) should be taken into account. Features of concrete affect the quality coating.

In this regard, the development of a methodology for ensuring the quality of the painted surface of building products and structures and control methods is an important scientific, technical, and economic problem. The solution of this problem as a whole will contribute to an increase in the service life of protective and decorative coatings. One of the common types of destruction of coatings of cement concrete is the appearance of cracks. There are known works [1–8] in which the regularities of the appearance of cracks in coatings on metal substrates are described. However, the resistance of coatings of cement concrete has not been studied sufficiently.

2. Stress state of coatings under exposure operational factors

For analysis, the reasons for the destruction of the paint and varnish facades of buildings were used, the Pareto diagram, allowing for a variety of existing defects to distinguish those that make a significant contribution to the assessment of the quality of the appearance of coatings. When analyzing the Pareto chart, the 80/20 rule was used. For example, priority factors were identified, which fall into 80% of the cumulative curve [9–16]. The survey was carried out on residential 5-storey houses, which are located in accordance with GOST 9.039–74 "Corrosive aggressiveness of the environment" in the climatic region IY (moderately cold) and GOST 16350–80 "Climate of the USSR. Regionalizing and statistical parameters of climatic factors for technical purposes." The facades were painted with calcareous and cement per chlorinated vinyl CPCV paints. Colorful compositions were applied to the plaster thickness of 1.5–2 cm. When inspecting the painted surface, the following types of defects were detected: cracking, flaking, weathering, dirt retention of coatings, wet spots, and different tonality. The number and types of defects were determined visually (GOST 9.407–2015 Unified system of protection against corrosion and aging. PAINTWOOD COATINGS. Appraisal method). The names of the types of defects and the number of their appearances for calcareous and CPCV coatings that take after different service lives are given in **Table 1**.

Pareto diagrams with all types of defects for their calcareous CPCV coatings are shown in **Figures 1–3**. Analysis of survey results indicates that the list of defects in coatings, constituting 80% of the cumulative curve, consists mainly of cracks along the vertical joint at the end of the building, different tonality of color, and peeling. All of these factors remain constant for both coatings. This allows us to consider them a source of "failure" regardless of the type of coating. In this case, such a defect as cracks in the coating along the vertical joint of the panels goes in the Pareto diagram in the first place and is 22.6–66.6% of the total number of defects, depending on the type of coverage and exploitation term.

As the coatings age, there is a change in the specific gravity of the priority defects that affect the quality of their appearance, as well as the appearance of new types of defects. Therefore,

№ defect	Defect denomination	Numeric appearance of defects		
		Calcareous coating, 1 year of operation	**Calcareous coating, 5 years of operation**	**CPCV coating, 5 years of operation**
1	Crack in the coating along vertical joint at the end of the building	80	100	100
2	Flaking of coatings on the ends enclosing panels of loggias	21	100	80
3	Flaking of coatings at the base of metal roofs of entrances	13	84	80
4	Flaking of coatings on the facade	3	72	35
5	Different tonality of coloring	2	31	30
6	Wet spots at the bottom joint of balconies with panels	—	26	30
7	Weathering of the color	—	25	—
8	Other	11	12	25

Table 1. Types and number of defects of protective and decorative coatings.

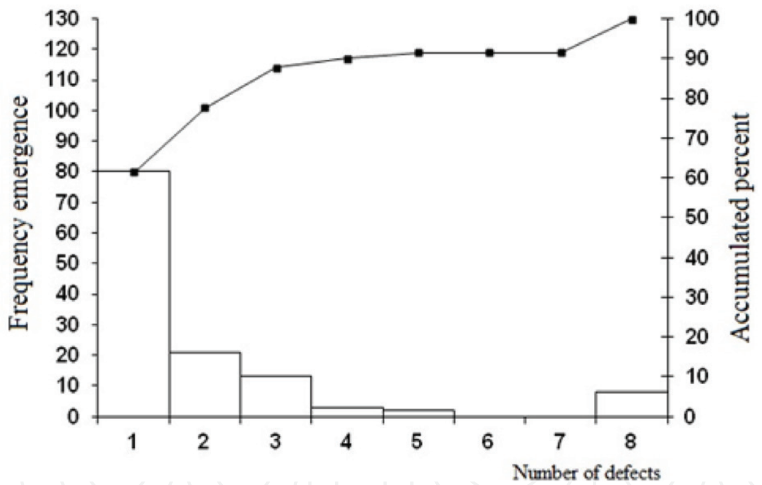

Figure 1. Pareto chart for lime coating (1 year of operation).

after 3 years of operation of the calcareous coating, defects such as flaking of the coatings at the base of the metal roofs of the porch and at the ends of the fencing panels of the loggias are observed, the total specific gravity of which is 41.4%. The priority defects after 5 years of operation include cracks in the coating, along the vertical joint at the end of the building, exfoliation coating, and different tonality of color. A similar list of defects is also characteristic for CPCV coatings. Of this follows that the efforts of all specialists in developing the formulation of building paint compositions, the technology of their application should be aimed at increasing the crack resistance of protective-decorative coatings, since this type of defect is the most characteristic and widespread.

