

THE EFFECT OF CERAMIC SUBSTRATE MOISTURE ON THE ADHESION OF WATERPROOFING COATINGS

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Abstract

The aim of this article is to present issues related to the impact of substrate moisture on the adhesion of various types of waterproofing used on ceramic surfaces. The work focuses on a detailed analysis of the results of bond strength tests, which were carried out at different substrate moisture levels ranging from 0% to 12%. Six different types of waterproofing materials were analyzed in the tests. Each material was tested at a minimum of five substrate moisture levels, which made it possible to assess its performance under varying moisture conditions. The results showed that an increase in substrate moisture clearly reduced the bond strength. The highest adhesion values were achieved at low moisture levels (0% - 2%), while the lowest values were achieved at the highest levels (11% - 12%). The pull-off test was used in the study. The results obtained were compared with the requirements declared by the manufacturers in the technical data sheets.

Keywords: waterproofing, adhesion, bonding strength, ceramic substrates

1. INTRODUCTION

The selection of the appropriate waterproofing material depending on the type and technical condition of the substrate is a key factor determining the effectiveness and durability of the waterproofing system. One of the most important factors affecting the quality of the bond between the coating and the substrate is the moisture content of the substrate material, which directly affects the adhesive properties of the waterproofing products used. According to literature data, the optimal substrate moisture content should not exceed 4% - 5% to ensure effective bonding of the waterproofing layer [1]. In practice, however, it is permissible to use materials designed for application on damp surfaces, providing that certain technological requirements specified in the technical documentation are met. Excess moisture interferes with the material's bonding and curing, gradually diminishing the coating's durability and adhesion, and potentially causing detachment. The ceramic brick under investigation is characterized by high porosity and capillary water absorption capacity, which poses a challenge for the design of coatings with the

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appropriate consistency and penetration properties. Among the most recent studies in this area, it is worth highlighting the work of Costa et al. [2], which analyzed the effect of mixing water content on mortar rheology and its adhesion to ceramic brick substrates. The authors demonstrated that increasing the water content in the mixture promoted the formation of capillary channels, which facilitated penetration into the microporous structure of the brick. As a result, with a water content of 17% by weight/mixture, a 54% increase in adhesion was observed compared to mixtures with lower moisture content. At the same time, the squeeze flow test revealed a significant reduction in mortar displacement on the brick (up to 60%) compared to a non-absorbent substrate, highlighting the dominant role of the brick's absorption properties in shaping the mortar-substrate contact.

Bituminous coatings are particularly sensitive to moisture, as the presence of water can interfere with polymerization and drying processes. In such cases, it may be necessary to dry the surface or use primers with properties that block capillary moisture migration. If there are doubts about the level of moisture, it is recommended to conduct adhesion tests under real conditions, which allows for the assessment of the applicability of a given material solution [3].

However, it is worth noting that excessively dry substrates can also have a negative impact on adhesion, especially in the case of systems based on hydraulic binders, such as mineral coatings. In such cases, the manufacturer often recommends prior controlled moistening of the substrate to achieve proper adhesion. Publication [4] suggests that a certain low level of moisture can improve bonding strength, but the optimal value is typically a few percent to maintain a balance between absorption and excessive surface dilution.

In addition to moisture parameters, the quality of surface preparation also has a significant impact on the effectiveness of the waterproofing system. The substrate should be load-bearing, clean, and free of contaminants such as dust, grease, oil, cement slurry, or deposits. Any loose fragments should be removed, and defects and cracks should be filled with appropriate repair materials. Additionally, in order to increase adhesion, it is recommended to mechanically treat the surface – e.g. by grinding, milling or sandblasting – which allows to obtain the correct roughness profile and increase the contact area between the coating and the substrate [5-7].

The results of studies published by Tsukagoshi et al. [8] confirm that both moisture and the presence of cracks in the substrate have a significant impact on the effectiveness of waterproofing systems. The authors demonstrated that increased moisture not only reduces the adhesion of the coating, but also results in insufficient bridging of cracks and microcracks. In the case of mineral and bituminous coatings, a loss of material continuity was observed in the areas of cracks, especially when the moisture level exceeded 4% - 5%. Such defects led to accelerated degradation of the waterproofing system and water migration through the weakened area.

An important reference in the context of the durability of waterproofing systems were also under the observations of Maj and Ubysz [9]. The authors pointed out that the key factor leading to coating failure was the insufficient matching of material properties to the type of substrate, as well as errors in surface preparation and coating application. Although the research concerned concrete tests, the identified mechanisms of adhesion degradation also apply to systems used on ceramic brick, where the complex porosity and absorbency of the material require careful control of application parameters. The importance of the porosity of ceramic substrates for the effectiveness of waterproofing was confirmed by the research of Niu et al. [10], who analyzed the influence of coating parameters on adhesion to porous silica substrates. The authors demonstrated that effective coating of porous ceramics was achievable through appropriate control of both technological and structural parameters. These findings

can also be applied to substrates such as ceramic brick, which, due to its capillarity and roughness, requires a precisely tailored application technology [11].

