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Research Article

Evaluation of the Temperature Impact on the Stress State of Protective and Decorative Coatings Taking into Account the Porosity of the Cement Substrate

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Abstract

The object of research is the stress-strain state of protective and decorative coatings of external enclosing structures. The purpose of the research is to evaluate the stress-strain state of protective and decorative coatings under the action of temperature, depending on the porosity of the substrate, the thickness of the coating. The article presents the results of the calculation of stresses depending on the thickness of the paint coating, the size of the pores in the contact zone "coating-substrate". The SCAD Office software module was used to assess the stress state of the coatings. A comparison is made of the stresses in the coating when pores of different radii are filled with a paint composition and in the absence of pore filling. It has been established that under the action of an alternating temperature in the coatings, a change in the deformed state occurs, characterized by alternation of compressive and tensile stresses. The magnitude of internal stresses decreases with decreasing coating thickness. With a decrease in the radius of the pores filled with the ink composition, the stresses in the zone of contact between the coating and the substrate decrease, and in the center of the pore filled with the ink composition, they increase. As the pore radius decreases, the difference between the stress values on the coating surface and in the zone of contact between the coating and the substrate decreases. There is a change of signs of stress in the zone of contact between the coating and the substrate, and in the center of the pore filled with the ink composition. Recommendations are given for choosing the type of paint.

Introduction

One of the common types of failure of paint and varnish coatings on cement concrete is cracking and peeling [1-3]. Studies [4-6] present an analysis of the stress development mechanisms in thin coatings to enable modeling of the stress state of the resulting coatings and subsequent prediction of the required properties. The authors found that the magnitude and sign of internal stresses in coatings depend on many factors related to the conditions and method of application of the coating to the substrate, as well as the nature of their growth. Thermal stresses make a significant contribution to the overall stress level in thin coatings.

In natural conditions, paint compositions on building facades, in addition to the effects of moisture (in the form of precipitation) and varying relative air humidity, are also affected by temperature. When exposed to alternating temperatures, coatings undergo changes in their deformation state, characterized by alternating compressive and tensile stresses [7-10]. The coating-substrate contact zone contains pores unfilled with paint. It has previously been established that the presence of pores in the coating-cement substrate contact zone contributes to a more heterogeneous stress-strain state compared to a smooth, non-porous substrate [11-14].

According to the theory of brittle fracture, cracking of coatings will occur if the internal tensile stresses are greater than or equal to the cohesive strength Rp [15-17]. Based on the relationship between long-term and short-term strength, the cracking condition has the form [18-23].

$$\sigma_{max} > 0.5R$$

where R is the short-term strength.

It is of interest to evaluate the influence of the presence of pores and their sizes on the stress state of coatings and to assess the cracking of coatings.

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Experimental methodology

Heavy concrete with a coefficient of linear thermal expansion (CLTE) of 10.0 * 10^{-6} 1/deg was used as the substrate. Polymer-lime paint was used as the paint composition. The CLTE of the coating was 8.3 * 10^{-6} 1/deg. To study the stress state of coatings, we have considered the case of a coating applied to concrete and bonded to it by adhesive forces. The coating layer is in a flat stress state.

Calculations were performed for Moscow conditions using the SCAD Office software module. The studies were conducted using several schemes, namely: scheme type a – finishing layer thickness of 1 mm, pores filled; scheme type b – finishing layer thickness of 1 mm, pores unfilled; scheme type c – no pores (Figure 1). Calculations were performed for each model, and stress-strain schemes were obtained, which were used for the analysis. For each sample, nine schemes were identified in which stresses were examined in more detail (Figure 1d).

The computational model consists of finite shell elements with a size of 0.1 x 0.1 mm. The material of the substrate and paintwork was assigned by assigning the element the values of the modulus of elasticity, the Poisson's ratio, and the coefficient of linear thermal expansion for the corresponding material. The boundary conditions were applied to the substrate opposite the paint layer and limited movement in all 6 possible directions. To prevent the effect of sealing on the stress-strain state (hereinafter referred to as VAT) in the paint layer and in the area of contact with the substrate, the boundary conditions were located at a distance of at least 5 thicknesses of the paint composition. The temperature effect was defined as compressive or tensile forces acting on the paintwork. The calculations were carried out for the climatic conditions of Moscow. The air temperature for the conditions of Moscow was taken in accordance with Code of Rules SP 131.13330.2025 "Building Climatology".

