Review

Evaluation of the Adhesion between Overlays and Substrates in Concrete Floors: Literature Survey, Recent Non-Destructive and Semi-Destructive Testing Methods, and Research Gaps

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Abstract: Non-destructive testing (NDT) and semi-destructive testing (SDT) have recently been more frequently used for the evaluation and condition assessment of concrete floors in various types of buildings. The subject of the article is to briefly introduce the reader to the problem of adhesion between overlays and substrates in concrete floors and to illustrate the current state of knowledge on the subject. The aim of this paper was to briefly describe the recently used non-destructive and semi-destructive testing methods and the parameters useful for characterizing the adhesion between overlays and substrates in concrete floors, as well as the methods useful to characterize the functional properties of the overlays. A recent literature survey, related to the adhesion between the overlays and substrates in concrete floors, is thus shown. Special emphasis was placed on the critical review of the current research results. Based on the analysis of the literature review, research gaps have been presented in order to highlight future research directions.

Keywords: non-destructive testing; semi-destructive testing; cement mortar; pull-off adhesion; overlay; substrate; functional properties; abrasion resistance; subsurface tensile strength; hardness

1. Introduction

Non-destructive testing (NDT) and semi-destructive testing (SDT) have recently been more frequently used for the evaluation and condition assessment of concrete floors in various types of buildings [1]. Nowadays, concrete floors are commonly used in civil engineering [2–4], and they are made of overlays that are placed on the substrate [5]. The most important properties of overlays are associated with their proper adhesion to the substrate, as well as their corresponding functional properties, such as abrasion resistance, subsurface tensile strength or hardness [6].

A floor is a horizontal interior element in a building, normally consisting of an overlay (flooring) applied on the substrate. The substrate is placed on the base. The load, which impacts on the overlay, is transferred to the base. The substrate is the structural support of the floor and transfers the load to the ground directly or indirectly through other elements of the building (e.g., a slab floor and walls) [7].

It should be added that an overlay has to be adapted to functional requirements, e.g., by applying a finishing layer on it [8]. Nowadays, floors with concrete layers are generally being used in most residential building objects. They are used, among others, in residential and public buildings, warehouses, production buildings, and one and multilevel car parks.

A concrete floor consists of an overlay that is usually made of cement mortar and substrate (Figure 1). The substrate is usually made of concrete. Between the overlay and the substrate, a bonding agent can also be applied. The interphase zone between the overlay and substrate can be set apart,

which according to literature can be divided into the near-surface zone of the overlay mortar (NSZ-OM) and the near-surface zone of the concrete substrate (NSZ-CS). Other names are shown in Figure 1.

Figure 1. Explanation of basic definitions used in the article.

These floors are popular in residential, civil, and industrial buildings, e.g., in indoor car parks [9]. As is shown in Figure 2, floors, depending on the used material, can be divided into: mineral floors, floors of epoxy resins, bituminous, artificial paneling, ceramic, stoned, and steel. However, floorings made of cement composites and concrete hardening are the most often used.

Figure 2. Types of floorings, depending on the material of which they are made (based on Reference [10]).

The aim of the article was to introduce non-destructive and semi-destructive testing methods, the parameters connected with the issue of adhesion between overlays and substrates, and also the functional parameters of the overlay in concrete floors. The literature survey and review of current research results are shown. The research gaps are also presented in order to highlight future research directions.

2. Overview of Recent Non-Destructive and Semi-Destructive Testing Methods Used to Assess the Adhesion between Overlays and Substrates in Concrete Floors

A proper method should be chosen, depending on the requirements concerning the carried-out repair [11]. The methods of testing the bond between a concrete substrate and an overlay can be divided, depending on the direction of load application, into three groups [12]. Tests to determine the bond between the concrete substrate and the overlay are shown in Figure 3.

Figure 3. Tests to determine the bond between the concrete substrate and the overlay: (a) pull-off, (b) shear, (c) slant shear, (d) splitting.