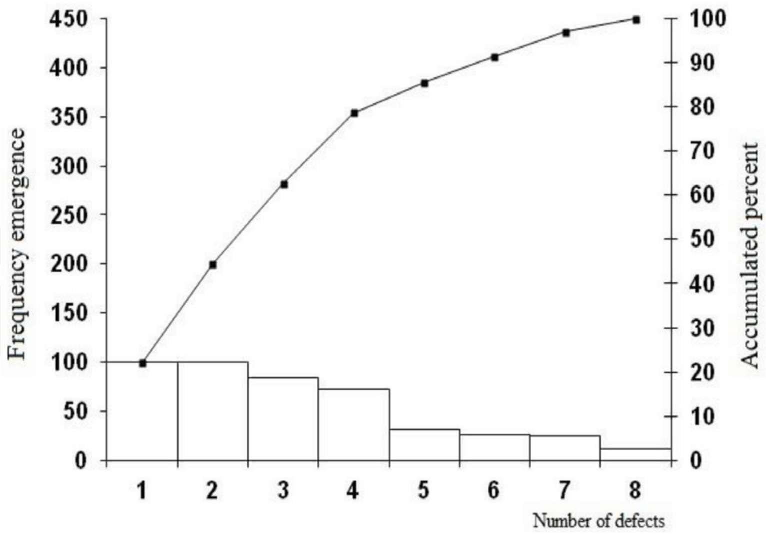

Figure 2. Pareto chart for the calcareous coating (5 years of operation).

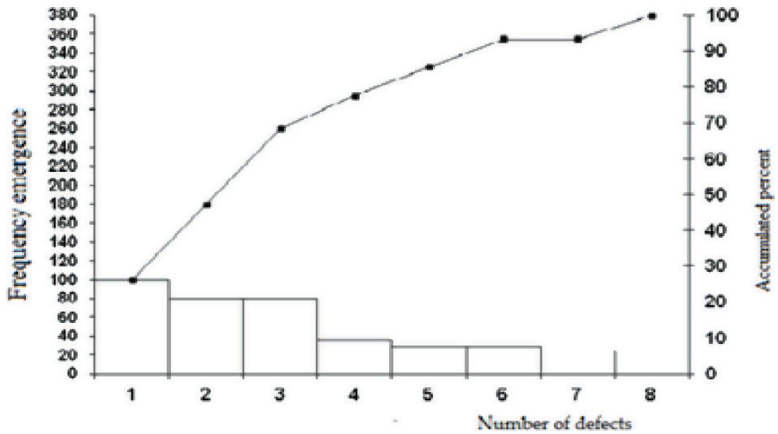

Figure 3. Pareto chart for CPCV coating (5 years of operation).

Results of the experimental researches testify that in use of protective-decorative coatings of external walls of buildings, there is a change of the mechanism of their destruction from elastic-plastic to friable, that is, "embrittlement" of coatings is observed. According to the linear mechanics of destruction, a cracking fissuring of coatings happens [17, 18], if

$$K_1 \geq K_{1c} \tag{1}$$

K_1-coefficient of intensity of tensions,

K_{1c}-critical value of coefficient of intensity of tensions.

Considering that a main type of destruction of protective-decorative coatings is cracking fissuring, it is of practical interest to estimate parameters of crack formation of coatings during an aging. At present, there are several methods for assessing the crack resistance of coatings [19–22]. The determination of critical coefficient of intensity of tensions K_{1c} was carried out by us according to the technique [23] based on a ratio between the crack length, a print of the Vickers indenter, and viscosity of destruction. We are invited to assess the cracking of polymer coatings using the technique, based on the ratio between the crack length, the Vickers indenter print, and the fracture toughness. This technique is successfully used to assess the fracture toughness (K_{1c}) of ceramics.

In this method, the value of the stress intensity factor K_{1c} is determined from the length of the radial cracks formed in brittle materials from the corners of the Vickers indentation. To obtain a semi-empirical dependence of the length of radial cracks on crack resistance and hardness, the approach proposed by A. Evans and E. Charles is used. Dependence "normalized crack resistance $(K_{1c}/H\alpha^{1/2})\cdot(H/E)^{1/2}$-normalized length of radial cracks C/α" is described by the following equation:

$$\left(K_{1c}/H\alpha^{1/2}\right)\cdot(H/E)^{1/2} = A\cdot(C/\alpha)^{-B}, \tag{2}$$

where H is Vickers hardness; A and B are empirical coefficients.

From expression (2), we obtain:

$$K_{1c} = AH\alpha^{1/2}(E/H)^{1/2}(C/\alpha)^{-B}. \tag{3}$$

If the value of hardness does not depend on the load on the indenter, then Eq. (3) can be written in the form:

$$K_{1c} = const\,(E/H)^{1/2}P/C^{B}, \tag{4}$$

where P is the load on the Vickers indenter.

