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ASSESSMENT OF THE ADHESION STRENGTH OF DETONATION-SPRAYED METAL-CERAMIC COATINGS ON CONCRETE SUBSTRATES

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Abstract
Introduction. The efficiency and successful application of various protective coatings necessitate the investigation of coating–substrate interactions to ensure durability and reliability. Adhesion is a key parameter that determines the quality of bonding between a coating and a substrate surface. Existing methods for its assessment are continually being improved to enhance accuracy, versatility, and applicability to various types of coatings and substrates. **Purpose of the study**. The study is aimed at assessing the adhesion strength of coatings deposited by detonation spraying onto heavy-concrete surfaces and refining the methodology for determining adhesion strength for the corresponding tests. **Methods**. In the course of the study, Raman spectroscopy, axial pull-off adhesion testing, optical microscopy, and rotational viscometry were used. **Results**. Adhesion strength tests were performed on Ti–TiO_x coatings deposited on concrete substrates by detonation spraying of powders under different modes. The resulting coatings exhibit high adhesion strength to the substrate, ranging from 0.32 to 3.77 MPa, and low porosity. A special fixture was pre-developed for adhesion testing of specimens with linear dimensions of 30 mm and larger. A study was conducted on the applicability of a series of epoxy resins for adhesion testing. It was found that, when testing coatings on porous substrates, it is important to consider the viscosity of the adhesive agents, since highly mobile formulations may penetrate deeply into the specimen and distort the results.

Keywords: adhesion strength; coatings; concrete; adhesion testing methodology; epoxy resin.

Introduction

The development of coatings for construction materials and composites addresses a range of challenges related to improving their performance characteristics, enhancing durability, functionality, aesthetics, etc. There exists a vast variety of coatings designed for specific purposes (Bessmertnyy et al., 2019; Bondarenko et al., 2024; Klyuchnikova et al., 2018; Montemor, 2014), as well as numerous mechanical testing methods for evaluating their adhesive properties (Chen et al., 2014; Zaytsev et al., 2021).

Adhesion assessment methods based on sandwich specimens (double-cantilever beam and four-point bending) allow measurement of fracture energy under different loading modes. The scratch test and the Rockwell indentation method are widely used for quantitative and qualitative evaluation of adhesion through radial stresses and critical loads (Croll, 2020; Ma et al., 2020; Vereschaka et al., 2019; Zhang et al., 2024). For wood coatings, the cross-cut test is applied, enabling visual assessment of adhesion based on coating detachment (Hang et al., 2024). For thick coatings, the transverse scratch test is used to evaluate cohesive strength (Croll, 2020). In practical applications — more often for organic coatings — pull-off tests and peel tests are also commonly employed (Falsafein et al., 2018; Haselrieder et al., 2015).

Adhesion of coatings strongly depends on the surface structure and texture, as well as its roughness (Croll, 2020). Sandblasting and laser texturing increase the contact area, thereby improving adhesion (Harfouche et al., 2024; Heidarinejad and Ashrafizadeh, 2024). An increase in coating thickness may lead to the accumulation of internal stresses at the interface, which reduces adhesion (Heidarinejad and Ashrafizadeh, 2024; Ma et al., 2020).

An analysis of several international and domestic standards describing methods for evaluating the adhesion properties of various types of coatings was carried out.

ASTM C633-24 specifies the procedure for determining the adhesion or cohesion strength of thermally sprayed coatings by applying a tensile load perpendicular to the coating surface. The method is intended for assessing either the bond strength between the coating and the substrate or the internal strength of the coating itself.

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The standard covers coatings applied by plasma spraying, arc spraying, detonation spraying, and high-velocity oxy-fuel (HVOF) spraying. Coatings may consist of metals, ceramics (oxides, carbides), or combinations thereof.

The method is applicable to coatings thicker than 0.38 mm (0.015 in). This limitation is due to the use of an adhesive, which may penetrate thin coatings and distort the test results. The coating is applied to one side of the substrate, after which a loading fixture is bonded to the coated surface using an adhesive. A tensile load normal to the coating plane is then applied until failure of the specimen. The crosshead displacement rate is 0.013–0.021 mm/s (0.030–0.050 in/min). The maximum recorded load is used to calculate the bond strength.

Adhesive or cohesive strength is calculated as the ratio of the maximum load to the cross-sectional area of the specimen. Failure may occur at the substrate–coating interface (adhesive failure), within the coating itself (cohesive failure), or within the adhesive layer. The failure location is determined using a microscope with magnification up to 100x. The report must include the coating type, application method, substrate material, test parameters, and a detailed description of the failure mode.

The method is limited to coatings capable of withstanding tensile loads at room temperature, although testing at cryogenic temperatures is also possible. The application of this method to very thin or brittle coatings requires additional investigation and may necessitate new adhesive materials to avoid distortion of the results.

ASTM D3359-23 describes methods for evaluating the adhesion of organic coatings to a substrate using pressure-sensitive tape and includes two primary approaches — Method A and Method B. Both are based on applying pressure to the coating using an adhesive tape and then rapidly removing it. The distinction lies in the shape and number of cuts made on the coating surface.