The first group of methods assumes testing under tension stress. They are the pull-off method (Figure 3a) and the splitting prism method (Figure 3d). The splitting method is based on applying a longitudinal compressive load on the interface of the concrete substrate and the overlay. The second group of methods assumes testing under shear stress. The direct shear method is shown in Figure 3b. The third group assumes both compression and shear stress working together. The slant shear method is shown in Figure 3c. In practice, the pull-off method [13], in which adhesion is assessed by measuring the strength of pulling off the repaired layer of the substrate, is most often used [14]. The scheme of the pull-off and the view of the used equipment is shown in Figure 4. In this method, the measurement of the pull-off adhesion f_b between the repaired layer and the substrate is carried out on the basis of the measurement of the value of the pulling off strength of the steel disk with a digital or indicating manometer. Drills in the overlay of a diameter of $D_f = 50$ mm and a depth that is shown in Figure 4 are performed in this method. Then, steel discs are glued to the overlay and pulled off the substrate surface at an angle of 90 degrees. The increase of the value of pull off stress should be equal to 0.05 MPa/s. The pull-off method is quantitative because it enables the pull-off value f_b to be determined as follows (1):

$$f_b = \frac{4F_b}{\pi D_f^2} \quad (1)$$

where:

F_b —the failure load (N)

D_f —the diameter of drilling core (m)

Figure 4 shows the scheme of the pull-off method and the view of the testing device.

Figure 4. The scheme of the pull-off method (a) and a view of the testing device (b).

When taking into consideration the durability of the overlay, an appropriate pull-off adhesion f_b between the overlay and the substrate of 1.5 MPa is demanded for repaired overlays and 0.5 MPa for newly built overlays.

The durability of a floor, especially when it is heavily loaded because of driving cars or loading trucks, depends significantly on the proper bonding between the overlay and the substrate [15]. The technical measure of the bonding is the value of pull-off adhesion f_b , which is determined with the semi-destructive pull-off method. According to requirements for floors included in Reference [16], it is demanded that the minimum value of pull-off adhesion f_b between the overlay and the substrate is equal to no less than 0.5 MPa. If the value of adhesion is equal to 0, it would mean that so-called delamination has appeared, i.e., a complete lack of adhesion.

3. Overview of Recent Non-Destructive and Semi-Destructive Testing Methods Used to Assess the Functional Properties of Overlays

3.1. Abrasion Resistance—Boehme Test

The basis of the method is to subject the examined sample, with section dimensions of 71×71 mm, to 16 cycles of abrasion on a rotating abrasion wheel (Boehme wheel) [17]. Each cycle consists of even spilling of 20 g of carborundum abrasive sand on the Boehme wheel, attaching the sample to the handle, loading it with a force of 294 ± 3 N and then subjecting it to 22 rotations of the disc in each cycle. After each cycle, the sample should be turned at 90 degrees, and after every four cycles, it should be weighed. Then, abrasion, as the mass decrease or volume decrease of the sample after 16 cycles, should be calculated as follows (2):

$$\Delta V = \frac{\Delta m}{\rho_R} \quad (2)$$

ΔV —decrease of volume after 16 cycles (in cubic millimeters)

Δm —decrease of mass after 16 cycles (in grams)

ρ_R —the density of the examined sample, or in the case of multilayer samples, abrasion layer density (in grams per cubic millimeters)

Figure 5 shows the scheme and view of the Boehme test device.

Figure 5. The scheme (a) and view (b) of the Boehme test device.

3.2. Subsurface Tensile Strength—Pull-Off Test

The pull-off method is also used to determine the subsurface tensile strength [18]. In order to assess the strength, drilling in the overlay of 50 mm diameter and to a depth of around 15 mm is carried out. Then, the steel discs are glued to the surface of the overlay and the pulling off force is applied. The subsurface tensile strength can be calculated as below:

$$f_{hs} = \frac{4F_b}{\pi D_f^2} \quad (3)$$

where:

F_b —the failure load (N)

D_f —the diameter of drilling core (m)

Figure 6 shows the scheme of the pull-off method according to subsurface tensile strength testing.

Figure 6. The scheme of the pull-off method according to subsurface tensile strength testing.

3.3. Surface Hardness—The Sclerometric Method

The scheme of the sclerometric method, together with the view of the testing device and the relation between the compressive strength and rebound number are presented in Figure 7.

Figure 7. The scheme of the sclerometric method (a), the view of the testing device (b), and the typical relation (c) between the rebound number and compressive strength (based on References [19,20]).