The most common semi-empirical equation of this type is given as follows:

$$K_{1c} = 0.028\,H\alpha^{1/2}(E/H)^{0.5}(C/\alpha)^{-1.5} \tag{5}$$

where H is Vickers hardness;

E: the modulus of elasticity;

C: half-length of radial cracks;

α: half-length of the diagonal of the print.

The critical coefficient of intensity of tensions was determined by a formula:

$$\mathrm{K_{1c} = 0.028\,Ha^{0.5}(E/H)^{0.5}(C/a)^{-1.5}} \tag{6}$$

where hardness by Vickers;

P: loading on indents;

C: semi-length of radial cracks;

a: semi-length of print diagonal.

As colorful structures in the work, polyvinyl acetate cement PVAC and polymer-calcareous paints were applied, and as a substrate—cement and sand solution. After curing, the painted solution exemplars were subjected to alternate freezing and thawing and also to humidification and a thermal aging. During tests with the help of Vickers indenter, we measured a print diameter and length of radial cracks which are formed on both sides from a print. Hardness by Vickers was calculated on a formula:

$$H = \frac{2P}{d^2} \sin \frac{\alpha}{2}, \tag{7}$$

where d: diameter of a print;

α: angle at indenter top.

The dependence of the size of the semi-diagonal of the imprint on the load on the indenter is described by the equation:

$$a = A \cdot P^{0.5}. \tag{8}$$

The exponent is 0.5, as it should be when the hardness of the material does not depend on the magnitude of the load. The dependence of the length of radial cracks on the load is fairly accurately approximated by an equation of the form:

$$C = B \cdot P^{0.67}. \tag{9}$$

In order that the critical value of the intensity factor K_{1c}, measured by the method of indentation, did not depend on the load, exponent must be equal to 2/3 (≈ 0.67). The results of previous research work show that most protective and decorative coatings have a fragile character of destruction, which gives grounds to apply this technique to assess the crack resistance of paint and varnish coatings. From the experimental data obtained, a correlation was established between the semi-diagonal of the imprint and the load on the indenter P, which is described by expression (8).

For the PVAC coatings tested after curing obtained dependence

$$a = 0.087\, P^{0.5}. \tag{10}$$

For polymer-calcareous coatings

$$a = 0.124\, P^{0.5}. \tag{11}$$

For coatings based on oil paint

$$a = 0.097\, P^{0.5}. \tag{12}$$

For coatings KO-168

$$a = 0.141\, P^{0.5}. \tag{13}$$

Eqs. (10)–(13) indicate that the exponent a is a = 0.5, that is, this should be the case if the hardness is independent of the load in accordance with Eq. (8). After a certain duration of thermostating of the coatings, a decrease in coefficient A in Eq. (8) indicates an increase in their hardness. So, for example, after 100 h of thermostating, the following dependences were obtained:

For the PVAC coatings

$$a = 0.065\, P^{0.5}. \tag{14}$$

For polymer-calcareous coatings

$$a = 0.085\, P^{0.5}. \tag{15}$$

For coatings based on oil paint

$$a = 0.073\, P^{0.5}. \tag{16}$$

The analysis of the obtained results testifies that the dependence of the half-length of radial cracks C on the load P in the coatings is approximated by the equations:

For polymer-calcareous coatings

$$\mathrm{C} = 0.0327\, P^{0.67}. \tag{17}$$

For the PVAC coatings

$$\mathrm{C} = 0.042 P\, 0^{0.67}. \tag{18}$$

For coatings KO-168

$$\mathrm{C} = 0.252\, \mathrm{P}^{0.67}. \tag{19}$$

In the work applied, the following types of paints are listed in **Table 2**.

The results of experimental studies indicate that in the process of aging protective-decorative coatings of external walls of buildings, there is a change in the mechanism of their destruction from elastic-plastic to brittle, that is, "embrittlement" of coatings is observed [24–29]. Test results are provided in **Table 3**. It was established that in PVAC and the polymer-calcareous coatings on a solution substrate, the "embrittlement" occurs after a particular duration of impact of alternate freezing and thawing. The presence of a crack was determined visually and also with the aid of a magnifier at a magnification of 30 times.

Type of paint	Name of indicators			
	Viscosity, s	**Drying time, no less. h**	**Adhesion, point**	**Life, year**
PF-115	60–120	24	1	5
MA-15	64–140	24		
PVAC	40–100	3	1	5
Water dispersive (facade)	40–45	1		5
Nitrocellulose NC-123	60–100	3	1	3
Polymer-calcareous	40–60	24	2	5
Acrylate class "Universal"	40–60			3

Table 2. Technical characteristics of the paints.

The critical coefficient of intensity of tensions was determined by formula (6). The size of the diagonal of the Vickers indenter print was measured using a magnifier. Cracks in coatings at cave-in of an indenter Vickers appear only after 15–20 testing cycles. The value of critical coefficient of intensity of tensions of PVAC coating is equal to K_{1c} = 0.088 MH/m$^{3/2}$, and for polymer-calcareous coating, K_{1c} = 0.069 MH/m$^{3/2}$.