Method A involves making two intersecting cuts on the coating surface, forming an X-shaped pattern. A transparent or semi-transparent adhesive tape 25 mm wide, with an adhesion strength of 6.34–7.00 N/cm, is then applied to the coating. The tape is removed rapidly at an angle of 180°, after which the area of coating detachment from the substrate is visually assessed.

Method B involves creating a lattice pattern consisting of six or eleven parallel cuts in two perpendicular directions, forming a lattice. After applying and removing the adhesive tape, the result is evaluated on a scale from 0 to 5, where 5 indicates no coating damage and 0 indicates severe detachment of the coating down to the substrate.

The standard requires the use of a sharp cutting tool (a scalpel or knife) to make the cuts in the coating. A steel ruler or similar rigid guide is used to ensure cut accuracy. The cutting tool must be in good condition — preferably new or recently sharpened — to ensure clean, even cuts. It is also essential to use adhesive tape from the same manufacturer and batch for all tests, since adhesive properties may vary between batches. This is necessary to ensure repeatability and comparability of results.

Adhesion is assessed visually, which requires appropriate operator training. The influence of environmental conditions (temperature and humidity) is also taken into account, as these factors may affect both the coating and the adhesive tape. When conducting tests on non-metallic substrates, the standard recommends using either Method A or Method B depending on the characteristics of the substrate; however, the accuracy of the data for such materials has been studied to a lesser extent.

ASTM D4541-22 establishes a procedure for measuring the pull-off strength of coatings applied to metal and other rigid substrates using portable adhesion testers. The method is intended to evaluate the adhesion strength between the coating and the substrate or between individual coating layers by applying a normal (perpendicular) force to the tested surface until coating failure occurs. The process involves the use of a fastening element, referred to as a “dolly” or “stub”, which is bonded to the coating surface with a special adhesive. After the adhesive has cured, a gradually increasing force is applied to the fastening element using a portable adhesion tester, which records the maximum force attained before failure.

The standard describes five different testing procedures (designated as Methods B–F), each with its own features depending on the type of equipment used and the test conditions. Test results may vary significantly depending on the substrate material, coating thickness, adhesive type, and other parameters; therefore, they cannot be directly compared without accounting for these factors. It is important to note that Method A, which was included in earlier versions of the standard, has been removed because it was specifically developed for testing concrete substrates and has been transferred to a separate standard, ASTM D7234-22.

The testing process may lead to coating failure. The standard recommends using testers capable of applying a concentrated load to a small area, which allows testing even on surfaces with limited accessibility. In addition, the test procedure may require consideration of substrate flexibility and loading rate to avoid distortions in the results.

Test results are expressed in MPa or psi. The document provides detailed instructions on how data should be recorded and interpreted, including the description of the surface failure and detachment location. The method requires thorough documentation of all testing parameters and conditions, including equipment type, adhesive properties, and substrate characteristics.

ISO 2409:2020 describes a method for assessing the adhesion of coatings within multilayer paint systems. The standard is intended for testing coatings on flat surfaces using the cross-cut method, which makes it possible to evaluate the adhesion of coating layers to the substrate or to each other. The procedure involves applying the coating to a special panel, after which parallel cuts are made on its surface, followed by intersecting cuts that form a lattice pattern.

The dimensions of the cuts depend on the coating thickness and the type of substrate. For coatings up to 60 μm thick, the spacing between cuts is 1 mm; for coatings up to 120 μm, the spacing is 2 mm; and for coatings thicker than 120 μm, the spacing is increased to 3 mm. Evaluation is carried out visually, determining the degree of coating detachment on a scale from 0 to 5, where 0 indicates no detachment and 5 represents complete detachment of the coating within the cross-cut area.

The standard also considers parameters that may affect test results: surface preparation, coating thickness and application method, and environmental conditions. The document emphasizes the importance of using a sharp cutting tool to ensure clean cuts and maintaining uniform pressure during the procedure. The method is applicable to both metallic and non-metallic substrates, including plastics and wood; however, results may vary depending on the substrate type and its mechanical properties.

ISO 4624:2023 describes test methods for determining the adhesion strength of paint coatings using axial pull-off testing. The primary objective of the standard is to determine the minimum stress required to break the bond between the coating and the substrate. The standard provides three procedures: Method A (using two dollies), Method B (testing from one side only, using a single dolly), and Method C (using dollies, one as a painted substrate).

Tests are performed using cylindrical metallic dollies with a diameter of 20 mm, which are bonded to the surface of a special panel. For testing on concrete substrates, dollies with diameters up to 100 mm are permitted. The test panels are subjected to a gradually increasing pull-off force applied perpendicular to the panel plane until failure occurs.

The measured results depend on the strength of the bonding layer between the coating and the substrate, as well as on the failure mode: adhesive failure (separation at the coating–substrate interface) or cohesive failure (rupture within the coating itself). Various factors may influence the results, including the mechanical properties of the substrate, coating curing conditions, type of adhesive used, etc. Proper centering and alignment of the dollies play an important role in ensuring measurement accuracy.

ISO 16276-1:2007 specifies methods for assessing the adhesion of corrosion protection coatings applied to steel surfaces. The standard focuses primarily on adhesion testing procedures using standard panels, coating application methods, and curing and testing conditions.

