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Repair Composite Adhesion Strength: A Comparison of Testing Methods

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Abstract: The adhesive strength of repair composites to concrete substrates was assessed through both Ukrainian and European standard test methods. The types of adhesion loss observed included adhesive failure along the contact layer (AF-S), and cohesion failure along the substrate (CF-S). The Ukrainian method showed adhesive bond loss in 90.5% of samples (181 out of 200), while the European method showed loss in 76% (152 out of 200). However, under identical conditions, the EU standard showed greater consistency (standard deviation 0.25) than the Ukrainian standard (standard deviation 0.42 and 0.32). The effect of pull-off techniques on failure models varied depending on the epoxy thickness and the mechanical testing performed. Repair composites meeting the highest Ukrainian structural class criteria (PM1) were classified as R3 materials according to the European standard. This research highlights that statistical analysis shows a significant improvement in reliability with an increased number of pull-off tests.

Keywords: adhesion strength; repair system; concrete; standards

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1. Introduction

In recent years, the use of multi-component cementitious mixes has expanded significantly in various applications. These composites are extensively used to reinforce or repair existing structures and to build new components. A significant amount of Europe's annual construction budget is allocated to the refurbishment and maintenance of existing structures, and this amount is expected to rise as the number of concrete structures continues to grow. For example, the estimated annual cost for maintaining and repairing bridges in Europe ranges between EUR 4 and 6 billion. Replacing these bridges, however, would be an even more substantial expense, exceeding EUR 400 billion [1,2]. According to [3], 50% of the repaired structures exhibit a durability of less than 10 years, which is significantly lower than the anticipated 25-year lifespan. There are some factors that can affect the success of a repair system, such as material choice, construction techniques, or a combination of these factors [4–7]. To achieve monolithic behavior, multi-layered concrete requires sufficient interfacial bond strength to ensure effective load transfer between all concrete components. Structural restoration should not be seen only as a simply technical task of applying a repair mixture to damaged sections. Instead, it is a multifaceted process that encompasses the inspecting and diagnosing of the structures, identification of the root causes of damage, planning the repair work, and selection of suitable materials, systems, and technologies [8]. Although applying repairing mixes shows promise as a method for structural rehabilitation, careful consideration of both early-age performance and long-term durability is necessary. A strong bond at the interface between the repaired substrate (damaged surface), primer composition (contact layer), and new repair composite is crucial for ensuring effective load transfer and the activation of repair materials in existing structures. The thickness of a repair overlay varies depending on the removed damaged subsurface layer and can reach several centimeters. Interlayer bonding between the materials is crucial for the element's long-term durability, as the contact layer is typically the weakest point [9]. This interface layer between zones can be subjected to various types of stresses throughout the operational life of the repaired construction, including stresses caused by restrained drying shrinkage [10,11]. Furthermore, material discontinuity, high porosity, and presence of micro-cracks make the interface between concrete components a critical zone within the composite [11]. As mentioned [12], the interface zone can contain hydration products of cement with larger crystals of $Ca(OH)_2$, resulting in lower bond strength; however, this microstructure has a dual effect. The filling of pores by hydration products in the old concrete substrate creates mechanical interlocking, enhancing bond strength compared to the epoxy-to-concrete interface. Each layer's properties, directly related to its composition, are crucial for the repair system's compatibility. Bond strength at the interface is largely influenced by the properties of the repair material itself. Moisture and hydrated products from the repair medium penetrate the dry substrate, forming a strong shear bond between the old and new materials [13,14]. This "adhesive" mechanism depends on both mechanical anchorage between the new material and old substrate and chemical adhesion forces. Nevertheless, the specific stresses generated at these interfaces and the effectiveness of cement paste as an adhesive have not been fully explored. Adequate adhesion is crucial for maximizing the durability of the repaired system; at the repair joint, it facilitates load transfer and ensures uniform stress distribution [15]. Sufficient adhesion ensures the maximum ability of the repaired system to absorb the workload [16]. The repair system is effective if it provides load transfer and ensures uniform distribution of stresses in the element [17]. Therefore, great attention needs to be paid to the determination of the adhesion strength of the repair composite to the concrete base when developing repair systems.

As noted [15,18], the connection between the repair material and the concrete substrate can weaken and eventually fail due to various stresses (Figure 1).

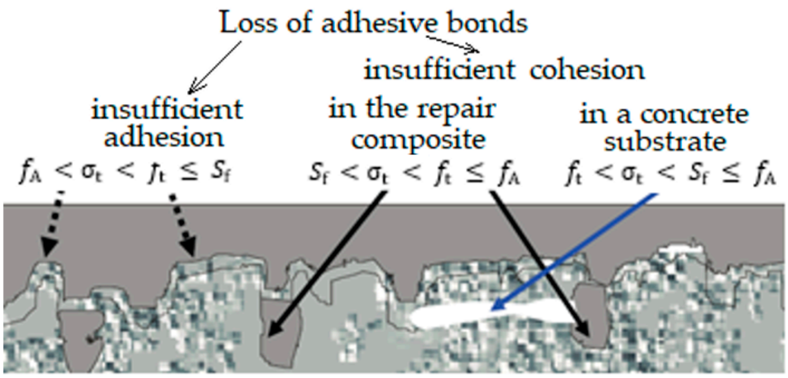


Figure 1. Types of adhesive bond loss: σ_t–internal shrinkage stress; S_f —tensile strength of the repair material; f_t—tensile strength of the concrete substrate; f_A—adhesive strength.