Introduction into a compounding of PVAC paint, the fibrous asbestos increases crack resistance of coatings. Thus, even after 20 cycles of alternate freezing-thawing, the "embrittlement" of coating is not observed. The comparative analysis of data shows that at the same intensity of influences of the environment coatings with a fibrous asbestos possess the smaller value of coefficient of intensity of tensions, after eight cycles of alternate freezing-thawing K_1(PVAC) = 0.078 MH/m$^{3/2}$ and K_1(PVAC with 1% of asbestos) =0.073 MH/m$^{3/2}$.

Humidification of coatings leads to a decrease of an elastic modulus and hardness of coatings that reduces a danger of crack formation at deformation of a wall construction. Humidification of coatings for 30 days does not cause crack fissuring of coatings. The coefficient of intensity of tensions of PVAC coating after curing is equal to K_{1c} = 0.06 MH/m$^{3/2}$, and after humidification K_{1c} = 0.054 MH/m$^{3/2}$. Similar data are obtained and for the polymer-calcareous coatings.

At studying a thermo aging, it was recorded that the increase of time of thermoaging leads to natural increase of value of coefficient of intensity of tensions. For example, after a thermoaging of polymer-calcareous coatings for a 100-h increase, the value of coefficient of intensity of tensions is observed from K_{1c} = 0.044 MH/m$^{3/2}$ (after curing) to KK_{1c} = 0.053 MH/m$^{3/2}$, and after 200 h value makes KK_{1c} = 0.0546 MH/mm$^{3/2}$. Considering that properties of a protective-decorative coatings are defined among other factors by properties of the painted construction and are heterogeneous on an extension, we followed up and carried out the calculation of tensions arising in coatings as a result of the influence of various factors according to a technique [30]. It will allow approaching the choice of materials research factors of the increase of crack resistance of coatings more reasonably. The conducted researches are justification for recommendations at developing the compounding of colorful structures, at carrying out research works with the use of technique of an assessment of crack resistance of coatings according to the offered scheme. It will allow to more reasonably predict firmness of coatings and also to optimize finishing structures for the purpose of receiving coatings with a complex of the given properties.

Type of coatings	Type of influence	Loading P, H	Hardness of coating, H, H/мм^2	The relation of crack semi-length C to the size of semi-diagonal of print	Coefficient of intensity of tension, K_{1c}, MH/м$^{3/2}$
PVAC	After curing	47.39	61	1	0.06
	Three cycles of freezing-thawing		137	1	0.075
	Eight cycles of freezing-thawing		164	1	0.078
	15 cycles of freezing-thawing		179	1.2	0.088*
	Humidification 15 days		49	1	0.058
	Humidification 30 days		37	1	0.054
	Thermoaging 100 h		85	1	0.065
	Thermoaging 200 h		104	1	0.068
Polymer- calcareous	After curing	47.39	27	1	0.044
	Three cycles of freezing-thawing		45	1	0.05
	20 cycles of freezing-thawing		70	1.54	0.069*
	Humidification 15 days		23	1	0.055
	Humidification 30 days		16	1	0.040
	Thermoaging 100 h		55	1	0.053
	Thermoaging 200 h		62	1	0.0546
PVAC (1% asbestos by weight of cement)	After curing	47.39	44	1	0.055
	Three cycles of freezing-thawing		130	1	0.073
	Eight cycles of freezing-thawing		130	1	0.073
	20 cycles of freezing-thawing		133	1	0.074

*Critical coefficient of intensity of tensions.

Table 3. Parameters of a crack for the formation of a protective-decorative coating.

3. Persistence of varnish-and-lacquer coatings to cracking in the process of environmental impact

In accordance with the statistical theory of the strength of solids, the probability of destruction of coatings is determined by the presence and concentration of defects, including on the surface of the coatings. Thus, the quality of the appearance of the coatings among other factors

Name of paint	Type of corrosion attack	Number of defects	Surface roughness, Ra, мкм	Coefficient of intensity of stresses K_1, МН/м$^{3/2}$
Alkyd enamel PF-115	Hardening	36	0.12	0.01561
		30	0.10	0.01035
		18	0.08	0.01002
	Five freeze-thaw cycles	39	0.47	0.01708
		32	0.36	0.01677
		25	0.23	0.01076
	10 freeze-thaw cycles	There is a peeling of the coating		
		36	2.58	0.01913
		31	2.21	0.01846
	13 freeze-thaw cycles	There is a peeling of the coating		
		56	3.10	0.02082
	15 freeze-thaw cycles	57	3.26	0.02123
Oil paint MA-15	Hardening	29	0.23	0.01855
		20	0.18	0.01177
		10	0.14	0.01170
	Five freeze-thaw cycles	There is a peeling of the coating		
		23	0.59	0.02056
		15	0.40	0.01864
	10 freeze-thaw cycles	26	1.69	0.02653
		20	1.46	0.02014
	13 freeze-thaw cycles	30	1.83	0.02903
		21	1.63	0.02134
	15 freeze-thaw cycles	33	2.1	0.02985
		26	1.95	0.02461
Nitrocellulose NC-123	Hardening	27	0.19	0.00986
		19	0.17	0.00984
		8	0.14	0.00824
	Five freeze-thaw cycles	30	0.52	0.01377
		21	0.48	0.01306
		12	0.16	0.01061
		Continuation of Table 4		
Nitrocellulose NC-123	10 freeze-thaw cycles	There is a cracking of the coating		
		28	2.78	0.01672
		18	2.32	0.01543
	13 freeze-thaw cycles	31	2.90	0.01802
		24	2.51	0.01701
	15 freeze-thaw cycles	28	2.65	0.01925