The study by Souza et al. [12] analyzed the impact of the adhesion of cement mortars to ceramic substrates on the durability of facades, emphasizing the importance of moisture conditions and the quality of surface preparation. It was demonstrated that the degree of moisture and the presence of surface defects could significantly reduce the bonding strength. Similar research on the impact of moisture cycles on the behavior of waterproofing materials was conducted by Aktas et al. [13], who analyzed the effectiveness of surface-applied hydrophobic agents on brick walls. The results showed a significant improvement in hydrophobic properties and a reduction in water absorption, while maintaining water vapor permeability. This suggests that, beyond the initial moisture content of the substrate, the full cycle of water exposure (contact–absorption–drying) has a substantial impact on waterproofing effectiveness. The authors pointed out that silane-siloxane creams reduced absorbency by as much as ~96%, while maintaining relatively low vapor permeability, which makes them potentially beneficial in conditions of exposure to wind-driven rain.

Łach et al. [14] analyzed the behavior of polymer-cement mortars on concrete surfaces intended for contact with drinking water, with particular emphasis on the influence of environmental conditions and surface preparation on adhesion quality. Their findings confirmed that the effectiveness of a waterproofing system depends not only on the composition of the sealing material but, more importantly, on the condition of the substrate surface—particularly its moisture content, cleanliness, and roughness profile [15].

According to the authors' current knowledge, the research results available in scientific literature and technical documentation mainly concern the adhesion of waterproofing coatings to concrete substrates. However, there is a lack of systematic, quantitative analyses of the effect of moisture on the adhesion of coatings to ceramic substrates, even though materials such as brick are commonly used in traditional and renovation construction. For this reason, the aim of this study was to fill this research gap by assessing the bonding strength of waterproofing coatings applied to ceramic substrates with varying moisture content. Six different types of waterproofing materials were analyzed in the tests. Each material was tested at a minimum of five substrate moisture levels, which allowed for an understanding of their behavior under various moisture parameters. Bond strength was measured using the pull-off method - PN-EN 1542.

2. MATERIALS

2.1. Ceramic substrate

In the study, solid ceramic bricks were used, meeting the requirements of strength class HD and class 20 in accordance with PN-EN 771-1:2011 [15]. This material was characterised by high technical and functional properties. The average compressive strength, standardised and determined perpendicular to the bearing surface, was 20 MPa. The gross volume density of the element was determined at 1850 kg/m³.

The nominal dimensions of the brick were 250 × 120 × 65 mm, with a unit weight of 3.8 kg. The bricks were classified in Euroclass A1 in terms of reaction to fire, confirming its non-combustibility. Water absorption remained below 14%, and resistance to freeze-thaw cycles has been rated at 15 cycles. In order to assess the frost resistance of the samples, they should first be cleaned of impurities using water and a brush, taking care to avoid mechanical damage. Any damage that occurs must be recorded prior to testing and excluded from the evaluation of results. The samples are subsequently saturated with water to constant mass and placed in a freezer at –15 °C, positioned on mesh trays with a minimum

spacing of 3 cm. After 4 h of freezing, the specimens are immediately immersed in water at 12 – 25 °C (at least 1.5 dm³ of water per 1 kg of sample), ensuring complete thawing within 4 h. Following thawing, the samples are visually examined for damage and for the presence of sediment in the water, after which they are subjected to the next freezing–thawing cycle. Each thawing stage is conducted in the same water. If premature damage occurs, such as cracking, chipping, scaling or delamination, the test is terminated and both the number of completed cycles and the type of damage are documented.

During the preparation of samples for testing, a visual selection of elements was carried out. Bricks of uniform colour, with a smooth and undamaged surface, were selected for further analysis. Specimens showing cracks, chips, salt efflorescence and other surface defects were eliminated.

2.2. Waterproofing materials

The study compared six waterproofing materials classified into three main groups: mineral-based materials (*M-1*, *M-2*, *M-3*), polymer-modified bituminous coatings (*B-1*, *B-2*) and synthetic polymer coatings (*A-1*). A summary of the technical properties of these materials is presented in Table 1, based on data from the manufacturers' technical data sheets. The table includes, among other things, the chemical composition of individual products, declared mechanical properties – in particular bonding strength (expressed in MPa) and crack bridging ability (expressed in mm). For material *A-1*, the manufacturer did not specify numerical values. However, due to its declared crack-bridging ability, it is marked with the symbol “✓” in Table 1.

Another important parameter analyzed was the water vapour diffusion resistance factor (*Sd*), which value affects the material's ability to allow the building partition to dry out. Lower values indicate high vapour permeability, while higher values indicate low water vapour permeability.

In addition, the manufacturers' recommendations for the application of individual materials were taken into account, including the required substrate moisture content (determined descriptively on the basis of visual assessment), the permissible air temperature range during application, the number and thickness of layers (recorded in the format “×”, e.g. 2 × 1 mm), as well as the preferred tools for applying the coating.

In the absence of specific information in the manufacturers' technical documentation, the designation “–” has been used in the table.