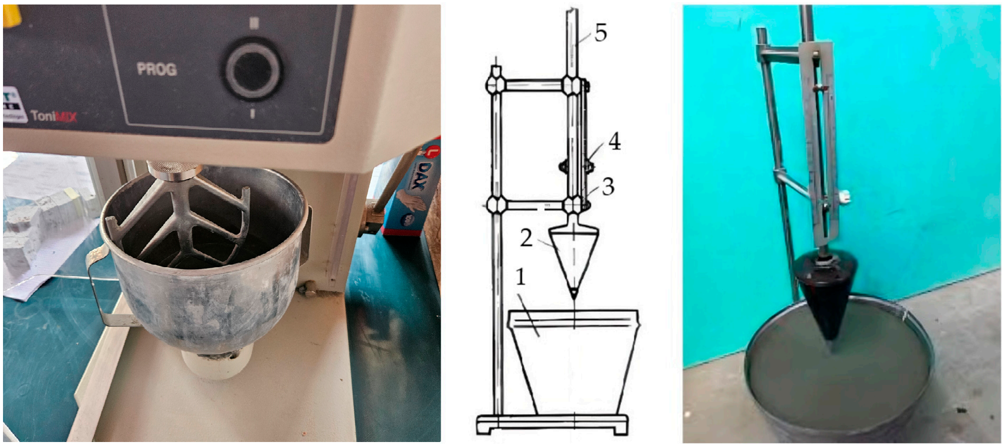
The variability of bond test results, depending on the adhesive bond failure mode [19–21], combined with the existence of multiple measurement approaches [22], poses a significant challenge for data comparison. The testing method significantly influences the measured bond strength, as demonstrated in [22]. Manufacturers' reported values may significantly overestimate actual strength depending on the method used. Consequently, a comparative analysis of various bond strength measurement methods is essential to establish the range of values obtained by each method [23]. The Ukrainian standard [24] determines adhesive strength by measuring the pull-off force using a Pull-Off Adhesion Tester on metal pullers attached to ceramic tiles, bonded to concrete mock-ups with a repair mortar. The European regulatory standards [25,26] define adhesion as the separation force measured similarly, but using metal pullers on circular dollies cut from the repair composite. The circular dollies used in the assessment are fabricated by cutting sections from a continuous layer of repair composite applied to a concrete substrate. It is important to note that the existing Ukrainian [24] and European [26] standards do not account for all relevant structural parameters beyond the scope of general recommendations. Consequently, this study aims to conduct a comprehensive evaluation of the adhesion strength of repair composites to concrete substrates and to assess the reproducibility of results when employing the measurement methods specified in the Ukrainian [24] and European [26] standards.

2. Materials and Methods

Repair composite samples were prepared using European cement PC–I 500 as a binder, while quartz sand with a 0.63 fraction served as the fine aggregate. The rheological properties of the solutions were controlled by incorporating water-redispersible vinyl acetate/ethylene copolymer powder DA 1400 VA–E RDP (Dairen, China) at 2% by mass of the mixture. Admixtures of SAP copolymer of anionic polyacrylamide and potassium acrylate (Sika, Aquagel, Denver, CO, USA) 0.2% by weight of the mixture and 0.5% of pure sodium aluminate $NaAlO_2$ (Density 2.602 g/cm^3 Melting point 1650 °C) were used to correct the consistency and hardening time, Figure 2.

Figure 2. Raw materials of the experiment.

Cement, quartz sand, and additives were placed in the mechanical mixer bowl and slowly mixed to create a homogeneous composition. Water was then added to the bowl and mixing continued until all ingredients were fully combined, Figure 3a. The quantity of water required to achieve the target working consistency was determined following the procedure outlined in [26]. This consistency was maintained across all solutions using a cone penetration test. The average immersion depth, which is the difference between the initial and one-minute readings (with an error of up to 1 mm), was averaged over two tests and rounded to the nearest centimeter to determine the mixture's mobility grade, as shown in Figure 3. Water was added to achieve a 7 cm cone immersion depth, as specified in DSTU B B.2.7-23 [27].



(**a**) (**b**)

Figure 3. Use of mechanical mixer for (**a**) mixing process and (**b**) determining the consistency by cone device: 1—bowl with mortar; 2—reference cone; 3—lock screw; 4—scale; 5—holders.