The relation between the hardness of concrete and the rebound number is the basis of this method [19–22]. Figure 7 shows the view of the hammer (also named Schmidt hammer) and the scheme of the sclerometric method. The main parts of the hammer are a plunger, spring, indicator, latch, and body. Position 1 in the scheme shows the hammer in the first part of the test. The plunger is applied in the testing place and the latch holding the hammer mass is locked. Position 2 in the scheme shows the hammer during the test when the body is pushing against the concrete surface. The spring tension is increasing, and the latch is still locked. Position 3 in the scheme shows the moment in the test when the latch is released, and the hammer mass is pushed against the plunger tip by the spring. The last position in the scheme (number 4) shows the moment when the hammer mass moves the indicator after impacting the plunger tip and rebounding. Then, the rebound number is read from the scale. The rebound number can also be used to estimate compressive strength or flexural strength. For this purpose, concrete has to be tested with the hammer. The compressive strength of control samples should then be determined (the control samples can be taken from the existing structure or prepared based on the same mix composition). Next, the relation between the rebound number and compressive strength is created (on the right side in Figure 7) and correlation analysis should be carried out using the least squares method (the hypothetical regression curve based on previous research can be taken into consideration for some conditions). However, it must also be stated that a large number of measuring points is necessary to obtain statistically reliable results. Despite the possibilities that the rebound hammer provides, there are factors affecting the results. The following limitations should be taken into consideration during the analysis: age of test specimens; surface and internal moisture conditions; the size, shape, and rigidity of the specimens; smoothness of test surface; type of coarse aggregate; type of cement; and carbonation of the concrete surface [23–27]. The hammer has recently also been used together with other non-destructive and semi-destructive testing methods to assess the compressive strength of concrete [27–32].

4. Overview of Recent Activities Used to Improve the Pull-Off Adhesion of Overlay with Substrate

The following activities to improve the pull-off adhesion f_b of overlay with substrate are used:

- Mechanical treatment of the surface of the substrate;
- Surface texturing;
- Removal of cement laitance from the concrete substrate surface;
- Surface exposure of the aggregate;
- Surface strengthening of the concrete substrate with bonding agents;
- Modifications of the material of the overlay.

4.1. Mechanical Treatment of the Surface of Substrate

In recent years, a great deal of research has been carried out according to the influence of the morphology of a concrete surface to its bonding with the overlay [33–37]. The methods of evaluating a concrete surface were performed by, among others, Santos and Julio [38], Mathia et al. [39], and Garbacz et al. [40]. At present, the scanning electron microscopy (SEM) method is increasingly used for this purpose [41–43]. The principle of this method is as follows: An electron gun generates the electron beam. When the electrons enter the concrete surface, low energy secondary electrons are generated. The intensity of the secondary electrons depends on the concrete surface morphology and, therefore, an SEM image of the surface is created as a function between the intensity of secondary electrons and the position of the scanning electron beam. This method provides many advantages, such as high magnification and resolution of obtained images at nanoscale, or the possibility to determine the chemical composition of studied samples. Generally, the available methods of treatment can be divided into three main groups: cleaning and non-invasive removal methods, coarsening methods, and invasive removal methods. Each type of the above-mentioned groups contains methods that differ with the mechanism of treatment, and this is why it has particular applications. The exemplary views of the concrete substrate surface after treatment are shown in Figure 8.

Figure 8. The exemplary view of the concrete substrate surface after shot-blasting (a) and patch grabbing (b).

Figure 9 shows the division of several concrete treatment methods, depending on their type.

From the methods presented in Figure 9, the cleaning and non-invasive types of methods contain grinding and low-pressure cleaning. Attrition is the mechanism of grinding. This method reveals the fine grain aggregate due to the removal of cement laitance, loose fragments, and other impurities. Water erosion is the mechanism of treatment of low-pressure cleaning. It enables the removal of water-soluble contamination and brittle cementitious material from the surface. The second group (coarsening) contains milling, scabbling, and shot-blasting/sand-blasting. Hitting is the method of treatment for milling. Milling allows for the obtention of a regular profile of parallel grooves on the surface, the removal of the whole cement laitance, and the levelling of large irregularities (up to 20 mm). Scabbling is based on using pneumatic devices such as hammers, piston-mounted bits, etc. It removes the material of the overlay near to its surface (up to 6 mm depending on the used device). The shot-blasting and the sand-blasting mechanism of treatment is spraying. These methods remove brittle material, cement laitance, and dirt from the overlay surface, and reveal the coarse aggregate. The profile of the surface after these treatments depends on the granulation and abrasiveness of the surface material of the overlay. The invasive removal methods contain flame treatment and hydrodemolition (also named water jetting or water-blasting). Flame treatment uses pressure expansion by steam and removes fragments of concrete (a maximum of 6 mm). In turn,