Name of paint	Type of corrosion attack	Number of defects	Surface roughness, Ra, мкм	Coefficient of intensity of stresses K_1, MH/м$^{3/2}$
Water dispersive (facade)	Hardening	192	0.44	0.01688
		113	0.34	0.01481
		80	0.24	0.01308
	Five freeze-thaw cycles	229	0.89	0.02103
		135	0.76	0.01799
		94	0.70	0.01409
	10 freeze-thaw cycles	232	3.01	0.02305
		141	2.55	0.01967
		97	1.85	0.01503
	13 freeze-thaw cycles	233	3.65	0.02636
		148	3.10	0.02013
		106	1.98	0.01723
	15 freeze-thaw cycles	247	3.80	0.02752
		153	3.40	0.02432
		114	2.80	0.02056
Acrylate, class Wagon	Hardening	160	0.24	0.01283
		120	0.22	0.01193
		86	0.20	0.01137
	Five freeze-thaw cycles	210	0.74	0.01716
		134	0.60	0.01513
		108	0.55	0.01391
	10 freeze-thaw cycles	215	2.40	0.02146
		150	1.77	0.01692
		117	1.44	0.01403
	13 freeze-thaw cycles	223	2.62	0.02342
		161	1.83	0.01863
		123	1.63	0.01608
	Freeze-thaw cycles	228	3.30	0.25631
		176	2.31	0.02018
		129	1.96	0.01801

Table 4. Crack resistance of coatings depending on the quality of their appearance in the process of freezing-thawing.

determines the resistance of the coatings to failure, in particular, to cracking. To establish the connection between the fracture toughness indexes of coatings and the quality of their external type in the process of a corrosive environmental impact, we conducted the following

Name of the paint composition	The change in coefficient of intensity of stresses K_1, МН/м$^{3/2}$					
	Alter hardening	Five cycles	Eight cycles	11 cycles	13 cycles	15 cycles
Alkyd enamel PF-115	0.01561	0.01804	There is a peeling of the coating			
	0.58	0.83				
	0.01035	0.01581	There is a peeling of the coating			
	0.4	0.58				
	0.01002	0.01264	There is a peeling of the coating			
	0.21	0.32				
Oil paint MA-15	0.01855	0.02004	There is a peeling of the coating			
	0.8	1.43				
	0.01177	0.01658	There is a peeling of the coating			
	0.69	0.94				
	0.01170	0.01342	0.01532	There is a peeling of the coating		
	0.46	0.65	0.93			
Nitrocellulose NC-123	0.00986	0.01564	There is a cracking of the coating			
	0.78	1.02				
	0.00934	0.01268	0.01586	There is a cracking of the coating		
	0.6	0.79	1.12			
	0.00824	0.01194	0.01302	0.01683	0.01968	There is a cracking of the coating
	0.32	0.44	0.68	1.18	1.32	
Water dispersive (facade)	0.01488	0.01568	0.01932	0.02236	0.02393	0.02538
	3.01	3.42	3.58	3.72	3.94	4.16
	0.01471	0.01496	0.01906	0.02198	0.02363	0.02506
	2.55	2.76	2.96	3.16	3.28	3.34
	0.01308	0.01386	0.01896	0.02106	0.02186	0.02483
	1.85	1.94	2.08	2.34	2.46	2.61
Acrylate, class Wagon	0.01282	0.01462	0.01768	0.02068	0.02238	0.02368
	2.4	2.62	3.12	3.28	3.38	3.52
	0.01193	0.01266	0.01701	0.02032	0.02113	0.02309
	1.77	1.94	2.26	2.43	2.64	2.83
	0.01137	0.01204	0.01632	0.01958	0.02073	0.02298
	1.51	1.63	1.84	1.96	2.18	2.31

Table 5. Crack resistance of coatings depending on the quality of their appearance in the process of moistening-drying.

experiment. Colorful compositions were applied using a brush on the solvent substrates in two layers with intermediate drying for 24 h. The following color compositions were used: alkyd grade enamel PF-115, oil paint MA-15, nitrocellulose enamel НЦ-123, paint acryl ate class

"Universal," and acrylic water dispersion paint (facade). Different quality of the appearance of the coatings was created by changing the porosity of the substrate and the rheological properties of the paint compositions. During the tests, the colored solution samples were subjected to various types of corrosion attack, namely alternating freezing-thawing according to the regime: 4 h freezing at a temperature of −18°C, 20 h of thawing, moistening-drying according to the regime: 20 h of moistening at room temperature and 4 h of drying at a temperature of 60°C.