The adhesive strength indicators for all studied compositions of cement samples were determined using the DYNA Z16 apparatus (Proceq SA, Schwerzenbach, Switzerland) (Figure 4) in accordance with [24,28,29]. The load was applied to the metal puller with an increase in the rate of load application of 250 ± 50 N/s.

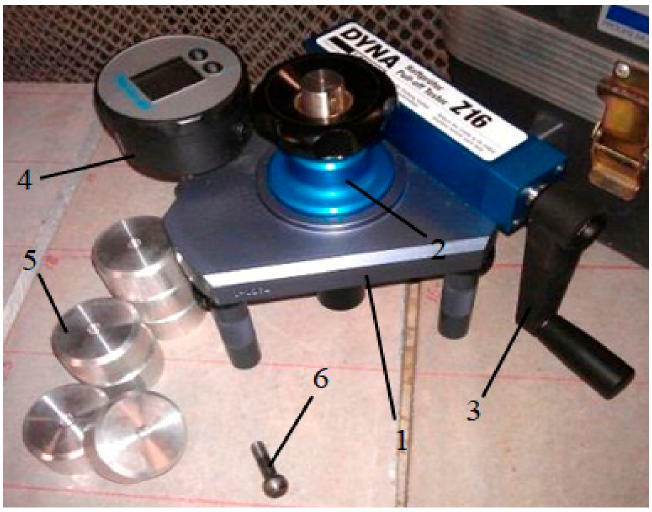


Figure 4. Pull–Off tester DYNA Z16: 1—canvas; 2—retainer; 3—load supply; 4—manometer; 5—a test steel dollies, Ø50 mm; 6—draw bolt, M8.

Reference concrete slabs of size 450 × 450 × 45 mm, manufactured following the requirements of the standard [30], were used as a concrete substrate; composition specification and properties are given in Tables 1 and 2.

Table 1. Composition of concrete slabs.

Component	Specifications
Binding	Portland cement type PC II/A–S–400
Aggregate	gravel sand, particle size 0–8 mm, continuous curve of granulometric composition A-B
Binder/aggregate mass ratio	1:5
W/C ratio	0.5

Table 2. Properties of reference concrete slabs.

Properties	Specifications
Consolidation	90 s on a vibrating table at 50 Hz
Endurance	24 h under normal conditions
Water absorption	on the surface 2.0–8.0 cm^3 after 4 h

In accordance with [25], a primer based on a dispersion of synthetic resins and Ceresit CT 19 fillers was used as a contact layer.

To evaluate adhesion parameters according to [24], repair composite strips (maximum thickness 10 mm) were applied to pre-prepared concrete slabs using a 6 × 6 mm square-toothed spatula. Ceramic tiles were then glued to the composite according to [30], and then the dollies of the pull-off tester were placed on the tiles.

For adhesion testing, Ø50 mm diameter × 10 mm thick repair composite specimens were prepared as per EN 1542:1999 [25]. These specimens were cored from a continuous layer applied to concrete slabs [30] (Figure 5). Pull-off tester dollies were then attached to the hardened specimens using a two-component epoxy adhesive [25].

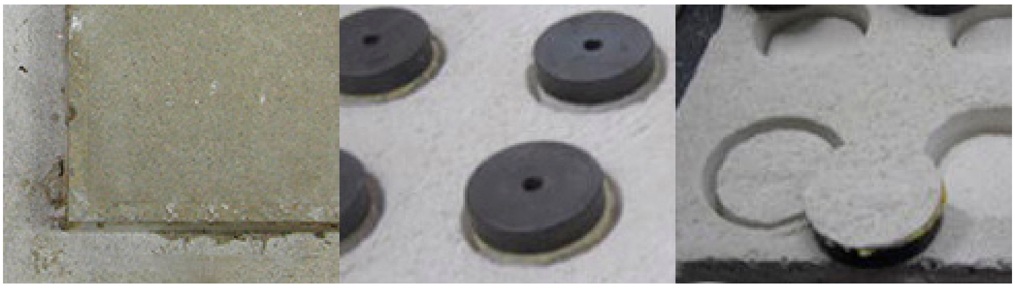


Figure 5. Reference concrete slabs prepared for pull-off testing with applied repair composite and cut-out specimens.