Table 1. Characteristics of waterproofing materials, information obtained from technical data sheets

MATERIAL	COMPOSITION	BOND STRENGTH [MPa]	LAYER THICKNESS	TIME TO ACHIEVE IMMUNITY [days]	BRIDGING OF CRACKS [mm]	SUBSTRATE MOISTURE	VAPOUR PERMEABILITY <i>Sd</i> [m]	APPLICATION TEMPERATURE [°C]	METHOD OF APPLICATION
MINERAL-BASED WATERPROOFING									
M-1	cement, aggregates, polymers	-	2 x 1mm	7	-	<i>matt - moist</i>	-	+5 / +30	<i>brush, trowel</i>
M-2	cement, aggregates, polymers, microsilica, fibres	1.5	2 x 1.5 mm	7	0.9 - 1.25	<i>slightly moist</i>	< 5	+5 / +35	<i>trowel, spray</i>
M-3	mineralized, sulfate-resistant	-	1 x 2 - 3 mm	-	-	-	< 0.6	+5 / +30	<i>brush</i>

POLYMER-MODIFIED BITUMINOUS COATING									
B-1	bitumen, polystyrene	-	2 x 1.5 – 2 mm	-	> 2	-	-	+5 / +35	trowel
B-2	polymer modified bitumen, fibres	-	1x 3 - 4 mm	2 - 3	> 2	dry, slightly - moist	> 117	+5 / +35	trowel
SYNTHETIC POLYMER COATING									
A-1	synthetic resins	1.6	> 0.5 mm	1	✓	dry	> 5	+5 / +35	roller, brush, trowel

3. METHODOLOGY

The bond strength to the substrate was tested using the pull-off test method, in accordance with the guidelines of PN-EN 1542:2000 [18]. The measurement was performed using a specialised measuring device (pull-off tester). The procedure involved adhering a metal disc to the surface of the coating being tested using a suitable adhesive, and then gradually applying an axial force perpendicular to the surface until it breaks away. The bond force was recorded automatically and converted into a unit of area, allowing the adhesion to be expressed in units of stress – megapascals [MPa].

The advantage of this method is its high precision and the possibility of obtaining quantitative results, which makes it particularly useful in the evaluation of coatings used in conditions of increased operational requirements. The disadvantage is the need for specialised equipment and appropriate preparation of the surface and samples, which may increase the time and cost of the test [19]. The test can be carried out on various types of substrates, including concrete [20-21], wood [22] and ceramics.

3.1. Achieving the desired humidity

In order to obtain the desired moisture content of the material, the procedure began with drying the samples to a constant weight, followed by soaking in water. The drying process was carried out in a climate chamber at a temperature of $100\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$ until the weight stabilised, confirming the complete removal of free moisture. Next, the samples were weighed and the amount of water required was calculated using the formula for mass moisture content, ensuring that, after immersion, the samples reached the intended moisture level. The samples were soaked to achieve a moisture content of 1% to 12%. To prevent water evaporation, the samples were wrapped in foil after soaking. The bricks were left for 14 days, with regular turning to ensure uniform water distribution throughout the material. The mass moisture content at all stages of the test was determined by the gravimetric (laboratory) method [23-24]. The gravimetric method is a laboratory technique for measuring moisture content, which involves weighing a material sample in its natural state, then drying it to a constant mass, and weighing it again. The difference between the mass before and after drying corresponds to the mass of water contained in the sample, allowing for the determination of the mass moisture content [25].

3.2. Coating application

The application of products to prepared ceramic substrates was carried out in accordance with the technical data sheets and guidelines of the manufacturers of waterproofing materials. All application activities were carried out under controlled conditions, taking into account the requirements for substrate moisture, ambient temperature, layer thickness and the selection of application tools, including the necessary priming of the substrate.

3.3. Coating cut

Test holes were made on the surfaces of waterproofing coatings using drill bits with an internal diameter of 50 mm. A set consisting of a steel stabilising base and two types of drill bits adapted to the type of waterproofing was used to carry out the process. Core bits with a serrated working edge were used to cut rigid and flexible mineral micro-mortars, while core bits with a continuous cutting edge were used for layers in the form of liquid film coatings. In each case, all layers of waterproofing were completely cut through to the ceramic substrate.

Two holes were drilled on opposite faces of each sample, giving a total of four measuring points per brick. The holes were positioned approximately 70 mm from the side edges of the element to ensure repeatability and to minimize the influence of edge effects on the results.

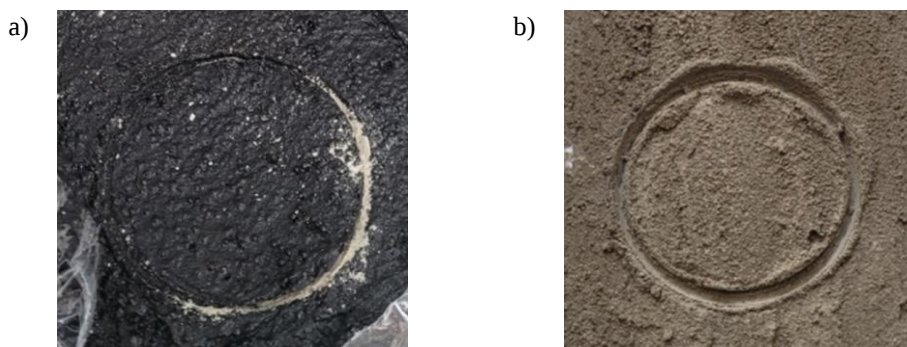


Fig. 1. a) Cut in coating B-1, b) Cut in coating M-3

3.4. Bonding steel discs

Steel measuring discs were placed on the previously prepared surfaces with incisions and glued to the insulating layer using a two-component epoxy resin with a hardener. The bonding process was carried out in laboratory conditions, following the manufacturer's recommendations regarding mixing proportions, ambient temperature and setting time. After the adhesive had hardened, which took an average of 24 hours, the actual strength test was carried out.