During the experiment, the concentration of defects on the surface of the coating was also determined. The number of defects was determined on the surface area of 64 cm^2. The coating surface roughness was determined by profilograph TR-100 state. The results of the studies are given in **Tables 3** and **4**. It was found that during the test, the cracks appear locally and are formed near the defects on the surface of the coating. In particular, after five test cycles on the surface of the coating based on MA-15 paint, surface roughness, R_a = 0.23 μm, surface cracks visible to the naked eye appeared, and on the coating with a roughness index Ra = 0.14 μm—after 15 test cycles. Similar patterns are also characteristic for other coatings (**Table 4**). It is established that with an increase in the roughness of the coating surface, the value of the stress intensity coefficient is increased. Therefore, for example, the surface roughness of a coating based on PF-115 ink is R_a = 0.12 μm, the stress intensity factor K_1 = 0.01561 $MN/m^{3/2}$, a decrease in the roughness of the coating surface Ra = 0.08 μm leads to a decrease in the stress intensity factor to K_1 = 0.01002 $MN/m^{3/2}$. Similar patterns are also characteristic for other types of coatings.

The results (**Table 5**) show that the nature of the destruction of the coatings during the corrosive action of the medium is not the same. Therefore, coatings based on oil and alkyd paint are characterized by peeling, coatings based on acrylate class Universal, nitrocellulose, and water dispersion paint-cracking. Regardless of the type of coating and the corrosive effect of the medium, there is an increase in the roughness of the coating surface and coefficient of intensity of stresses.

4. The influence of the porosity of the substrate on crack resistance of protective-decorative coating

The operational stability of protective-decorative coatings of the outer walls of buildings is significantly influenced by processes occurring both in the coating itself and at the interface of the "substrate-coating" contact [6]. The strength of the adhesion of protective-decorative coatings to the concrete substrate depends significantly on the quality of the substrate. The quality of the substrate, first of all, is understood as its macro- and microstructure, the degree of its homogeneity, providing the desired solidity contact layer, its density, and porosity. Features of the porous substrate, such as cement concrete, mortar, and so on, have a significant effect on the formation of the structure and properties of the coatings applied. The analysis of the results (**Table 6**) indicates that the porosity of the substrate has a great influence on the nature of the destruction of the protective and decorative coating. At the same time, it should be noted that the nature of the destruction, for example, of PVAC coatings, has a significant difference from polymer-based coatings. Thus, for example, an increase in the porosity of the substrate from 20 to 28% leads to a reduction in the crack resistance of polymer-calcareous coatings.

Name of coating	Impact type	Hardness H, N/mm^2	The ratio of the half-length of the crack C to the size of the semi-diagonal of the imprint a	Coefficient of intensity of stresses, K_1, MH/м$^{3/2}$
1	2	3	4	5
PVAC on glass	Hardening	37	1	0.051
	Five freeze-thaw cycles	76	1	0.072
	Eight freeze-thaw cycles	85	1.27	0.083*
(P = 20%)	Hardening	85	1	0.065
PVAC	Five freeze-thaw cycles	125	1	0.08
	10 freeze-thaw cycles	140	1	0.084
	11 freeze-thaw cycles	180	1.4	0.088*
Continuation of Table 6				
1	2	3	4	5
(P = 28%)	Hardening	75	1	0.065
PVAC	Five freeze-thaw cycles	80	1	0.066
	10 freeze-thaw cycles	102	1	0.08
	15 freeze-thaw cycles	174	1.23	0.083*
PVAC on a brick substrate (P = 40%)	Hardening	73	1	0.077
	Five freeze-thaw cycles	176	1.3	0.085*
(P = 20%)	Hardening	21.7	1	0.024
Polymer-calcareous	Five freeze-thaw cycles	47.6	1	0.05
	10 freeze-thaw cycles	52.2	1	0.052
	20 freeze-thaw cycles	60.8	1.54	0.06*
(P = 28%)	Hardening	27	1	0.029
Polymer-calcareous	Five freeze-thaw cycles	38	1	0.04
	14 freeze-thaw cycles	57	1.2	0.056*
(P = 20%)	Hardening	61	1	0.027
Acrylate class "Universal"	Curing on preliminary putty surfaces	22	1	0.004

*Critical coefficient of intensity of stresses.

Table 6. Parameters crack education of protective-decorative coatings depending on the porosity of the substrate.