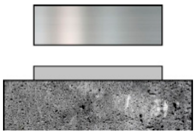
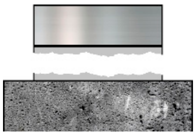
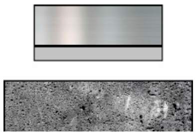
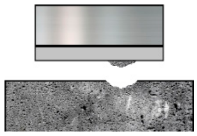
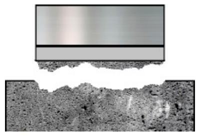
The most reliable data on the quality of adhesion of repair composites to concrete slabs were obtained by considering only the results of AF-S and CF-S types of adhesive bond loss in both cases (Table 3). The selection of AF-S (adhesive failure along the contact layer) and CF-S (cohesion failure along the substrate) failure types for analysis prioritizes the most critical aspects influencing the long-term durability and performance of the repair system. AF-S failure directly indicates problems with the interface bond between the repair composite and the substrate, while CF-S failure highlights weaknesses in the repair material's internal cohesion. These failure modes are thus considered the most relevant indicators of overall system performance, providing more reliable data for evaluating the effectiveness of repair strategies than other less critical failure modes. For each of the two adhesion testing methods of repair composites to the surface of concrete slabs, 20 samples were made for each of 10 reference slabs. To obtain statistically robust results for comparison, a total of 150 samples per adhesion testing method were selected for analysis. These samples were chosen from an initial set of 200 samples (20 samples per slab, across 10 slabs) after careful inspection to eliminate any showing defects or signs of improper application that could affect adhesion strength.

The indicator of the value of adhesion between the repair composites and the surface of the reference plates f_A (MPa) was determined as follows:

$$f_A = P_n / F \quad (1)$$

where P_n—pull-off force (failure load, N); F—the contact area of the test specimens with the surface of the dolly (mm^2).

Table 3. Types of adhesion loss [16].

Type	**I**	**II**	**III**	**IV**	**V**
Marking	AF-A	CF-RC	AF-S	CF-S	
Scheme					
Fixation					
The nature of the loss of adhesion	failure of adhesive contact	weak cohesion of the repair composite	failure along the contact layer	partially weak cohesion of the concrete substrate	weak cohesion of the concrete substrate

Note: AF—adhesive failure; CF—cohesion failure; A—adhesive; RC—repair composite; S—substrate.

3. Results

In Table 4 are the results, including the adhesion strength of repair composites with reference plates as per the method described in [24], and the average adhesion index values. It should be noted that out of the initial 200 samples of the researched repair composites, 181 samples (90.5%) showed a loss of adhesive bond with reference plates of the AF-S and CF-S type. In general, samples achieved a relatively high bond strength.

Table 4. The results of the adhesion measurement range from the minimum to the maximum value according to [24].

		Number of Experimental Plate									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Adhesion strength, R_A, MPa	1	1.231	1.966	1.338	0.785	1.689	1.946	1.934	0.594	1.969	0.977
	2	1.607	2.029	1.928	1.966	2.213	1.991	1.982	2.001	2.063	2.025
	3	2.067	2.043	2.023	1.976	2.271	2.040	1.987	2.074	2.111	2.059
	4	2.102	2.078	2.109	1.978	2.307	2.148	2.187	2.160	2.114	2.122
	5	2.300	2.126	2.124	2.165	2.364	2.256	2.371	2.207	2.246	2.139
	6	2.365	2.137	2.151	2.287	2.389	2.318	2.389	2.286	2.431	2.153
	7	2.397	2.211	2.294	2.293	2.418	2.339	2.400	2.328	2.485	2.319
	8	2.431	2.271	2.422	2.438	2.505	2.384	2.520	2.506	2.548	2.359
	9	2.454	2.292	2.494	2.572	2.515	2.422	2.644	2.517	2.593	2.378
	10	2.559	2.710	2.660	2.730	2.653	2.473	2.699	2.538	2.628	2.397
	11	2.762	2.740	2.690	2.835	2.682	2.478	2.895	2.643	2.746	2.497
	12	2.838	2.755	2.827	2.845	2.815	2.490	2.926	2.745	2.755	2.676
	13	2.840	2.813	2.836	2.903	2.819	2.785	2.940	2.868	2.765	2.776
	14	2.905	2.960	2.963	2.925	2.959	2.791	2.959	2.950	2.806	2.867
	15	2.913	2.962	2.971	2.958	2.963	2.856	2.981	2.977	2.858	2.896
Mean bond strength, $\overline{R_A}$		2.385	2.406	2.389	2.377	2.504	2.381	2.521	2.36	2.475	2.309
σ		0.467	0.356	0.440	0.553	0.321	0.273	0.367	0.559	0.292	0.452

Marked in gray in the table are the samples that displayed deviations from the average adhesion index of 30% or more.

The analysis reveals a significant range (nearly 5 times) in adhesion strength values, ranging from a minimum of 0.594 MPa to a maximum of 2.963 MPa, suggesting the influence of various factors such as material quality, application technique, and environmental conditions on the bonding process of repair composites. Moreover, it commonly happens that the close spacing of pull-off adhesion samples can weaken the nearest areas, causing a wide range of adhesion values due to localized damage from testing forces. Significant variations in adhesion were also observed by the authors [31]. Ramos and colleagues emphasize that the acceptable coefficient of variation (COV) for adhesion is not universally defined; however, a COV of 40% is suggested to be acceptable, provided there are at least five valid pull-off tests. It is important to establish an upper limit for each application, ideally determined by the manufacturers.