3.5. Bond strength test

The adhesion test was performed using a DYNATEST DTEpico 2500 device [26], capable of measuring forces up to 25 kN with an accuracy of 0.01 kN. The device meets the requirements of PN-EN 1542, has a stable tripod-based construction and a test disc mounting system with an M12 thread, which ensures axial force transfer and minimises measurement errors resulting from eccentric loading.

The steel measuring disc was fixed in the apparatus holder with a threaded screw, ensuring a rigid connection with the tensioning system. After stabilising the system and properly stiffening the measuring structure, the force meter was reset to zero. Then, using the apparatus knob, the tensile force was increased until there was a sudden drop in the readings, corresponding to the maximum bond force.

The final result, corresponding to the bond force converted to a unit of area [MPa], was read from the electronic display of the device.

The tests were carried out with a continuous, controlled increase in stress at a pull-off speed of (0.05 ± 0.01) MPa/s, in accordance with the guidelines. Maintaining a constant load rate allowed for repeatable and comparable results regardless of the type of coating tested.

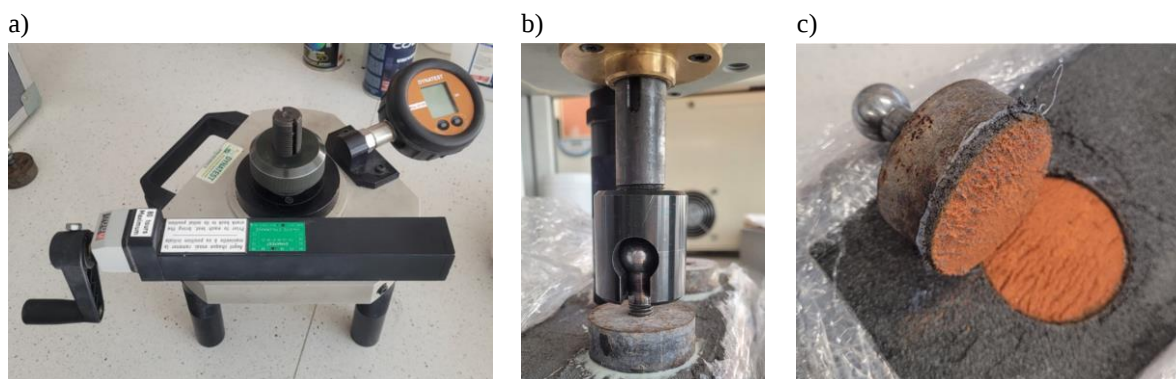


Fig. 2. a) Measuring device, b) Disc mounted in the device holder, c) Detachment of the waterproofing coating together with the material structure - after testing

3.6. Analysis of the fracture surface

During the pull-off bond strength tests, three characteristic types of damage to the waterproofing layers were observed, in accordance with the classification criteria of PN-EN 1542 [18] and observations published in [14]. Publication [27] describes five possible tear mechanisms, but the three most common ones coincide with the results obtained in this study. This convergence confirms the typical nature of damage under test conditions similar to real-life conditions.

Type I – *delamination within the insulating layer* – involves the detachment of only the first layer of the waterproofing coating, without damaging the ceramic substrate. This mechanism indicates predominant adhesive failure at the coating-air interface or cohesion within the material layer itself.

Type II – *complex detachment of the coating and partial damage to the substrate* – involves the detachment of the first layer together with fragmentary detachment of the ceramic surface. This type of damage indicates high adhesion, but varying quality of adhesion within the surface zone.

Type III – *damage to the ceramic substrate* – involves complete detachment of the waterproofing layer with destruction of the brick structure. This type of damage is considered a desirable result of the adhesion test, as it indicates that the adhesive strength of the coating exceeds the cohesive strength of the substrate.

In Fig. 3 representative examples of each of described damage mechanisms is presented. Observation of the location and nature of the damage provided valuable information on the quality of the bond between the protective layer and the substrate, as well as the effectiveness of the waterproofing system.