The standard provides two principal test methods: the bending test and the pull-off test. The bending test is intended for evaluating adhesion under conditions in which the coating is subjected to mechanical stress during deformation. The pull-off test (using dollies) is used to determine the force required to detach the coating from the substrate. The standard also addresses surface preparation procedures — cleaning and pre-treatment — which are critical for achieving reliable coating adhesion to the substrate.

The coating thickness and selection of materials for testing are regulated to ensure representativeness and repeatability of test results. The standard also describes methods for documenting and presenting test data, including the parameters that must be reported: the type of equipment used, testing conditions, and the characteristics of the coating failure.

GOST 28574-2014 establishes detailed methods for determining the bond strength (adhesion) of protective coatings applied to concrete and reinforced concrete structures, including those used in aggressive environments. The standard includes both quantitative and qualitative testing methods for paint, mastic, and film coatings.

1) The quantitative method for determining the adhesion of paint coatings by pull-off strength is intended for both laboratory and field testing. The test is based on measuring the force required to detach the coating from the concrete surface by bonding a metallic dolly (stub) and using an adhesion tester. Laboratory testing is performed on concrete cube specimens with dimensions of 100×100×100 mm or 70×70×70 mm. Compliance with the coating application and curing procedures specified in the technical requirements is an important prerequisite.

During testing on full-scale structures, coating areas are selected at a spacing of no less than 300 mm from each other, and metallic dollies are bonded for subsequent pull-off measurements. The testing parameters include uniform loading at a rate not exceeding 1 MPa/s, with recording of the detachment time, which must fall within 30 to 90 s. The equipment used must be capable of generating a pull-off force of at least 5 MPa.

The method also provides for visual evaluation of the failure mode, which may include: adhesive failure along the coating–concrete interface, cohesive failure within the coating itself, or failure within the concrete body. Test results must be processed carefully: the mean adhesion strength is calculated with exclusion of extreme values that deviate from the arithmetic mean by more than 15 %.

2) The qualitative cross-cut method is used for field testing and consists of creating cross cuts on the coating followed by inspection and assessment of the degree of peeling. The qualitative evaluation is based on the number and size of detached coating fragments, allowing classification of adhesion into corresponding categories.

3) The quantitative method for determining the adhesion of film coatings is used to evaluate the peel strength of film coatings. Testing is conducted on laboratory specimens consisting of concrete substrates with applied protective film coatings. Peel strength is determined using special devices, which enables accurate measurement of adhesion strength.

Thus, the analysis of coating adhesion properties is an important task in the process of coating evaluation; however, modern standards do not always consider the method of coating application, the composition of the substrate and coating, or their structural characteristics.

Subject, Objectives, and Methods

The adhesion strength of the coatings was evaluated using a PSO-10MG4 adhesion tester (Stroypribor Special Design Bureau, Russia).

Concrete of strength class B30 was used as the substrate material.

The coatings were produced using the unique scientific facility “Research Complex for the Deposition and Investigation of Nanostructured Functional Coatings” at the Shukhov Belgorod State Technological University (https://ckp-rf.ru/catalog/usu/3552744/), which represents a multi-chamber detonation system (https://ckp-rf.ru/equipment/search_usu/3557868/). In this setup, combustion of a propane–butane mixture generates a detonation wave that travels along the barrel, accelerating particles of the spray-on material introduced near the end of the barrel. The powder then strikes the substrate at supersonic velocity, forming a dense coating. In this study, coatings were produced by detonation spraying using titanium powder PTS-1, obtained by crushing titanium sponge.

Two series of specimens were prepared under different spraying conditions: the first series (specimens 1–4) used a standoff distance of 120 mm and a speed of 1200 mm/min; the second series (specimens 5–8) used a standoff distance of 200 mm and a speed of 2000 mm/min. The coatings in the first series had a thickness of approximately 70 μm, and those in the second series — approximately 20 μm. The coating exhibited a mixed-phase composition $Ti–TiO_x$, where x = 0–2.

Selection of the required characteristics to ensure the stiffness of the designed support plate was carried out using the KOMPAS-3D software and the APM FEM module for finite element analysis.

The composition of the epoxy resins was analyzed by Raman spectroscopy using a B&W Tek i-Raman Plus spectrometer in the range of 200–3,000 cm^{-1}.

The viscosity of the epoxy resins was determined using a FUNGILAB EVO Expert rotational viscometer with an R6 spindle at a rotation speed of 10–150 rpm.

Microscopic studies were performed in the visible field using an MT-24RF upright optical metallographic microscope (SIAMS, China) with the SIAMS 800 software package (SIAMS, Russia). This hardware-software complex provides a horizontal scanning function with image accumulation and subsequent stitching.

Results and Discussion

Among the methods and procedures reviewed, two principal approaches can be distinguished for evaluating the adhesion properties of coatings: (1) pull-off testing using adhesives and dedicated mechanical devices, and (2) the use of cuts followed by visual inspection of the surface.

Pull-off testing is the most suitable option for examining coatings produced by thermal spray methods, since such coatings typically exhibit a low-porosity structure with high hardness and cohesion. This structure prevents the penetration of cutting tools without causing significant damage to the coating outside the cut area.