hydrodemolition enables the removal of concrete fragments of up to 19 mm, depending on the water pressure. Recent research has shown that shot-blasting of a concrete substrate surface improves the level of adhesion of the cement mortar overlay with the substrate [44–48]. Figure 10 shows the relation between the pull-off adhesion f_b between the overlay and the existing concrete substrate and the method of treatment of the concrete substrate surface.

Figure 9. Division of concrete treatment methods (based on Reference [5]).

Figure 10. The test results of the pull-off adhesion f_b between the overlay and the existing concrete substrate using the pull-off method (based on the results presented in Reference [44]). Methods of surface treatment: T1—patch grabbed (raw) surface, T2—formed after contact with formwork (as cast) surface, T3—mechanically grinded surface, T4—shot-blasted surface.

Figure 10 shows that only an increase of the effective relative surface area (of the substrate) does not cause the considerable increase of adhesion that is noticeable in the case of the raw surface and as cast surface (T1 and T2). Moreover, only exposure of the aggregate (on substrate surface) does not cause the visible increase of the level of adhesion that is noticeable in the case of the mechanically grinded surface T3. Only simultaneous increasing of the effective relative surface area and exposure of the aggregate considerably increases the level of adhesion, as was the case for the shot-blasted surface T4.

However, Franck and De Belie [49], in order to determine the influence of the way of treating the concrete surface on the value of R_a and R_q parameters (Figure 11), subjected the surface of a concrete floor to research with the jointless method laser beam. The figure shows that the values of arithmetical mean height (R_a) and root mean square deviation (R_q) of the concrete surface subjected to sand-blasting are about eight times higher than for the raw surface, and about two times higher than for the wire brushed surface.

Figure 11. The effect of the surface treatment method on the value of: (a) arithmetical mean height (R_a) of the concrete surface, (b) root mean square deviation (R_q) of the concrete surface. The surface treatment methods were marked as follows: I—as cast surface, II—wire-brushed surface, III—sand-blasted surface (based on the results presented in Reference [49]).

The research shows that together with increasing the fraction of pores Φ and the number of pores within the interphase zone, the value f_b decreases. In the case of substrate, the relation is the opposite—together with increasing the fraction of pores Φ and the number of pores in the near surface zone of the concrete substrate (NSZ-CS), the value f_b increases [50–54]. The relations between the total fraction of pores and the pull-off adhesion f_b are shown in Figure 12a. In turn, the relations between the number of pores and the pull-off adhesion f_b are shown in Figure 12b.

Figure 12. Relation of the pull-off adhesion f_b of the overlay with the substrate with regard to fraction of pores ϕ (a) and number of pores (b): IZ—interphase zone, NSZ-CS—the near surface zone of the concrete substrate, NSZ-OM—the near surface zone of the mortar overlay (based on the results presented in Reference [50]).

4.2. Texturing of the Surface of the Concrete Substrate

The second way to improve the pull-off adhesion f_b between the concrete substrate and the overlay is by texturing the substrate surface. The division of the texturing method is presented in Figure 13.

Figure 13. Division of concrete texturing methods.

From the methods presented in Figure 13, dragging the jute texturing method is based on mechanical or manual pulling of the jute fabric over the concrete surface. It is a cheap method, but the texture that is created according to this method is small (around 0.2 to 0.6 mm). The brushing method consists of brushing the fresh concrete mix using steel brushes. It can be performed at a texture depth in the range of 2 to 3 mm. The advantage of this method is the fast texturing of the concrete surface. Nevertheless, attention should be paid to the depth of brushing, because too deep texturing can reveal the reinforcement and cause its corrosion. The method that assumes leaching of the cement paste from the cement overlay surface consists of brushing or jetting water that rinses the unbound layer of this

mortar. Increasing the friction coefficient of the surface is the advantage of this method, despite the fact that it is expensive. Moreover, after application of this method, the surface can have a decorative function. The grooving method is based on grooving the concrete surface by using metal forks in order to obtain a series of grooves on the surface (the depth of each groove is around 6 mm). The acid etching method is based on applying a hydrochloric acid solution on the concrete surface by brushing. It is an effective method of removing the cement laitance, but it is rather expensive. Texturing has recently been applied to increase the pull-off adhesion f_b of epoxy resin coatings to the concrete substrate [51] and cement mortar overlay to the concrete substrate [52].