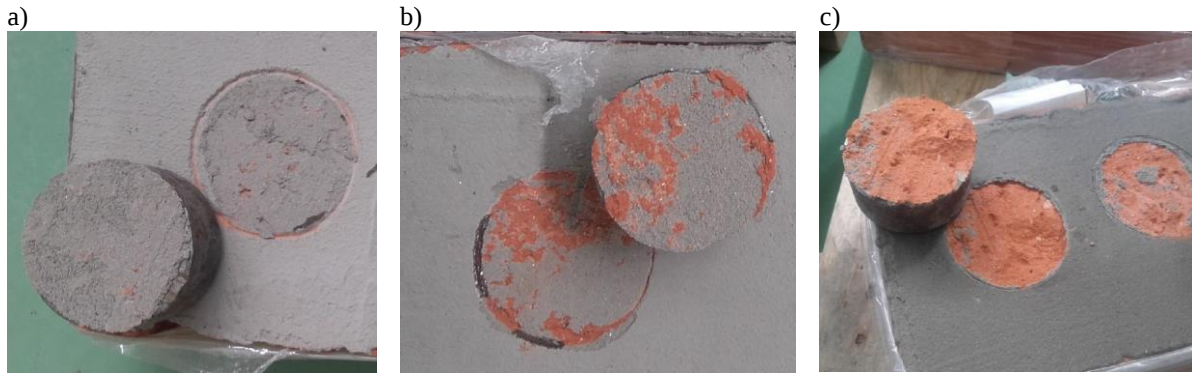


Fig. 3. Types of damage: a) first type, b) second type, a) third type

4. RESULTS

Each time, the bond strength tests were carried out on at least six independent samples for each material variant and substrate moisture content range, which ensured an adequate level of representativeness and statistical reliability of the results obtained. Table 2 summarises the average bond strength values for individual waterproofing materials obtained in specific ranges of ceramic substrate moisture content: 0% - 2%, 3% - 4%, 5% - 6%, 7% - 8%, 9% - 10% and 11% - 12%. For three of the analyzed products (*M-2*, *B-2*, *A-1*), tests were carried out in the full range of six moisture content ranges. For the remaining three materials (*M-1*, *M-3*, *B-1*), the tests were limited to five ranges due to technological limitations or the characteristics of the material.

The only relevant information regarding the bond strength of waterproofing coatings in domestic literature was found in the PN-EN 14891 [28] According to this standard, the minimum adhesion value for waterproofing coatings applied beneath ceramic coverings is 0.5 MPa. Unfortunately, this value applies solely to under-tile waterproofing systems. A similar situation occurs in the case of ETAG 022 [29] and ETAG 033 [30] documents, as well as the current EAD 030352-00-0503 [31] and EAD 030350-00-0402 [32], where the need for testing is indicated but no specific minimum bond strength values are provided. This implies that the only reliable sources of reference are the guidelines used in practice or the requirements specified by manufacturers.

Table 2. The effect of ceramic brick moisture content on bond strength depending on substrate moisture content. The results show average values from the measurements taken

BOND STRENGTH [MPa] – (AVERAGE VALUES)							
WATERPROOF		SUBSTRATE HUMIDITY [%]					
TYPE	MATERIAL	0% – 2%	3% – 4%	5% – 6%	7% – 8%	9% – 10%	11% – 12%
MINERAL-BASED WATERPROOFING	<i>M-1</i>	1.72 MPa		0.58 MPa	0.51 MPa	0.47 MPa	0.41 MPa
	<i>M-2</i>	0.87 MPa	0.66 MPa	0.62 MPa	0.45 MPa	0.41 MPa	0.30 MPa
	<i>M-3</i>		1.27 MPa	1.12 MPa	0.97 MPa	0.96 MPa	0.73 MPa

POLYMER-MODIFIED BITUMINOUS COATING	B-1		0.67 MPa	0.67 MPa	0.75 MPa	0.71 MPa	0.60 MPa
	B-2	0.81 MPa	0.61 MPa	0.53 MPa	0.50 MPa	0.33 MPa	0.10 MPa
SYNTHETIC POLYMER COATING	A-1	1.18 MPa	0.81 MPa	0.53 MPa	0.35 MPa	0.15 MPa	0.09 MPa