One of the serially produced domestic devices enabling mechanical adhesion testing of coatings is the PSO series of adhesion testers. In this study, a PSO-10MG4 device (Fig. 1) is used, providing a maximum load of 10 kN and equipped with a standard pull-off test area of 50×50 mm.

Fig. 1. PSO-10MG4 adhesion tester

A key drawback of this device is the distance between its supports — 85 mm — which renders it unsuitable for testing small-sized specimens.

The solution to this limitation is to design a custom fixture that ensures compliance with both GOST 28574–2014 and ASTM C633-24. The fixture must enable testing of specimens sized from 30×30 mm, which is constrained by the diameter of the opening in the support plate and the pull-off cylinder. The pull-off area can be adjusted to match ASTM requirements, where the test area diameter is 1 inch (25.4 mm). In this case, the pull-off area will be 2,026 mm^2.

To perform pull-off testing on a coating applied to a 40×40 mm specimen, proper support must be provided between the test device and the specimen. Therefore, for the three-support configuration of PSO-10MG4, the most appropriate solution is a triangular plate with a 27 mm diameter opening, ensuring both the free movement of the test area and the maximum possible bearing surface for the specimen.

A number of tasks arise in the development of such a fixture:

1. Adjusting the length of the hinge screw due to the increased distance to the specimen caused by the support plate.

2. The pull-off plate is a consumable component, since it may later be cut to obtain a polished cross-section for microscopic examination of the failure mode. There are two possible ways to fabricate this part:

a) using a metal rod with a diameter of 1 inch and subsequently welding an M10 nut of the corresponding steel grade;

b) cutting a thicker plate from a metal rod with a diameter of 1 inch and forming an internal thread.

3. The designed plate must provide sufficient stiffness to prevent bending during testing.

In this regard, prior to performing adhesion tests, the components were designed together with a model of the PSO-10MG4 apparatus (Fig. 2), ensuring compatibility with the dimensions of the concrete specimens coated with Ti–TiO_x.

The stiffness of the support plate can be adjusted by two main parameters: the plate thickness and the material used. The required characteristics were selected using the KOMPAS-3D software package and the APM FEM module for finite element analysis (Fig. 3).

As a result of numerical modeling, the following minimum parameters required to ensure the stiffness of the developed support plate were obtained: a thickness of 6 mm and steel grade C40 according to GOST 1050–2013 with a yield strength of σ_y = 330 MPa and σ_v = 570 MPa. The analyzed model also shows that a significant portion of the stresses is concentrated in the hinge screw, which must also be manufactured from C40 steel, with a stretched-rod diameter of 7 mm.

Before testing, the specimen is degreased, and all fine and dusty particles are removed from the surface using compressed air. The pull-off plate is then bonded to the coating surface using an epoxy adhesive. As the epoxy adhesive, epoxy-diane (ED) resin with the addition of polyethylene polyamine (PEPA) in the amount of 10 wt% may be used. The bonded pull-off plate is then conditioned in accordance with the requirements for the epoxy

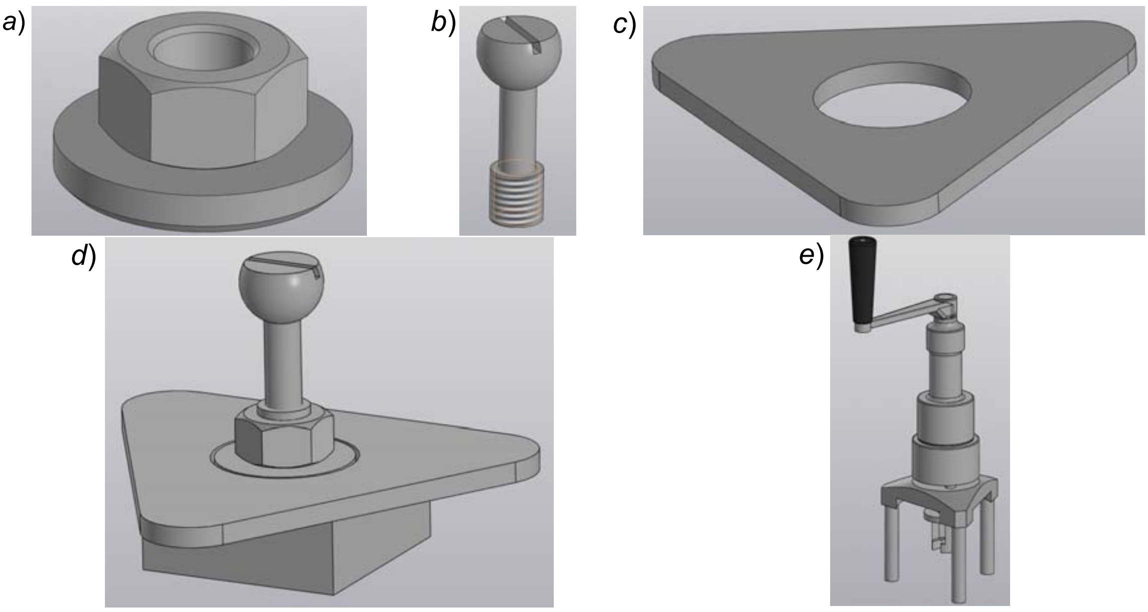

Fig. 2. 3D models of the fixture for adhesion testing using the axial pull-off method: *a* — version of the pull-off plate with a nut; *b* — hinge screw; *c* — support plate; *d* — assembled configuration prepared for pull-off testing; *e* — PSO-10MG4 testing apparatus