After calculating the average adhesion strength for each plate, the deviation in individual measurements from these average values was determined:

$$\sigma_{\overline{R}_A} = \sqrt{\frac{\sum(X_i - \overline{X^2})}{n-1}} \quad (2)$$

where X_i represents each individual mean adhesion strength, $\overline{X}$ is the sample mean adhesion strength, n = 10 is the sample number.

According to the data, the dispersion of the average values of adhesion on all reference plates is 0.00456, which indicates the high repeatability of the results of the measurement method. The number of samples that showed deviations from the average adhesion index (2.411 MPa) by 30% or more was 71 units from 200; the values are marked in gray in the table. Taking into account the requirements for the adhesive strength index according to the Ukrainian standard [24], the distribution of the received classes for mixtures used in the repair of concrete and mortar surfaces, as well as for mortar mixtures and the mortars based on them is as follows: PM1—132 samples (88%), PM2—132 samples (88%), and PM3—148 samples (98.6%).

As shown in Figure 6, the standard deviation values across the specimens range from approximately 0.25 to 0.55. Notably, specimens on plates 4 and 8 exhibit higher deviations, both around 0.55, indicating significant variability in bond strength for these samples. In contrast, plates 6 and 9 show the lowest deviations, around 0.25, suggesting a more consistent bond quality for these 30 samples.

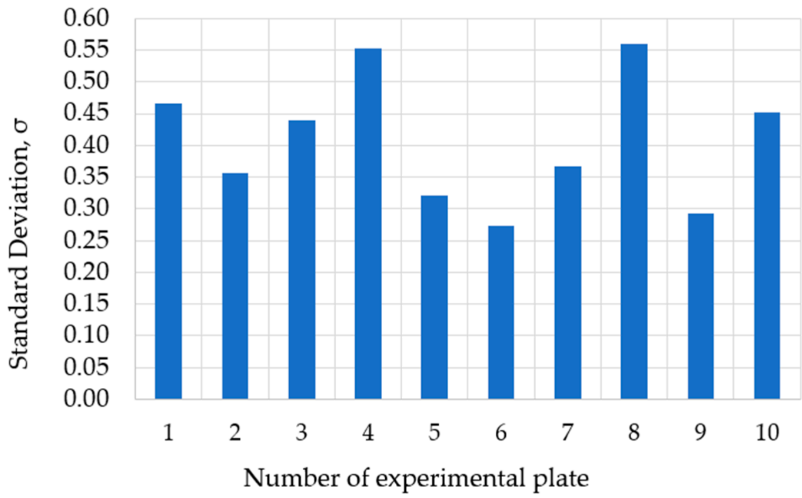


Figure 6. Relations between the calculated deviation and the experimental concrete plates made according to the Ukrainian standard.

The results of measuring the bond strength values of repair composites with reference plates according to the European regulatory method [25] and the average values of the adhesion index are shown in Table 5. Contrary to the data reported for the method in [24], the results obtained by [25] revealed that 152 out of the initial 200 repair composite samples (76%) exhibited a loss of adhesive bond consistent with AF-S and CF-S type reference plates.

Table 5. The results of the adhesion measurement range from the minimum to the maximum value according to [25].

		Number of Experimental Plate									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Adhesion strength, R_A, MPa	1	1.657	1.727	0.561	0.270	1.565	0.124	0.370	0.742	1.547	1.582
	2	1.675	1.765	1.050	1.552	1.636	0.862	1.590	1.528	1.563	1.591
	3	1.835	1.785	1.595	1.600	1.657	1.238	1.664	1.542	1.646	1.620
	4	1.985	1.806	1.627	1.675	1.789	1.419	1.843	1.845	1.765	1.665
	5	1.994	1.842	1.745	1.709	1.818	1.621	1.855	1.886	1.886	1.729
	6	2.034	1.909	1.838	1.931	1.967	1.625	1.984	1.938	1.936	1.862
	7	2.050	2.146	1.889	2.005	1.981	1.627	2.126	1.960	2.071	2.021
	8	2.068	2.242	1.931	2.038	2.134	1.637	2.132	1.975	2.129	2.030
	9	2.163	2.289	1.947	2.185	2.244	1.639	2.132	2.037	2.265	2.196
	10	2.194	2.315	2.063	2.217	2.336	1.801	2.138	2.059	2.269	2.199
	11	2.214	2.356	2.183	2.259	2.440	1.930	2.188	2.121	2.310	2.224
	12	2.391	2.428	2.247	2.393	2.530	2.083	2.237	2.204	2.340	2.292
	13	2.413	2.445	2.335	2.424	2.538	2.207	2.369	2.422	2.344	2.504
	14	2.504	2.464	2.365	2.536	2.539	2.223	2.581	2.453	2.410	2.544
	15	2.555	2.484	2.558	2.563	2.554	2.413	2.587	2.530	2.574	2.562
Mean bond strength $\overline{R_A}$		2.116	2.134	1.862	1.957	2.115	1.63	1.986	1.949	2.07	2.042
σ		0.265	0.283	0.501	0.554	0.353	0.558	0.514	0.428	0.317	0.341

Marked in gray in the table are the samples that displayed deviations from the average adhesion index of 30% or more.