4.3. Removal of Cement Laitance from the Concrete Substrate Surface

It is known that removing the cement laitance from the concrete substrate surface improves the level of the pull-off adhesion f_b between the overlay and the substrate [55–57]. Figure 14 shows the relation between the pull-off adhesion f_b and the methods of substrate treatment (removing and not-removing the cement laitance). It can be seen from the figure that methods of removing the cement laitance, for example, grinding (P3) or shot-blasting (P4), can increase the level of the pull-off adhesion f_b between the overlay and the substrate (compared to methods that do not remove it).

Figure 14. Relation of the pull-off adhesion f_b between the overlay and the substrate with regards to the method of treatment of the surface (based on the results presented in Reference [44]). Key: P1—patch grabbed (raw) surface, P2—formed after contact with the surface of formwork (as cast); treatment with removing cement laitance: P3—mechanically grinded surface, P4—shot-blasted surface.

4.4. Surface Exposure of the Aggregate

Sadowski et al. [44] used the 3D laser scanning method to correlate the contribution of exposed aggregate A_A visible on the surface of concrete substrate and being the effect of method of treatment with the value of pull-off adhesion f_b between concrete overlay and substrate. Four kinds of concrete surfaces: patched grabbed (raw), formed after contact with the framework (as cast), grinded, and shot-blasted were subjected to the research using an optical microscope. In such a way it was possible to state that the shape of aggregate A_A for the shot-blasted surface in the whole surface was the highest when compared to the surfaces treated in other ways. However, the correlation between the contribution of exposed aggregate A_A that was visible on the concrete surface substrate, and the pull-off adhesion f_b between the overlay and this substrate was impossible to obtain. On the other hand, it was shown that an increase of the contribution of exposed aggregate A_A together with increasing the developed interface area ratio S_{dr} , causes an increase of the value of pull-off adhesion f_b . On this basis, the following relation was created:

$$f_b(S_{dr}; A_A) = 0.32 + 0.043 S_{dr} + 0.0138 A_A \quad (4)$$

This equation reveals that the methods of treatment that increase only the developed interface area ratio S_{dr} (patch-grabbed surface and surface formed after contact with framework) do not cause an increase of the pull-off adhesion f_b . Moreover, an increase of just the contribution of exposed aggregate A_A does not cause an increase of the pull-off adhesion f_b (ground surface). Only an increase of the contribution of exposed aggregate A_A , together with the developed interface area ratio S_{dr} , significantly increases the pull-off adhesion f_b . This can be seen in the case of the shot-blasted surface.

4.5. Strengthening of the Surface of the Concrete Substrate with Bonding Agents

The research has also shown that using a bonding agent before laying the overlay on the concrete substrate surface improves the level of the pull-off adhesion f_b of the overlay with the concrete substrate [58–61]. Figure 15 shows the relation between shear bond strength and the method of substrate surface treatment. Moreover, for each method of surface treatment, three methods of applying the added concrete layer are shown: fresh concrete placed against hardened concrete without bonding agent applied in the interface, fresh concrete placed against hardened concrete with bonding agent applied in the interface, hardened concrete placed against hardened concrete with bonding agent applied in the interface.

Figure 15. The relation of shear bond strength with regards to the used bonding agent and the method of surface treatment: LAC—the left as cast surface, WB—the wire-brushed surface, DS-SHB—the dry shot-blasted substrate, SS-SHB—the saturated shot-blasted substrate (based on the results presented in Reference [58]).

As can be seen from the figure, the use of a bonding agent increased the shear bond between layers by almost double for the LAC, WB, and SS-SHB surfaces. The increase of shear bond strength in percentage terms for the DS-SHB surface with a bonding agent was twice as small when compared to the other surfaces (about 25%). When placing hardened concrete against hardened concrete, a bonding agent, in the case of the LAC and WB surfaces, caused a slight increase of shear bond strength when compared to placing fresh concrete against hardened concrete. In turn, this relation was opposite for the DS-SHB and SS-SHB surfaces. Bonding agents are also popular for increasing the adhesion between gypsum plasters and different substrates [62].