Results

The calculation results are shown in Tables 1,2, and Figures 2,3. Maximum shear stresses occur along the x-axis. When exposed to alternating temperatures, the coatings undergo changes in their deformation state, characterized by alternating compressive and tensile stresses. Analysis of the data presented in Figures 2,3 indicates that the magnitude of internal stresses decreases with decreasing coating thickness, due to strengthening by the adsorption forces of the substrate material.

Tables 1,2 show the stress values σ_x for the presence of paint-filled pores in the coating-substrate contact zone. It was found that as the radius of the paint-filled pores decreases, the stresses in the coating-substrate contact zone decrease, while they increase at the center of the paint-filled pore. It is also worth noting the reversal of stress signs in the coating-substrate contact zone and at the center of the paint-filled pore. This indicates a concentration of stresses in the pore area, which in turn can lead to cracking and delamination of the polymer coating.

As the pore radius decreases, the difference between the stress values on the coating surface and in the coating-substrate contact zone decreases. For example, for Moscow conditions in October, the difference between the stress values on the coating surface and in the coating-substrate contact zone for a pore radius of 1 mm is σ_x = -31.18*10^{-3} MPa, while for a pore radius of 0.3 mm, it is -18.22*10^{-3} MPa.

If the coating-substrate contact zone contains pores unfilled by the paint composition, a more uniform stress state

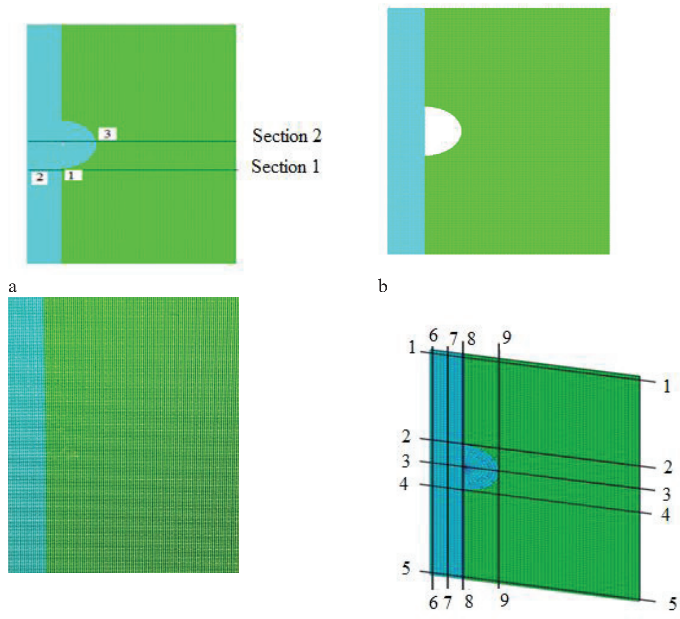

Figure 1: Schemes for calculating the stress state of coatings.

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Table 1: Stresses in a polymer-lime coating 1 mm thick (operating conditions in Moscow, the holes are filled with a paint composition).