The adhesion strength data demonstrate a considerable spread, with values ranging from a low of 0.124 MPa to a high of 2.558 MPa—a difference of over 20 times. These findings differ from previous studies made using the standard methods [24], which showed a smaller range spread of adhesion strength values.

The variance in the average adhesion values for all reference plates of 0.0233 is 5.1 times higher than this indicator in the method described in the Ukrainian standard [24]. Nevertheless, low dispersion means the adhesion values are consistently close to the mean, which suggests uniform data quality, and reflects reliability and control in measurements. Significant variations in minimum and maximum adhesion values may be attributed to the coating preparation technique, as bond strength is sensitive to how the substrate surface is prepared. Some results indicate that the mean values of bond strength can varying from 6.1% to 15.8% [21,23].

The average standard deviation values for the specimens range from approximately 0.25 to 0.55, as can be seen from Figure 7. Specimens of plates 4 and 6 exhibit the highest deviations, both close to 0.55, which is similar to the peaks observed in the Ukrainian standard. In contrast, the lowest deviations are found in specimens on plates 1, 2, and 9, with values between 0.25 and 0.3 indicating a relatively uniform bond strength. When the same binder is used with the same environmental conditions, the average bond strength deviations (Figures 6 and 7) for specimens of plates 1 and 2 according to the Ukrainian standard are approximately 0.42 and 0.32, respectively, indicating moderate variability from the average. In contrast, specimens of plates 1 and 2 tested according to the EU standard exhibit lower deviations of around 0.25, suggesting greater consistency.

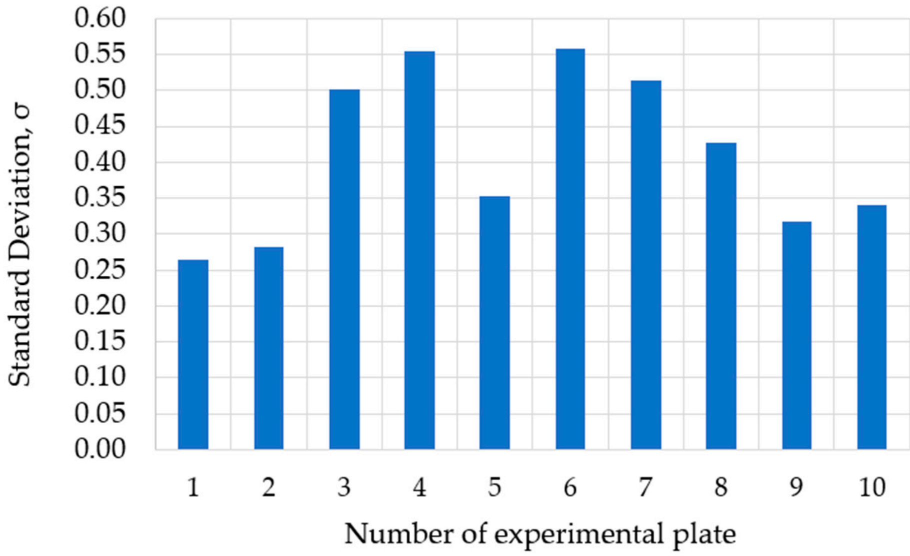


Figure 7. Relations between the calculated deviation and the experimental concrete plates made according to the EU standard.

The number of samples that showed deviations from the average adhesion index (1.986 MPa) by 30% or more was 69 units (the values are marked in gray in Table 5), which is almost similar to measurement results reported in the Ukrainian method [24]. Based on the adhesive strength index requirements outlined in the European regulatory document [25], the distribution of repair composite classes is as follows: R4—80 samples (53.3%), R3—141 samples (94%), R2—145 samples (96.6%), and R1—145 samples (96.6%).

The above results showed that the adhesion measurement method according to [25] has comparatively lower repeatability. The possible reason for the reduction in adhesive strength is a certain degree of damage to the bonds between the applied repair composite and the concrete substrate in the process of forming washer samples using a crown, namely the internal mechanical fixation of the composite in the rough surface of the substrate at the microscale level [32,33]. In addition, the thickness of the epoxy adhesive significantly influences the bond strength [34].

Comparing bond strength across different testing methods is challenging, even under identical environmental conditions, because the stress distribution within the bonded area can vary significantly depending on the testing approach. Nevertheless, based on the analysis of the obtained results, the same repair composites (samples from reference plates 3, 4, and 6–8), which meet the adhesion criteria (≥2.0 MPa) for the highest structural class of repair material PM1 as specified in Ukrainian standard [24], can only be classified as R3 class materials according to the European standard [25].