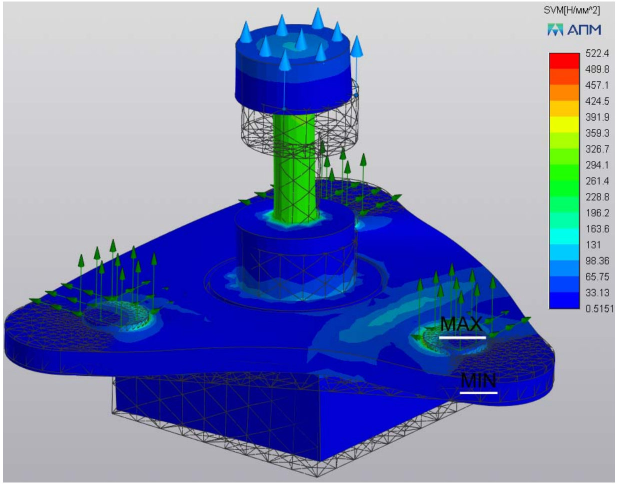

Fig. 3. Finite element computational model of the developed fixture

adhesive; for the ED + PEPA composition, the specimen should be conditioned for at least 24 h under standard conditions.

After the epoxy adhesive has fully cured, the hinge screw is threaded into the opening of the pull-off plate. The assembled system is inserted into the opening of the support plate and placed into the dedicated hinge socket of the PSO-10MG4 testing device. Next, a uniform load is applied at a rate not exceeding 1 MPa/s (following GOST 28574–2014). The adhesion strength is calculated as follows:

$$\sigma_a = F/A,$$

where F is the force obtained during testing, and A is the test area.

To select the most suitable epoxy resin for the tests, four samples were chosen:

ER1 — epoxy resin supplied in two syringes, both containing a transparent component;

ER2 — epoxy resin supplied in a dual syringe with a common plunger;

ERH — epoxy resin with hardener;

CWC — cold-welding compound.

Since manufacturers do not specify the composition of epoxy resins, their composition was analyzed using Raman spectroscopy (Figs. 4, 5).

Comparison of the spectra (Fig. 4) with reference data showed that all the epoxy resins correspond to the same chemical compound — poly (bisphenol A-co-epichlorohydrin), i.e., an epoxy resin obtained via the reaction of hydrogenated bisphenol A with epichlorohydrin. The halo and troughs observed in the CWC spectrum are associated with the presence of fillers (kaolin, titanium dioxide) and modifier (dibutyl phthalate), as specified by the manufacturer. In all cases, comparison with reference spectra yielded a hit quality (HQ) exceeding 90 %.

The hardener in ER1 is a solution of amine hardeners in propylene glycol (HQ = 90.53); the hardener in ER2 is triethylenetetramine (HQ = 89.08); the hardener in ERH is tetraethylenepentamine (HQ = 92.94); the hardener in CWC is most likely filled polyamine (HQ = 90.35) (Fig. 5).

Viscosity of the epoxy resin samples (Table 1) was examined under the following parameters: spindle R6, as it had been determined in advance that all resins behave as Newtonian fluids (their viscosity does not change with rotation speed); the rotation speed varied from 10 to 150 rpm, and the density of all resins was 1.15 ± 0.05 kg/cm^3. The cold-welding compound was not tested due to its extremely high viscosity.

During the study, the viscosity of ER1 and ERH either did not change over time or changed insignificantly. A rapid increase in the viscosity of ER2 was observed: within 5 minutes of measurement, the viscosity increased from 25,000 to 37,000 cSt (40 cSt/s), and within 1 hour the viscosity of ER2 became comparable to that of CWC.

Below is the procedure for conducting adhesion tests of coatings produced by detonation spraying on concrete substrates (Fig. 6).