Month	Stresses, σ_x, MPa*1$^{0\text{-}3}$														
	r = 1 мм			*r* = 0.9 мм			*r* = 0.8 мм			*r* = 0.6 мм			*r* = 0.3 мм		
	Section 1, point 1	Section 1, point 2	Section 2, point 3	Section 1, point 1	Section 1, point 2	Section 2, point 3	Section 1, point 1	Section 1, point 2	Section 2, point 3	Section 1, point 1	Section 1, point 2	Section 2, point 3	Section 1, point 1	Section 1, point 2	Section 2, point 3
07	7.4	-3.17	-21.07	6.34	-3.42	-21.37	5.57	-3.69	-22.1	3.41	-4.32	-23.05	0.83	-5.39	-26.9
08	-7.7	3.04	20.26	-6.18	3.28	20.49	-5.43	3.55	21.21	-3.35	4.14	22.52	-0.86	5.17	25.78
09	-20.77	3.68	58.54	-17.47	9.52	59.35	-15.66	10.29	61.36	-9.56	12.01	65.27	-2.32	15.01	74.79
10	-22.18	9.08	61.74	-18.69	10	62.44	-16.22	10.81	64.38	-10.11	12.59	68.51	-2.43	15.75	78.32
11	-22.06	3.94	60.89	-18.14	9.87	61.61	-16.07	10.67	63.72	-9.94	12.46	67.67	-2.54	15.53	77.4
12	-16.12	6.55	44.73	-13.28	7.26	45.09	-11.8	7.82	46.64	-7.37	9.1	49.52	-1.88	11.38	56.82
01	-9.42	3.85	26.27	-7.76	4.26	26.57	-6.88	4.6	27.45	-4.26	5.36	29.15	-1.05	6.71	33.33
02	3.33	-1.35	-9.15	2.83	-1.49	-9.27	2.52	-1.6	-9.59	1.53	-1.88	-10.14	0.39	-2.34	-11.63
03	28.42	-11.56	-79.04	23.44	-12.85	-79.93	20.82	-13.84	-82.67	12.99	-16.16	-87.7	3.29	-20.16	-100.44
04	25.13	-10	-68.77	20.32	-11.19	-69.34	18.32	-12.01	-71.81	10.99	-14.1	-76.33	2.81	-17.55	-87.43
05	13.32	-5.52	-37.34	11.28	-6.04	-37.78	9.9	-6.53	-39.07	5.95	-7.66	-41.49	1.52	-9.52	-47.6
06	7.47	-3.11	-21.23	6.32	-3.45	-21.37	5.41	-3.72	-22.13	3.34	-4.34	-23.44	0.84	-5.39	-26.88

Table 2: Stresses in a polymer-lime coating 1 mm thick (operating conditions in Moscow, the pores are not filled with a paint composition).

Month	Stresses, σ_x, MПa*10^{-3}														
	r = 1 mm			*r* = 0.9 mm			*r* = 0.8 mm			*r* = 0.6 mm			*r* = 0.3 mm		
	Section 1, point 1	Section 1, point 2	Section 2, point 3	Section 1, point 1	Section 1, point 2	Section 2, point a 3	Section 1, point 1	Section 1, point 2	Section 2, point 3	Section 1, point 1	Section 1, point 2	Section 2, point 3	Section 1, point 1	Section 1, point 2	Section 2, point 3
07	0.81	-3.18	-8.76	0.26	-3.58	-8.49	-0.01	-3.98	-8.24	-1.1	-4.84	-7.59	-2,2	-5,96	-6,59
08	0.81	3.05	3.58	-0.34	3.43	3.15	0.1	3.82	7.91	1.35	4.63	7.25	2,07	5,73	6,34
09	-2.26	3.75	24.84	-1.04	10.01	23.59	0.47	11.12	22.83	2.89	13.45	21.06	6,12	16,6	18,33
10	-2.57	9.24	25.55	-0.87	10.37	25.28	0.54	11.69	24.08	3.1	14.12	22.14	6,4	17,4	19,25
11	-2.77	9.08	25.18	-1.15	10.38	24.48	0.35	11.46	23.74	2.96	13.84	21.8	6,4	17,25	18,99
12	-1.96	6.68	18.49	-0.88	7.6	17.88	0.28	3.35	17.39	2.14	10.14	16	4,64	12,61	13,87
01	-1.06	3.96	10.33	-0.42	4.48	10.46	0.25	4.97	10.24	1.3	5.99	9.4	2,74	7,42	8,19
02	0.48	-1.37	-3.8	0.23	-1.56	-3.68	0.04	-1.73	-3.54	-0.39	-2.08	-3.28	-1,12	-2,6	-2,85
03	3.51	-11.97	-32.74	1.45	-13.47	-31.67	-0.6	-14.79	-30.8	-3.87	-18.02	-28.37	-8,15	-22,28	-24,64
04	2.79	-10.25	-28.5	1.33	-11.81	-27.68	-0.56	-12.94	-26.81	-3.45	-15.68	-24.69	-7,16	-19,44	-21,45
05	1.55	-5.63	-15.46	0.57	-6.37	-15.01	-1.74	-6.99	-14.55	-1.79	-8.49	-13.42	-4,79	-10,15	-11,64
06	0.77	-3.18	-8.75	0.2	-3.57	-8.49	-0.26	-3.98	-8.23	-1.12	-4.8	-7.59	-2,21	-5,97	-6,58