4. Conclusions

During the experimental studies, data on bond strength were obtained under adhesion testing. Cement samples from dry building mixtures for the repair and restoration of concrete and reinforced concrete structures and buildings were tested using measurement methods in accordance with Ukrainian and European standards. The following observations have been concluded from the work.

- According to the Ukrainian standard, 90.5% of samples showed adhesive bond failure (AF-S) caused by weak cohesion between the repair concrete and substrate (CF-S). In contrast, the European method indicated a 76% failure rate.
- Under identical conditions and using the same binders, the Ukrainian standard exhibited moderate variability, with standard deviations of 0.42 and 0.32 for plates 1 and 2, respectively. In contrast, the EU standard displayed greater consistency for these plates, with average deviations of approximately 0.25.

- Mechanical testing between concrete slabs and repair mortars deviated from the average adhesion index (2.411 MPa) by 30% or more in 71 units using Ukrainian methods, and 69 units using European regulations.
- The cohesion between epoxy glue and substrate improves the interface durability due to mechanical interlocking and chemical bonding.
- Reference plates meeting the adhesion criteria for the highest structural class of repair material PM1 as specified in the Ukrainian standard can only achieve an R3 classification according to the European standard.
- Statistical analysis shows that increasing the number of pull-off tests significantly improves the reliability of adhesion strength. However, careful interpretation is crucial; while some cases clearly indicate low adhesion, others require additional testing for definitive conclusions.
- When comparing concrete removal techniques, it is essential to consider the moisture conditions of the substrate concrete and the thickness of the adhesive layer.

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References

1. COST 345. Procedures Required for the Assesments of Highway Structures. Final Report. Available online: http://cost345.zag.si/Reports/COST_345_Summary_Document.pdf (accessed on 17 November 2024).
2. Nicol, S.; Roys, M.; Ormandy, D.; Ezratty, V. *The Cost of Poor Housing in the European Union*; Briefing Paper; BRE: Watford, UK, 2016; p. 76.
3. Czarnecki, L.; Geryło, R.; Kuczyński, K. Concrete Repair Durability. *Materials* **2020**, *13*, 4535. [CrossRef]
4. Taffesea, W.Z.; Sistonen, E. Service Life Prediction of Repaired Structures Using Concrete Recasting Method: State-of-the-Art. *Procedia Eng.* **2013**, *57*, 1138–1144. [CrossRef]
5. Wang, R.; Zhang, L. Mechanism and Durability of Repair Systems in Polymer-Modified Cement Mortars. *Adv. Mater. Sci. Eng.* **2015**, *2015*, 594672. [CrossRef]
6. Flaga, K. The Influence of Concrete Shrinkage on Durability of Reinforced Structural Members. *Bull. Pol. Acad. Sci. Tech. Sci.* **2015**, *63*, 15–22. [CrossRef]
7. Czarnecki, L. Polymer-Concrete Composites for the Repair of Concrete Structures. *MATEC Web Conf.* **2018**, *199*, 01006. [CrossRef]
8. Raupach, M.; Wolff, L. Standards and Guidelines for Repairing Concrete Structures. In *Failure, Distress and Repair of Concrete Structures*; Elsevier: Amsterdam, The Netherlands, 2009; pp. 141–168. ISBN 978-1-84569-408-1.
9. Reza, M.; Masih, M.; Nasibe, A.S.; Seyedreza, M. The impact of surface preparation on the bond strength of repaired concrete by metakaolin containing concrete. *Constr. Build. Mater.* **2015**, *80*, 76–83. [CrossRef]
10. Rashid, K.; Ahmad, M.; Ueda, T.; Deng, J.; Aslam, K.; Nazir, I.; Azam Sarwar, M. Experimental Investigation of the Bond Strength between New to Old Concrete Using Different Adhesive Layers. *Constr. Build. Mater.* **2020**, *249*, 118798. [CrossRef]
11. Daneshvar, D.; Behnood, A.; Robisson, A. Interfacial Bond in Concrete-to-Concrete Composites: A Review. *Constr. Build. Mater.* **2022**, *359*, 129195. [CrossRef]
12. Xiong, G.; Liu, J.; Li, G.; Xie, H. A way for improving interfacial transition zone between concrete substrate and repair materials. *Cem. Concr. Res.* **2002**, *32*, 1877–1881. [CrossRef]
13. Bentz, D.; Varga, I.D.I.; Muñoz, J.; Spragg, R.; Graybeal, B.; Hussey, D.; Jacobson, D.L.; Jones, S.Z.; LaManna, J.M. Influence of substrate moisture state and roughness on interface microstructure and bond strength: Slant shear vs. pull-off testing. *Cem. Concr. Compos.* **2018**, *87*, 63–72. [CrossRef]