4.6. Modifications of the Material of the Overlay

Research has shown that using additions in the form of silica fume, metakaolin, short carbon fibers, polypropylene fiber, styrene/acrylic powder, magnesium phosphate, and fly ash for the cement

mortar of the overlay is favorable in terms of the level of pull-off adhesion f_b between the overlay and the concrete substrate [63–73]). In turn, using quartz and glass powder as an addition to the cement mortar of the overlay does not have a positive influence on the level of its pull-off adhesion f_b [74,75]. Figure 16 presents the results of bonding strength tests with regards to the polypropylene fiber content in concrete. It can be seen that the addition of PP fiber in amounts of 0.45 and 0.9 kg/m³ significantly improved bond strength (about double) when compared to the reference concrete C1. However, the value of bonding strength started to decrease with an increase in PP fiber content (over 0.9 kg/m³).

Figure 16. Results of bonding strength tests with regards to the polypropylene fiber content in concrete. C1—concrete without addition, F1—concrete with PP fiber addition in an amount of 0.45 kg/m³, F2—concrete with PP fiber addition in an amount of 0.9 kg/m³, F3—concrete with PP fiber addition in an amount of 1.35 kg/m³ (based on the results presented in Reference [73]).

Figure 17 shows the influence of different amounts of quartz powder for modifying overlay concrete on the pull-off adhesion f_b between the overlay and the concrete substrate.

Figure 17. The influence of different amounts of quartz powder for modifying overlay concrete on the pull-off adhesion f_b between the overlay and the concrete substrate (based on the results presented in Reference [74]).

As can be seen in Figure 17, the addition of 10% and 20% of quartz powder in relation to the cement mass does not cause an increase or decrease of the value of pull-off adhesion f_b between the

overlay and the concrete substrate after 7 and 28 days of testing. In turn, the addition of 30% of the powder decreased the examined adhesion by around 15% after 7 days and by around 20% after 28 days. Figure 18 shows the influence of different amounts of quartz-feldspar powder for modifying overlay concrete on the pull-off adhesion f_b between the overlay and concrete substrate.

Figure 18. Influence of different amounts of quartz-feldspar powder for modifying overlay concrete on the pull-off adhesion f_b between the overlay and concrete substrate (based on the results presented in Reference [74]).

It can be seen in Figure 18 that the addition of quartz-feldspar powder to the overlay in each amount caused around a double decrease in the value of pull-off adhesion f_b between the concrete substrate and the overlay.

In Reference [70], the influence of early water exposure on the modified cementitious coating was described. The pull-off tests were performed to assess the influence. Figure 19 shows the relation between average tensile strength and time. The red curves are connected with the polymer coating, and the blue curves with the crystalline coating.

Figure 19. The relation between the average tensile strength (pull-off strength) and time for the polymer and crystalline coating: (a) rough substrate, (b) smooth substrate (based on the results presented in Reference [70]).

It can be seen from Figure 19a,b that the level of pull-off strength for the polymer coating was greater than for the crystalline coating. However, both coatings resulted in a pull-off strength greater than 1 MPa (after 120 h for the polymer coating and after 240 h for the crystalline coating).

5. Overview of Recent Activities Used to Improve the Functional Properties of the Overlay

Depending on the functional requirements of an object, as well as its durability, overlays should have proper strength and functional parameters [76,77]. The chosen parameters are shown in Table 1.

Table 1. The list of chosen strengths and functional parameters for floors.

Parameter	Value
Compressive strength	Minimum 20 MPa
Flexural strength	Minimum 5 MPa
Subsurface tensile strength	Minimum 1.5 MPa
Abrasion resistance	Maximum 22 cm ³
Hardness	Determined individually

In many cases, the failure to comply with technological and technical requirements has a negative effect on the condition of cement mortar floors [78]. In order to obtain parameters to the required level, the following additional activities, which are shown in Figure 20, are used:

Figure 20. Methods of improving the overlay functional parameters.