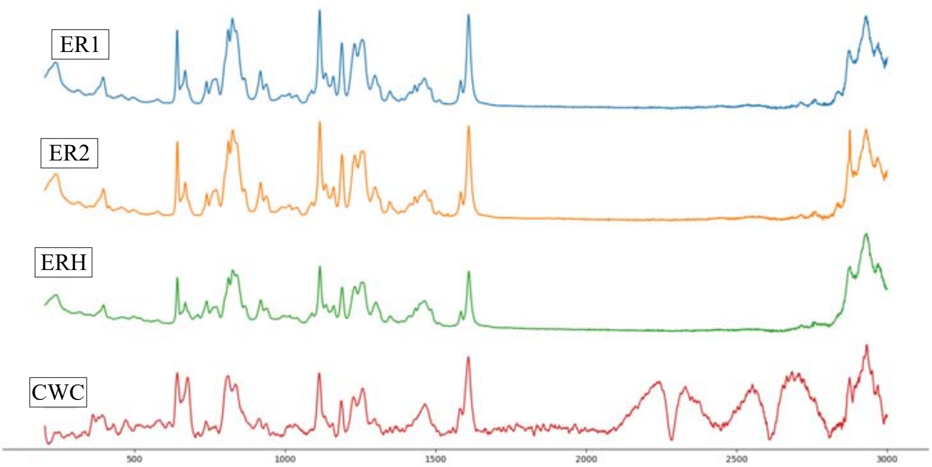

Fig. 4. Raman spectra of the epoxy resins

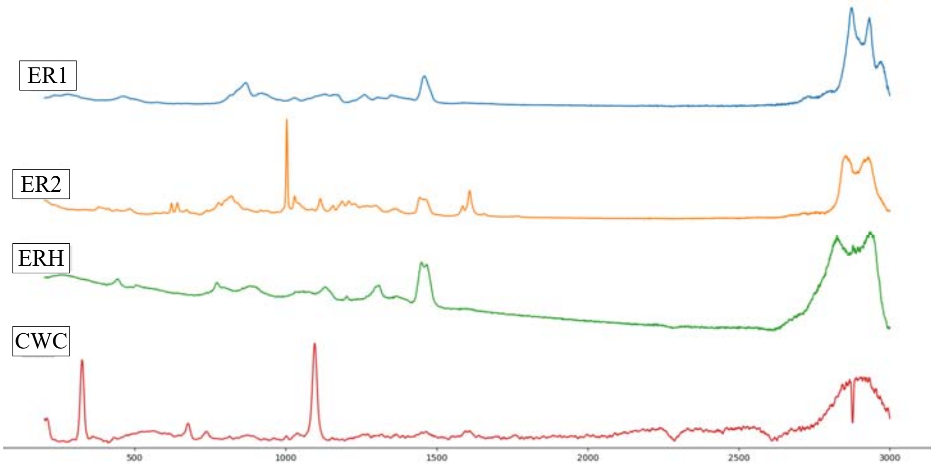

Fig. 5. Raman spectra of the hardeners

Table 1. **Viscosity of the epoxy resin samples**

Sample	ERH	ER1	ER2	CWC
Viscosity, cSt	2,940	3,700	25,000	–

During the adhesion tests, a multilayer PTFE spacer with a total thickness of 300 μm was placed between the support plate and the specimen to compensate for surface unevenness and prevent eccentricity during testing. This spacer thickness was selected under the condition that the surface roughness of the specimens (R_{max}, GOST 2789-73) does not exceed 100 μm. If the roughness exceeds this value, a thicker spacer is recommended.

Based on the results of the adhesion tests (Table 2) and the effectiveness of the adhesives used for determining adhesion strength, the resins were ranked in the following order: ER2 → CWC → ERH → ER1.

The least suitable resin was ER1, whose curing process took more than three days. Moreover, upon application it caused significant wetting of the

Fig. 6. Procedure for conducting adhesion tests

Table 2. **Adhesion strength values obtained using different epoxy resins**

Sample*	ERH		ER1		ER2		CWC	
	1	5	2	6	3	7	4	8
σ_a, MPa	1.52	3.62	2.03	3.77	0.65	1.77	0.53	0.32

* specimen numbering corresponds to Figs. 6–8.

surface, which may affect test results due to the penetration of the resin into the pores of the concrete and its subsequent impregnation.

ERH resin cured within 24 hours, but also exhibited high fluidity.

Cold-welding compound (CWC) is an acceptable option for performing the tests; however, its major drawback is the difficulty of achieving uniform application, which requires considerable effort. When working with thin specimens with coatings, there is a risk of damaging the integrity of the substrate (or the coating–substrate interface).

The most effective adhesive was ER2, which demonstrated the shortest curing time (less than 24 hours), as well as high viscosity combined with sufficient fluidity to allow uniform spreading across the specimen surface.

It should be noted that the numerical test results in this case cannot be interpreted unambiguously, since the surface morphology of the coatings and the internal structure of the specimens differed. Specimens from the first series exhibited a dense structure, whereas specimens from the second series showed significant porosity and therefore demonstrated higher adhesion strength due to shear forces arising from the penetration of the resin into the surface pores. For more mobile resins (ER1 and ERH), failure occurred along the cement stone–aggregate interface, which may indicate partial impregnation and, consequently, strengthening of the near-surface layer of the cement stone by the epoxy resin.

The concrete aggregate also exerted a significant influence on the adhesion strength. In most cases, failure occurred precisely along the concrete–aggregate interface, which should be taken into account when forming coatings and conducting normal pull-off tests.

After the adhesion tests, the specimens were embedded in ERH for further examination of their polished cross-sections using optical microscopy (Figs. 7 and 8). Fig. 7 shows coating segments with a total length of 10 mm. It is evident that nearly all coatings (except for ER1) detached either through the cement stone or along the cement–aggregate interface. It is worth noting that in areas where pores are present and the coating is absent, detachment occurred along the resin–concrete interface, whereas the concrete itself was not torn out. These findings indicate high adhesion of all obtained coatings to the concrete surface, and the adhesive used for the pull-off tests did not penetrate the concrete in any of the cases.