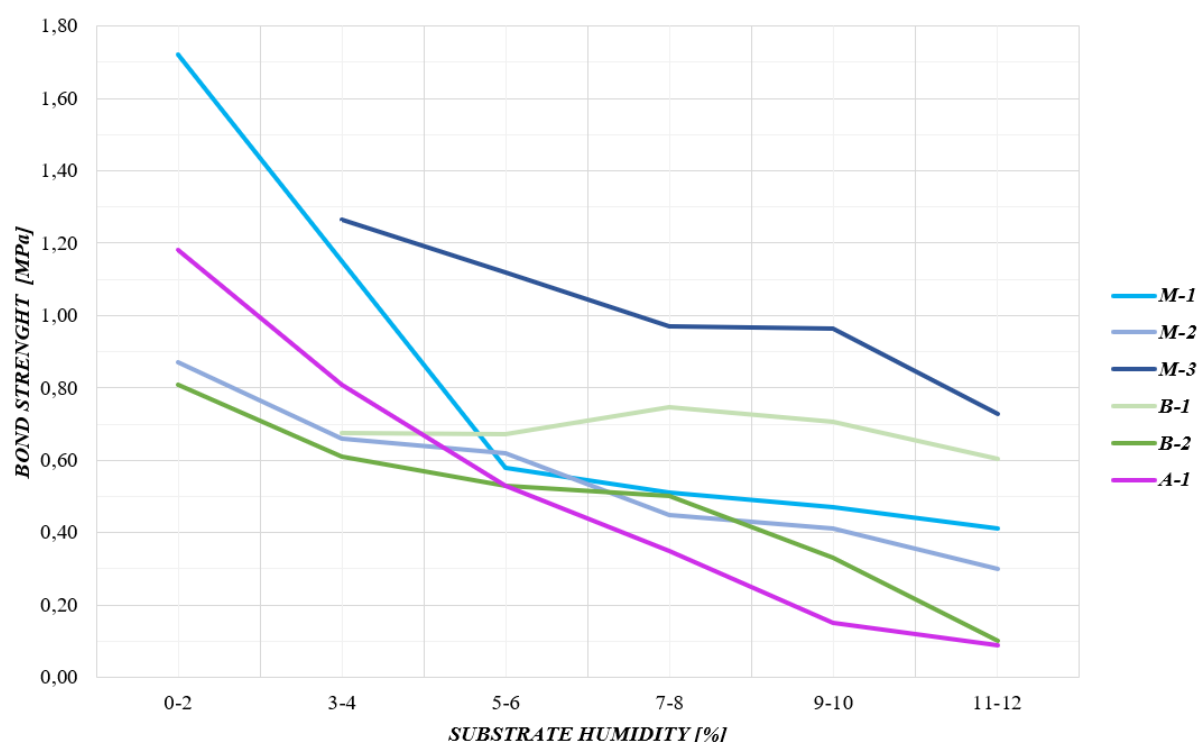


Fig. 4. Diagram showing the effect of ceramic substrate moisture on the adhesion of waterproofing

The results presented in Fig. 4 clearly indicated a significant influence of the moisture content of the ceramic substrate on the bond strength of the tested waterproofing coatings. For all analyzed materials, a decrease in adhesion was observed with increasing moisture content in the substrate.

The highest adhesion value was obtained for material *M-1* (mineral waterproofing) in the moisture range of 0% – 2% 1.72 MPa, which indicated very good bonding in dry conditions. However, this material showed a significant decrease in strength with increased moisture content – to 0.41 MPa at 11% – 12% moisture content. Materials *M-2* and *M-3* showed a similar trend, although their initial values were lower. In the case of both mineral-based waterproofing coatings (*M-1* and *M-2*), tested at substrate moisture levels of 0% – 2%, the highest bond strength values were obtained. These results should be considered controversial, as both the technical literature and manufacturers' data sheets recommend moistening the substrate in order to achieve higher adhesion values and to reduce the risk of cracking and delamination of the coating. In the authors' opinion, the results indicate the need for further, in-depth research on this type of substrate.

Among bituminous coatings, material *B-2* achieved the highest adhesion values in the low humidity range (0.81 MPa), but its decline in subsequent ranges was more linear, without sudden drops.

The synthetic material *A-1* (*synthetic resin coating*) showed the greatest susceptibility to moisture increase. Its strength decreased from 1.18 MPa at 0% – 2% to only 0.16 MPa at 11% – 12% humidity, making it the least resistant to substrate moisture of all the materials tested.

For relatively low substrate moisture content (up to 4%), only three of the six materials: *M-1*, *M-3* and *A-1* – achieved values exceeding the 1 MPa threshold, which indicated their potential suitability for use in more demanding conditions. With increasing substrate moisture content (above 5% – 6%), a systematic decrease in bond strength was observed in all tested cases. At the highest moisture content analyzed (11% – 12%), only two materials: *M-3* and *B-1* maintained adhesion at a level of at least 0.5 MPa, indicating their greater resistance to moisture during application. These conclusions are consistent with the results of Aktas study, which showed that excessive initial moisture content of the ceramic substrate can significantly reduce the adhesion of traditional bituminous and cement-polymer coatings.

When comparing the obtained results with the values declared by the manufacturers (available only for two materials), significant discrepancies were found. Materials *M-2* and *A-1* did not achieve the declared bond strength in any of the analyzed moisture ranges.

In [33], the authors conducted research on the adhesion of mineral waterproofing mortars to cement substrates exposed to changing climatic conditions, including freeze-thaw cycles and varying moisture levels. Pull-off tests were also performed in accordance with PN-EN 1542 to quantitatively assess the adhesive strength. The study showed that both the type of mortar and the environmental conditions had a significant influence on the adhesion obtained, with the lowest values recorded after exposure of the samples to cyclic freezing conditions and high initial humidity. These results confirmed that factors related to substrate moisture can significantly reduce the effectiveness of waterproofing systems. Although the study focused on concrete, its conclusions can serve as a reference point for analyses conducted on ceramic substrates.

The obtained results are consistent with the data presented in the study by Maranhão et al. [34], which investigated the effect of progressive moisture absorption on the bond strength of polymer-modified adhesive mortars. The authors demonstrated that once the moisture content reached 5%, the bond strength decreased by approximately 50%, and at a moisture content above 10%, this value decreased by more than 75%, reaching levels below 0.60 MPa. Importantly, in both cases, waterproofing systems were highly sensitive to moisture increase, regardless of the mortar composition or declared technical parameters. These observations highlight the need to limit substrate moisture during application and to consciously select materials with proven resistance to degradation in conditions of increased moisture.

Moreover, four of the six technical data sheets analyzed contained information on the recommended substrate moisture content for waterproofing. However, this information was not presented in the form of specific numerical values, but in the form of general terms such as: *matt-moist*, *slightly moist* and *dry*. In the authors' opinion, the lack of clear, measurable moisture values may affect the quality and durability of the waterproofing, as the interpretation of these descriptions may vary depending on the person performing the work and the environmental conditions.

5. STATISTICAL ANALYSIS

Automatic neural networks were used to statistically analyse the research results. Bond strength [MPa] was designated as the dependent variable, while the independent variables were the type of material and the moisture content of the substrate. The material type and substrate moisture content were assigned the following numerical codes, which were used in the regression equations and neural network calculations.