14. Beushausen, H.; Höhlig, B.; Talotti, M. The Influence of Substrate Moisture Preparation on Bond Strength of Concrete Overlays and the Microstructure of the OTZ. *Cem. Concr. Res.* **2017**, *92*, 84–91. [CrossRef]
15. Tilly, G.P.; Jacobs, J. *Concrete Repairs: Performance in Service and Current Practice*; Brepress: Garton, UK, 2007.
16. Fathy, A.; Zhu, H.; Kohail, M. Factors affecting the fresh-to-hardened concrete repair system. *Constr. Build. Mater.* **2022**, *320*, 126279. [CrossRef]
17. Shunmuga Vembu, P.R.; Ammasi, A.K. A Comprehensive Review on the Factors Affecting Bond Strength in Concrete. *Buildings* **2023**, *13*, 577. [CrossRef]
18. Faysal, R.M.; Bhuiyan, M.M.H.; Momin, K.A.; Tafsirojjaman, T.; Liu, Y. A Review on the Advances of the Study on FRP-Concrete Bond under Hygrothermal Exposure. *Constr. Build. Mater.* **2023**, *363*, 129818. [CrossRef]
19. Rashid, K.; Ueda, T.; Zhang, D.; Miyaguchi, K.; Nakai, H. Experimental and Analytical Investigations on the Behavior of Interface between Concrete and Polymer Cement Mortar under Hygrothermal Conditions. *Constr. Build. Mater.* **2015**, *94*, 414–425. [CrossRef]
20. Zanotti, C.; Borges, P.H.R.; Bhutta, A.; Banthia, N. Bond Strength between Concrete Substrate and Metakaolin Geopolymer Repair Mortar: Effect of Curing Regime and PVA Fiber Reinforcement. *Cem. Concr. Compos.* **2017**, *80*, 307–316. [CrossRef]
21. Manawadu, A.; Qiao, P.; Wen, H. Characterization of substrate-to-overlay interface bond in concrete repairs: A Review. *Build. Mater.* **2023**, *373*, 130828. [CrossRef]
22. Skazlić, M.; Borovina, B.; Gabrijel, I. Optimised Technology for Repair of Vertical Surface of Concrete Bridge Elements. *Organ. Technol. Manag. Constr. Int. J.* **2023**, *15*, 233–242. [CrossRef]
23. Momayez, A.; Ehsani, M.R.; Ramezanianpour, A.A.; Rajaie, H. Comparison of methods for evaluating bond strength between concrete substrate and repair materials. *Cem. Concr. Res.* **2005**, *35*, 748–757. [CrossRef]
24. *DSTU B V.2.7-126:2011*; Modified Dry Building Mixtures. National Standard of Ukraine: Kyiv, Ukraine, 2011.
25. *EN 1542:1999*; Products and Systems for the Protection and Repair of Concrete Structures. Test Methods. Measurement of Bond Strength by Pull-Off. British Standards Institution: London, UK, 1999.
26. *EN 1504-2:2004*; Products and Systems for the Protection and Repair of Concrete Structures. Definitions, Requirements, Quality Control and Evaluation of Conformity Surface Protection Systems for Concrete. British Standards Institution: London, UK, 2004.
27. *DSTU B B.2.7-23*; Construction Solutions. General Technical Conditions. National Standard of Ukraine: Kyiv, Ukraine, 1996.
28. *EN 1504-4:2004*; Products and Systems for the Protection and Repair of Concrete Structures—Definitions, Requirements, Quality Control and Evaluation of Conformity—Part 4: Structural Bonding. British Standards Institution: London, UK, 2004.
29. *EN 1323:2007*; Adhesives for Tiles. Concrete Slabs for Tests. British Standards Institution: London, UK, 2007.
30. *DSTU B V.2.7-282:2011*; Ceramic Tiles. Specifications. NDIBMV, 201. National standard of Ukraine: Kyiv, Ukraine, 2011.
31. Ramos, N.M.M.; Simões, M.L.; Delgado, J.M.P.Q.; de Freitas, V.P. Reliability of the pull-off test for in situ evaluation of adhesion strength. *Constr. Build. Mater.* **2012**, *31*, 86–93. [CrossRef]
32. Karimi, H.R.; Khedri, E.; Aliha, M.R.M.; Shaker, H.; Jafari Haghighatpour, P. Repair efficiency evaluation for cracked asphalt mixture pavement in different ambient temperatures using bitumen and polymer concrete as repair materials. *Constr. Build. Mater.* **2023**, *369*, 130556. [CrossRef]
33. Czarnecki, L. Adhesion—A Challenge for Concrete Repair. In *International Congress on Concrete Repair, Reinforcement and Retrofitting II*; Alexander, M.G., Beushausen, H.-D., Dehn, F., Moyo, P., Eds.; Taylor & Francis Group: London, UK, 2009; pp. 935–940.
34. Ohama, Y. *Handbook of Polymer-Modified Concrete and Mortars: Properties and Process Technology*, 1st ed.; William Andrew: Norwich, NY, USA, 1995.

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