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The appearance of cracks in indentation of the Vickers indenter in a polymer-calcareous coating on substrates with a porosity of P = 20% is observed after 20 cycles of freezing-thawing. The critical coefficient of intensity of stresses is K_{1c} = 0.06 MN/m$^{3/2}$. At porosity of the substrate, P = 28%, the appearance of cracks in indentation of the Vickers indenter occurs in the coatings after 14 cycles of freezing-thawing. This is explained by the appearance of a more inhomogeneous stress state in the coating. For PVAC coatings, it is characteristic that the fracture toughness increases with increasing porosity of the substrate from 20 to 28%. The critical value of coefficient of intensity of stresses for PVAC coatings in substrate porosity of 20% is K_{1c} = 0.088 MN/m$^{3/2}$. In this case, the appearance of cracks in the coating during the introduction of the Vickers indenter was recorded after 11 cycles of freezing-thawing. With a substrate porosity of 28%, the appearance of cracks is observed only after 15 cycles of freezing-thawing.

However, the change in the coefficient of intensity of stresses for PVAC coatings is extreme. So, for example, when using as a substrate of brick samples with a porosity of P = 40%, the fracture toughness of PVAC coatings is significantly reduced. Thus, the presence of cracks at the indentation of Vickers indenter is observed after five cycles of freezing thawing.

Preliminary preparation of the substrate surface has a significant effect on the crack resistance of protective and decorative coatings. So, for example, priming the surface of the substrate leads to an increase in the crack resistance of the coatings. At the same time, the appearance of cracks with the indentation of the Vickers indenter in the PVAC coating on a substrate with a porosity of P = 20% was observed after 15 cycles of alternating freezing-thawing. For some types of coatings PF-115 and water dispersive acrylate paint of the “Universal” class, it is very important in advance application of putty to the surface before staining to reduce the porosity of the substrate. This leads to an increase in the crack resistance of these coatings. Thus, the coefficient of the intensity of stresses of the acrylate coating applied to the surface of the substrate after its preliminary preparation was 0.004 MN/m$^{3/2}$, while without preparation—0.027 MN/m$^{3/2}$.

It was found that in coatings, “embrittlement” occurs after a certain time of moistening. Thus, cracks in the coatings with the indentation of the Vickers indenter appear on the coating of PF-266 on a substrate with a surface porosity of P = 0% and on a substrate with a surface porosity of P = 6.2% and humidity at the application of paint of 9.9%. For coatings MA-115 on a substrate with P = 6.7% and humidity at the time of application of paint W = 10.2%, peeling of the coating after 2 months of moistening is characteristic. Analysis of the experimental data (**Table 7**) shows that with increasing surface porosity of the substrate, a decrease in the stress intensity factor is observed up to a certain limit. Thus, with a load Π = 25.39 N, the value of the stress intensity factor K_c for coating PF-115 on a substrate with a surface porosity P = 0.13–1.2% after 2 months of moistening is K_c = 0.0376MH/m$^{1.5}$, and on a substrate with a surface porosity, P = 10.5%—0.0256 MH/m$^{1.5}$, and for the MA-15 coating, the values of the stress intensity factor are, respectively, 0.0257 MH/м$^{1.5}$ and 0.02147 MH/m$^{1.5}$.

Obviously, this is due to the fact that the pores on the surface of the substrate to some extent “extinguish” internal stresses and reduce the tendency to crack coatings. Increasing the substrate moisture at the time of application of the paint results in a more defective structure of the contact layer “coating-substrate” and a greater propensity to cracking. The stress intensity factor for PF-115 coatings at substrate moisture at the time of application of a paint composition equal to W = 10.4% after 2 months of wetting is K_c = 0.404 MH/m$^{1.5}$. Among other factors, the

Kind of colorful composition	Substrate moisture, %	Porosity of the substrate, %	Load, N	Coefficient of intensity of stresses, K_{1c}, $MH/m^{1.5}$
1	2	3	4	5
Alkyd PF-115	0	0.13	25.39	0.0379
Alkyd PF-268	0	0.9		0.0379
Oil MA-15	0	10.5		0.0256
	10.5	6.4		0.0404
	0	0.13		0.0554
	0	0.9		0.0554
	0	10.5		0.048
	10.4	6.4		0.054
	0	0.33		0.0257
	0	6.4		0.02147
	9.9	6.4		Peeling

Table 7. Parameters crack education of protective-decorative coatings.

state of the painted surface of the facades of buildings is determined by the time of application of the paint. So, for example, if the paint is applied in April-May, when the moisture of the substrate and the coating is high due to moisture migration from the side of the wall material, this can lead to premature failure of the coating. We evaluated the effect of substrate moisture on the properties of protective and decorative coatings, in particular, on their crack resistance. The analysis of the results (**Table 8**) shows that the substrate moisture at the time of application of paint has a significant effect on the crack resistance of the coatings. For example, when PVAC coating is applied to a dry surface, the appearance of cracks in the coating when Vickers indenter is introduced occurs after 20 cycles of freezing-thawing, the critical value of the stress intensity factor being $K_{1c} = 0.09$ $MN/m^{3/2}$. An increase in the initial moisture content of the substrate to W = 1% leads to a significant increase in the fracture toughness of the PVAC coating, with the appearance of cracks in the introduction of the Vickers indenter only after 25 cycles of freezing-thawing. A further increase in the substrate moisture during painting leads to the appearance of a more defective structure of the contact layer "coating-substrate" and a greater tendency of the coating to crack formation. Thus, an increase in substrate moisture to W = 4% led to the appearance of cracks in the introduction of the Vickers indenter after 10 cycles of freezing-thawing.