Table 3. Numerical codes set for materials and moisture range

text label	numerical
M-1	101
M-2	102
M-3	103
B-1	104
B2	105
B-2	106
B-3	107
A-1	108

text label	numerical
0-2	101
3-4	102
5-6	103
7-8	104
9-10	105
11-12	106

Repeating codes were used due to the property of neural networks, which automatically recognised the variable with the higher code as more important. In the generated regression equations, the codes should be entered according to the names of the independent variables.

As a result of the calculations, an *MLP 7-7-1* neural network with the following parameters was obtained:

Table 4. Neural network parameters

Index	Net. name	Training perf.	Test. perf.	Validation perf.	Training error	Test error
1	<i>MLP 7-7-1</i>	0.998436	0.994843	0.989110	0.000180	0.000527

Validation error	Training algorithm	Error function	Hidden activation	Output activation
0,004460	BFGS 122	SOS	Tanh	Identity

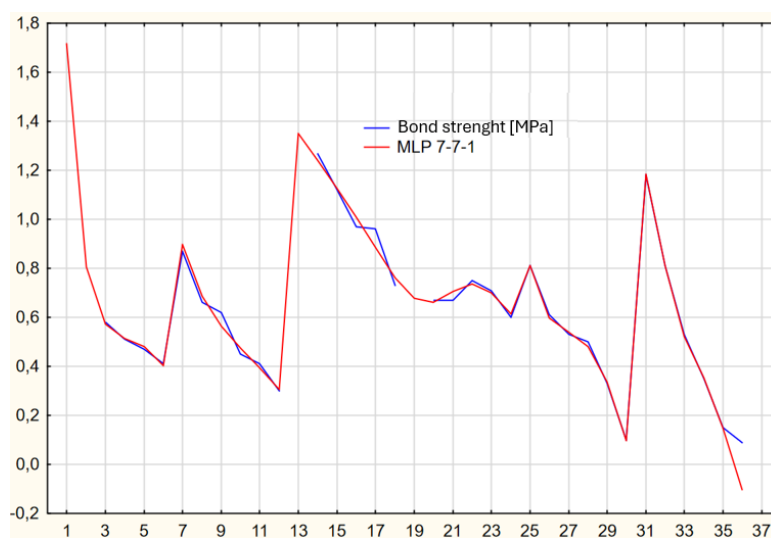


Fig. 5. Graph of input data and data generated by *MLP 7-7-1* neural network

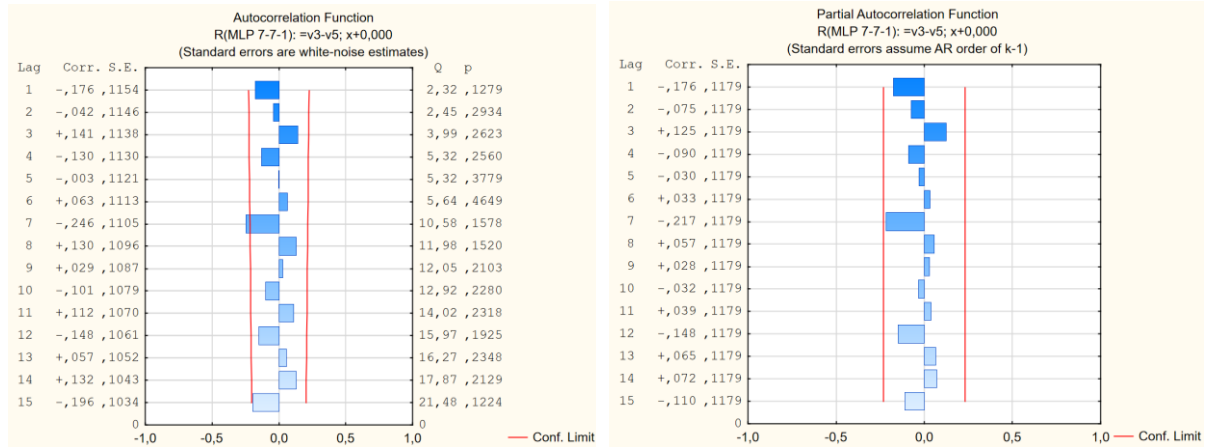


Fig. 6. Graphs of autocorrelation functions

The correctness of the generated neural network was confirmed by the absence of autocorrelation and partial autocorrelation of residuals – the residual series is white noise.