Fig. 8 presents 800 μm segments for each specimen. In all cases, strong adhesion of the coatings to the substrate and low porosity are observed, which is essential for reliable testing. For resin ER1, mixed failure occurred across three zones: failure within the resin, failure along the resin–coating interface, and failure through the

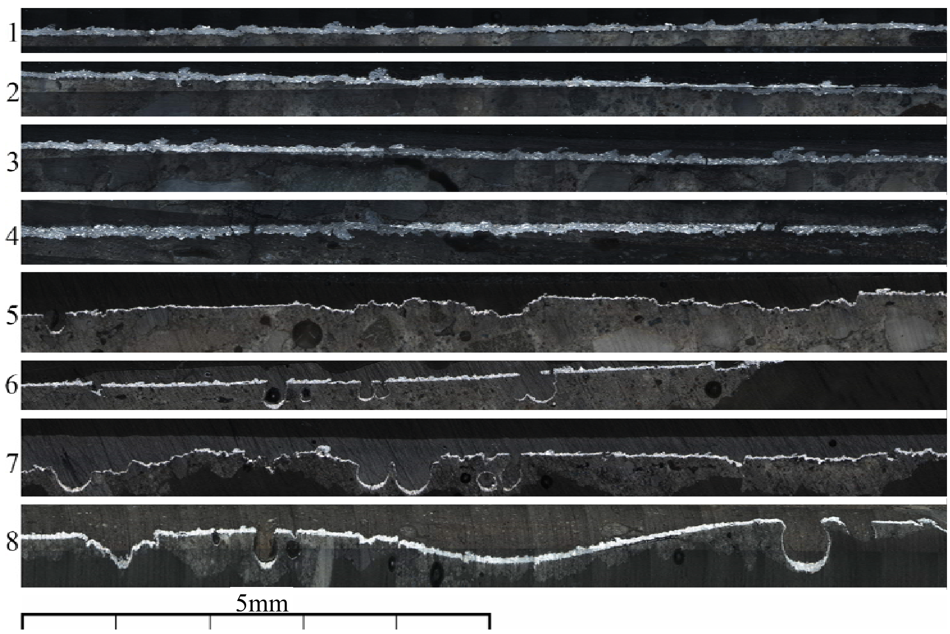

Fig. 7. Microscopic images of polished cross-sections of the coatings after adhesion tests over a 10 mm segment