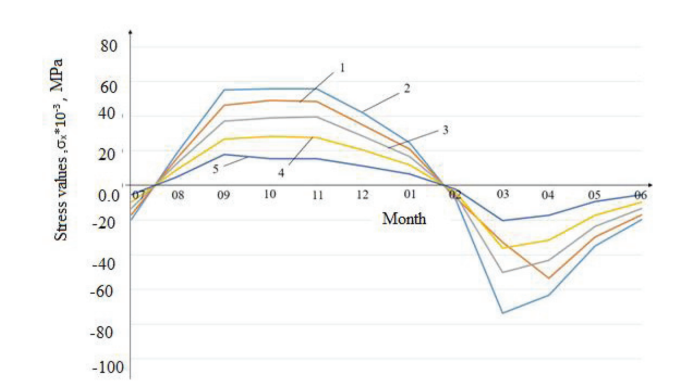

Figure 2: Changes in temperature stresses in the polymer-lime coating during the year in Moscow: 1 - coating thickness h = 1 mm; 2- coating thickness h = 0.8 mm; 3- coating thickness h = 0.6 mm; 4 - coating thickness h = 0.4 mm; 5- coating thickness h = 0.2 mm.

of one sign arises in the coating as the pore radius decreases (*r* < 0.8 mm). In large pores with a radius greater than 0.8 mm, the stresses in the coating-substrate contact zone and on the coating surface have different signs. For Moscow conditions in November, with a pore radius of 1 mm, the stresses in the coating-substrate contact zone are -2.77*10^{-3} MPa, while on the coating surface, they are +9.08*10^{-3} MPa.

The results of the calculations indicate that coating cracking will occur in the area of large pores. The short-term cohesive strength of polymer-lime coatings is R_{long} = 0.13 MPa, and the long-term cohesive strength is 0.065 MPa. Comparing the stress values with the long-term cohesive strength, it can be concluded that in some cases, coating cracking will occur as a result of thermal stress.

Conclusion

The effect of a porous cement substrate on the stress state of protective and decorative coatings on a cement substrate was determined. It was found that in the presence of large pores in the coating-substrate contact zone, the stresses at the coating-substrate contact zone and on the coating surface have different signs, indicating a stress concentration in the pore area, which in turn can lead to cracking and delamination of the polymer coating.

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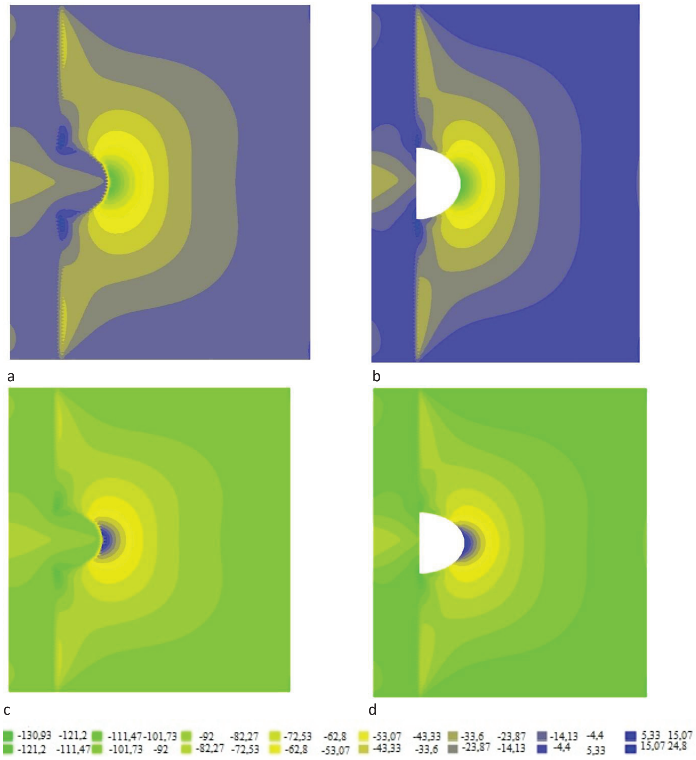

Figure 3: Distribution of stresses σx in the coating over the pore: a - filled with a paint composition; b - unfilled with a colorful composition; in the absence of pores. The coating thickness is 1 mm, the pore radius is 1 mm for the conditions of Moscow: a, b - in March; - in October. (Stress values are in MPa *10^{-3}).

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