The results of the analysis of fracture toughness indexes of coatings PF-115 indicate that after 15 cycles of freezing-thawing, the coefficient of intensity of stresses in coatings on absolutely dry substrate is $K_1 = 0.057$ $MN/m^{3/2}$, whereas for substrate moisture W = 4%— $K_1 = 0.026$ $MN/m^{3/2}$.

Coatings PF-115 on a dry substrate are characterized by peeling after 15 cycles of freezing-thawing, while at substrate moisture content W = 4%, peeling is not observed and after 35 freeze-thaw cycles. The obtained results make it possible to assume that an increase in the moisture content of the substrate leads to a significant decrease in internal stresses in the coating, which is apparently due to a decrease in the adhesion strength due to the presence of moisture on the surface of the substrate. However, for different types of coatings, the optimum moisture content of the substrate is characteristic. Increasing the optimum moisture content of the substrate leads to a decrease in the crack resistance of coatings.

Thus, the value of the moisture content of the substrate, established in the regulatory and technical documentation, in particular, W = 8% for water paint, is not correct. There is a value for the optimum moisture content of the substrate for each particular coating in terms of its fracture toughness. It is necessary to conduct extensive research to create a databank on the influence of substrate moisture on the crack resistance of protective and decorative coatings. This will help in the future to develop measures to create crack-resistant coatings.

Name of coating	Moisture of the substrate, W, %	Impact type	Hardness H, N, mm^2	The ratio of the half-length of the crack C to the size of the semi-diagonal of the imprint a	Coefficient of intensity of stresses, K_{1c}, MH/m$^{1.5}$
1	2	3	4	5	6
PVAC	0	Hardening	62	1	0.06
		Five freeze-thaw cycles	112	1	0.08
		10 freeze-thaw cycles	125	1	0.084
		20 freeze-thaw cycles	180	1.1	0.09*
PVAC	1	Hardening	32	1	0.018
		Five freeze-thaw cycles	80	1	0.022
		10 freeze-thaw cycles	102	1	0.08
		25 freeze-thaw cycles	112	1.08	0.09*
	4	Hardening	44	1	0.053
		Five freeze-thaw cycles	80	1	0.066
		10 freeze-thaw cycles	131	1.2	0.088*

Continuation of Table 8

1	2	3	4	5	6

Name of coating	Moisture of the substrate, W, %	Impact type	Hardness H, N, mm^2	The ratio of the half-length of the crack C to the size of the semi-diagonal of the imprint a	Coefficient of intensity of stresses, K_{1c}, MH/m$^{1.5}$
PF-115	0	Hardening	48	1	0.006
		Five freeze-thaw cycles	87	1	0.033
		10 freeze-thaw cycles	111	1	0.05
		15 freeze-thaw cycles	142	1	0.057 Peeling of the coating is observed
	1	Hardening	24	1	0.019
		Five freeze-thaw cycles	45	1	0.026
		15 freeze-thaw cycles	65	1	0.04
		20 freeze-thaw cycles	99	1	0.049
		30 freeze-thaw cycles	108	1	0.053
		35 freeze-thaw cycles	126	1	0.055 Peeling of the coating is observed
	4	Hardening	18	1	0.017
		Five freeze-thaw cycles	37	1	0.024
		15 freeze-thaw cycles	44	1	0.026
		20 freeze-thaw cycles	63	1	0.038
		30 freeze-thaw cycles	86	1	0.045
		35 freeze-thaw cycles	97	1	0.05

*Critical coefficient of intensity of stresses.

Table 8. Parameters crack education of protective-decorative coatings depending on the initial moisture content of the substrate.

5. Conclusion

A method for evaluating the fracture toughness of coatings of cement concrete is proposed. This is a method based on the relationship between the crack length, the Vickers indenter imprint, and the fracture toughness that is proposed. The numerical values of the coefficient of intensity of stresses in coatings are given, depending on the type and duration of aging, the porosity of the cement substrate.

It is established that with an increase in the roughness of the coating surface, the value of the stress intensity coefficient is increased. Increasing the substrate moisture at the time of application of the paint composition results in a more defective structure of the contact layer "coating-substrate" and a greater propensity to cracking. It has been revealed that there exists a value for the optimum substrate moisture for each particular coating in terms of its fracture toughness. It is shown that during the aging of protective and decorative coatings of the exterior walls of buildings, a mechanism of their destruction from elastic-ductile to brittle changes occurs.

The conducted researches are justification for recommendations at developing paints, at carrying out of research works with use of technique of an assessment of crack resistance of coatings according to the offered scheme. It will allow to more reasonably predict firmness of coatings and also to optimize finishing structures for the purpose of receiving coatings with a complex of the given properties.

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