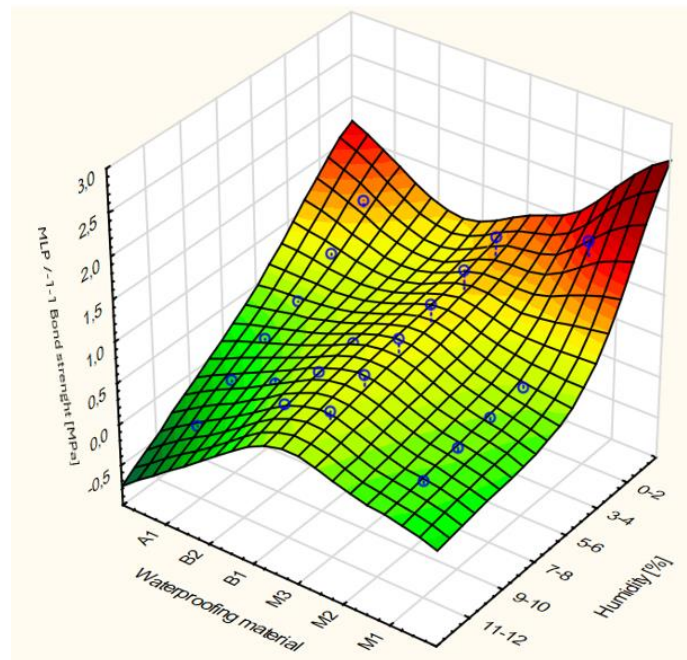
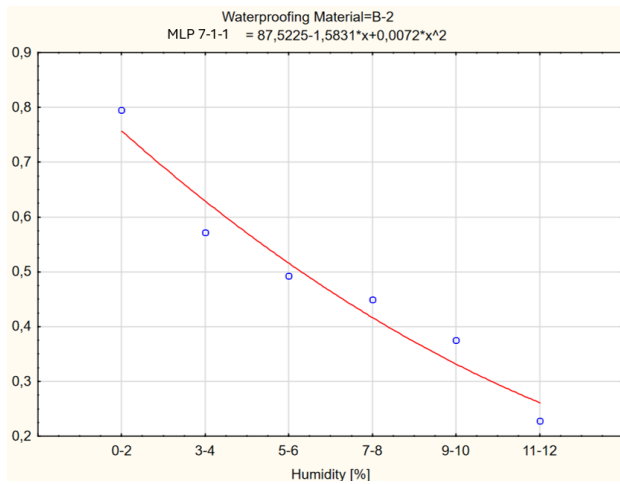


Fig. 7. Autocorrelation function diagrams 3D diagram of the relationship of *MLP 7-7-1* Bond strength [MPa] material type and substrate moisture content

The Fig. 7 emphasize significant differences resulting from the properties of the substrate. For this reason, regression equations were generated for each substrate separately. The results are summarized in the Table 5.

Table 5. Regression equations in relation to substrates and an example graph for material B-2

SUBSTRATE	REGRESSION EQUATIONS, $x = \text{moisture interval code}$	 Waterproofing Material=B-2 MLP 7-1-1 = $87,5225 - 1,5831 \cdot x + 0,0072 \cdot x^2$
M1	$828,7208 - 15,7434 \cdot x + 0,0748 \cdot x^2$	
M2	$112,4388 - 2,074 \cdot x + 0,0096 \cdot x^2$	
M3	$278,20995 - 2,248 \cdot x + 0,0246 \cdot x^2$	
B1	$-84,953 + 1,6976 \cdot x - 0,0084 \cdot x^2$	
B2	$87,5225 - 1,5831 \cdot x + 0,0072 \cdot x^2$	
A1	$422,609 - 795 \cdot x + 0,0374 \cdot x^2$	

The statistical analysis showed that it is possible to predict the bond strength of waterproofing coatings from a regression equation generated in the form of an *MLP 7-7-1* neural network with independent variables of substrate type and moisture content. The prediction error was 1.8%, classifies the forecast as very good. As an alternative forecasting approach, multiple regression analysis was applied. The test results were analyzed separately for each substrate, with substrate moisture adopted as the independent variable. The regression equations presented in Table 5 are characterized by a prediction error of less than 5%, which indicates a good forecast. It is therefore proposed to adopt the automatic neural network method for prediction, as it provides a lower prediction error compared to multiple regression.

6. CONCLUSIONS

The effect of ceramic substrate moisture on the adhesion of waterproofing coatings has been determined. Detailed conclusions:

- Only two (*M-2*, *A-1*) out of six technical data sheets specified requirements for the bond strength of waterproofing coatings. The authors find the lack of requirements for other materials missing, as bond strength is one of the basic parameters.
- None of the two products, for which a minimum bond strength was specified in the technical data sheet, achieved the value declared by the manufacturer.
- According to the PN-EN 14891 standard, the minimum bonding strength requirements for waterproofing coatings is 0.5 MPa. All products met the minimum value. In the case of three out of six materials, values above 1 MPa were achieved for relatively low substrate moisture content.
- For the mineral-based waterproofing systems (*M-1* and *M-2*), the highest bond strength values were obtained at the lowest substrate moisture level. These results are controversial, therefore, in the authors' opinion, further in-depth research on this type of substrate is necessary.

- Lack of precise values for substrate moisture content under waterproofing in manufacturers' technical data sheets.
- All tested waterproofing coatings showed a general tendency for the bonding strength to decrease with increasing substrate moisture content. The highest adhesion values were observed at low moisture levels of 0% - 2%, and the lowest in the range of 11% - 12%.
- The mineral sealing slurry with high sulphate resistance *M-3* exhibited by far the best strength parameters (bond strength). At low and medium moisture levels, the bond strength was clearly above 1 MPa. At higher substrate humidity levels (7% - 12%), the value decreased but remained well above 0.5 MPa.
- In the case of two products: two-component bituminous coatings *B-2* and liquid foil *A-1*, a very clear decrease in bonding strength was observed at high humidity levels. In both cases, at humidity levels above 8%, the strength values obtained were clearly below the requirements specified in the technical data sheets and standards.
- Based on the analysis of the data, it was found that for all the coatings tested, the moisture limit value ensuring sufficient bonding strength was in the range of 5% - 6%.

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