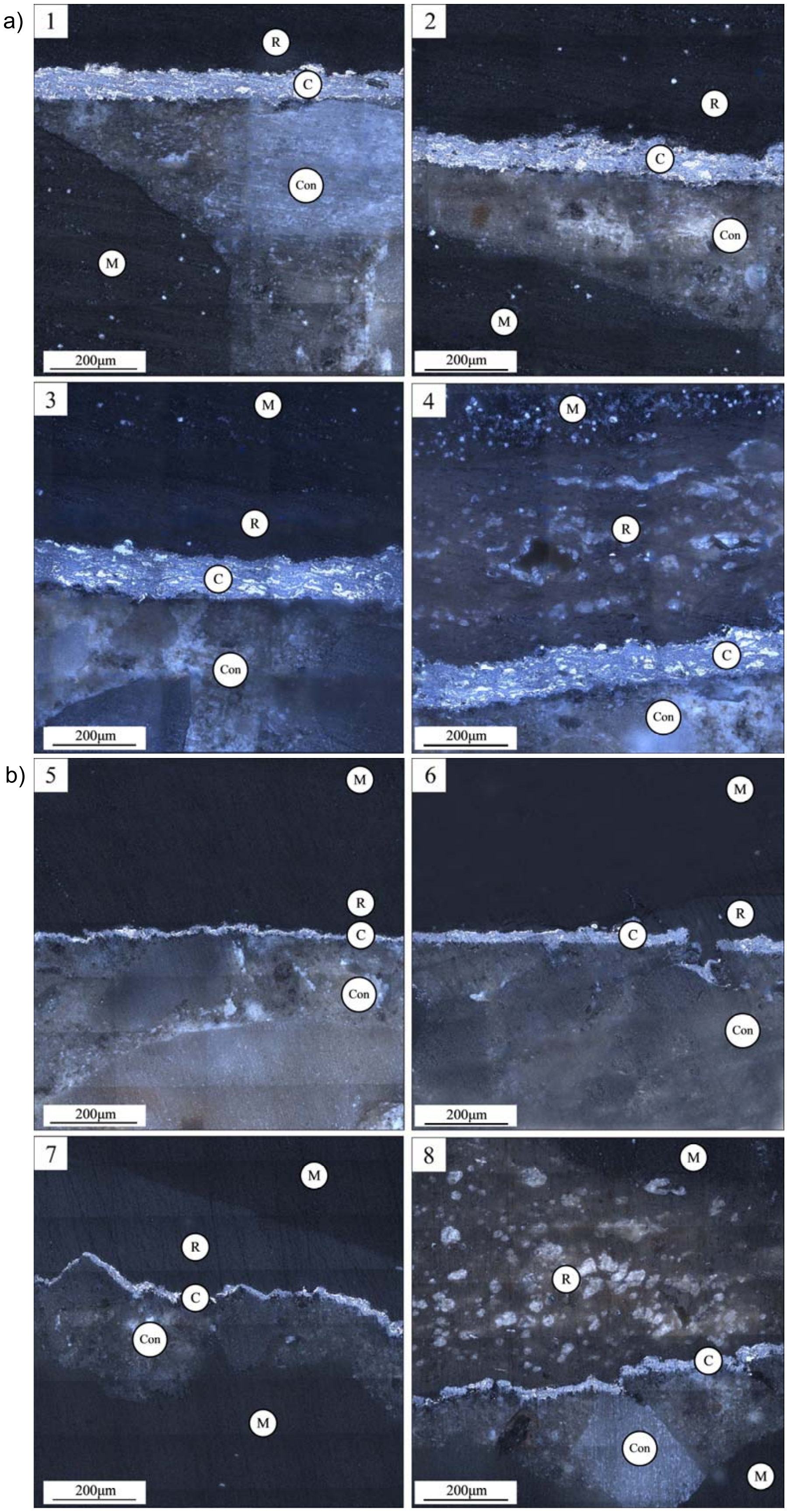

Fig. 8. Microscopic images of polished cross-sections of the coatings after adhesion tests:
a — spraying mode: standoff distance 120 mm, speed 1,200 mm/min; b — spraying mode: standoff distance 200 mm, speed 2,000 mm/min; 1, 5 — ERH; 2, 6 — ER1; 3, 7 — ER2; 4, 8 — CWC;
M — molding resin for polishing; R — resin used for adhesion testing; C — coating; Con — concrete

concrete, which is likely associated with poor-quality hardener or insufficient hardener content. For all other resins, failure occurred exclusively through the concrete. It should be noted that for CWC, local areas were observed where the resin had no contact with the coating, and therefore these tests cannot be considered reliable.

Conclusions

The adhesion strength of $Ti–TiO_x$ coatings on concrete substrates was determined using the axial pull-off method. Specimens produced under the spraying mode with a standoff distance of 120 mm and a speed of 1,200 mm/min exhibited adhesion strengths in the range of 0.53–2.03 MPa (with a coating thickness of approximately 70 μm). Specimens produced under the spraying mode with a standoff distance of 200 mm and a speed of 2,000 mm/min exhibited adhesion strengths in the range of 0.32–3.77 MPa (with a coating thickness of approximately 20 μm). It was found that the numerical test results are influenced by the surface morphology of the coatings, the structure of the concrete, the type of adhesive composition, and its viscosity. A high adhesion strength of all obtained coatings to the substrate and low porosity were noted.

Prior to testing, the procedure for evaluating the adhesion properties of coatings on concrete substrates was refined by developing an appropriate fixture considering the specimen dimensions, specifying the epoxy adhesive to be used, and introducing a PTFE spacer to compensate for surface irregularities of the coating.

The set of tests carried out made it possible to rank the adhesive compositions according to their potential applicability in assessing coating adhesion to the substrate material.

Thus, the following requirements can be established for the correct performance of adhesion tests:

– the coating on the concrete surface must have a continuous structure and minimal surface porosity;

– the coating must be applied directly onto the cement stone surface;

– the aggregate should be selected so that it is compatible with the cement stone in order to prevent detachment along the cement stone–aggregate interface;

– the epoxy resin must have sufficiently low viscosity to spread across the specimen surface, but must not penetrate the surface pores and impregnate the substrate material.

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ОЦЕНКА АДГЕЗИОННОЙ ПРОЧНОСТИ МЕТАЛЛОКЕРАМИЧЕСКИХ ПОКРЫТИЙ, ПОЛУЧЕННЫХ МЕТОДОМ ДЕТОНАЦИОННОГО НАПЫЛЕНИЯ, НА БЕТОННЫХ ПОДЛОЖКАХ

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Аннотация
Введение. Эффективность использования и успешное применение различных защитных покрытий обуславливают необходимость изучения взаимодействия покрытий с подложкой материала для обеспечения их долговечности и надежности. Адгезия является ключевым параметром, определяющим качество сцепления покрытия с поверхностью материала. Существующие методы её оценки постоянно совершенствуются для повышения точности, универсальности и применимости к различным типам покрытий и подложек. **Цель исследования**. Оценка адгезионной прочности покрытий, полученных методом детонационного напыления на поверхности тяжёлого бетона, корректировка методики определения адгезионной прочности для проведения соответствующих испытаний. **Методы**. Рамановская спектрометрия, исследование адгезионной прочности методом осевого отрыва, оптическая микроскопия, ротационная вискозиметрия. **Результаты**. Проведены испытания адгезионной прочности образцов покрытия $Ti–TiO_x$ на бетонных подложках, полученных методом детонационного напыления порошков при разных режимах. Полученные покрытия имеют высокую адгезионную прочность к подложке в диапазоне 0,32–3,77 МПа и низкую пористость. Предварительно разработана оснастка для проведения адгезионных испытаний на образцах с линейными размерами 30 мм и более. Проведено исследование применимости серии эпоксидных смол для адгезионных испытаний. Выявлено, что при испытании покрытий на пористых подложках важно учитывать вязкость применяемых клеящих средств, так как составы с высокой подвижностью могут проникать вглубь образца и искажать получаемые результаты.

Ключевые слова: адгезионная прочность; покрытия; бетон; методика адгезионных испытаний; эпоксидная смола.