Different types of fiber, such as polypropylene, polyethylene, nylon, aramid, and polyester are also commonly used as an additive to concrete in order to improve its mechanical and functional properties [79–84]. However, the most common overlay additives are polypropylene fibers [85]. In Reference [73], it was stated that the addition of polypropylene to concrete improves, among others, its compressive and flexural strength, impact resistance, and abrasion resistance. In turn, Song and Hwang [86] indicated that adding steel fiber to concrete increases its compressive strength by up to 15.3% and its splitting tensile strength by up to 98.3%. In general, an increase in compressive strength can improve abrasion resistance and subsurface tensile strength [87–90]. Despite this relation, the value of compressive strength can differ in the upper, middle, and bottom zone of the overlay [91,92], which

was proved by the carried out ultrasonic testing of the overlays [93,94]. The tensile strength, drying shrinkage, elastic modulus, and tensile relaxation of the overlay are affected to a great extent by curing conditions [57,95–97]. It was also reported that the properties of concrete may be affected by the manner of casting [98–100]. The next method of improving overlay functional properties is surface hardening. Many hardeners, such as mineral or metallic aggregate hardeners (iron, quartz, silica, corindon, etc.), polypropylene fibers, and metallic fibers [101–105] have been found to especially increase the abrasion resistance of the surface of concrete and mortar. The method of finishing and modifying the overlay material with micro/nano materials not only affects the abrasion resistance [106–114], but also different special properties such as aging resistance in high temperatures, self-cleaning, air purification, de-icing salt resistance or freeze/thaw resistance [115–119]. Impregnation of the surface of the overlay by different coatings (e.g., epoxy, acrylic, polyurethane, cementitious, polymer/clay nanocomposites) can increase its durability, as well as improve many functional parameters such as adhesive resistant, chemical resistance, chloride permeability, hardness, impermeability, abrasion resistance, heat resistance, shrinkage, etc. [120–129].

6. Perspectives and Research Gaps

It is shown in literature that modification of the mortar cement composition of the overlay with the addition of nanoparticles can increase the pull-off adhesion f_b between the overlay and the concrete substrate. However, there is a lack of wider research concerning this problem [130,131]. Figure 21 presents the values of pull-off adhesion f_b with regards to the concrete mixture type. The pull-off adhesion f_b was determined before and after freezing/thawing and wetting/drying cycles. Letters A and B refer to concrete with the addition of 15 (A) and 30% of fly ash (B). For the other symbols, the number refers to the replacement of fly ash by the mass of the binder, N refers to normal-setting concrete mixture, and R refers to rapid-setting concrete mixture. Each mixture marked with numbers had a 6% dosage of nano silica (by the mass of the binder).

Figure 21. Pull-off adhesion f_b of the repair assembly from pull-off test (based on the results presented in Reference [131]).

It can be seen in Figure 21 that the values of pull-off adhesion f_b for the A (1.3 MPa) and B (1.6 MPa) series were the lowest, and after F/T and W/D cycle exposure the values fell approximately by 30 to

50%. For the N and R series, the pull-off adhesion f_b values were in the range of 1.9 to 3.3 MPa, and after the F/T and W/D cycles the values increased approximately by 23 to 43%.

In Table 2, the so far studied features of concrete and mortars modified with the addition of nanoparticles are shown. The type of examined nanoparticles is shown in the upper part of the table, and the examined features are shown on the left. However, attention should be paid to the fact that there is a lack of research concerning the pull-off adhesion f_b between the overlay and concrete substrate and subsurface tensile strength.

Table 2. Selectively examined features of cement mortar and concrete with the addition of nanoparticles. (+ examined, - no data)

Examined Feature	The Kind of Nanoparticle						
	SiO ₂	Al ₂ O ₃	CuO	TiO ₂	ZnO ₂	Fe ₂ O ₃	Cr ₂ O ₃
Porosity	+	+	+	+	+	-	+
Absorptiveness	-	-	-	-	-	+	+
Water resistance	-	-	-	+	-	-	-
Freeze-thaw durability	+	+	-	+	-	-	-
Compressive strength	+	+	+	+	-	+	+
Tensile strength	+	-	-	-	-	+	+
Flexural strength	+	+	-	-	+	+	+
Abrasion resistance	+	+	+	+	-	-	-
Hardness	+	-	-	-	-	-	+
Subsurface tensile strength	-	-	-	-	-	-	-
Pull-off adhesion between overlay and concrete substrate	-	-	-	-	-	-	-

To sum up, there is a lack of research results concerning the influence of nanoparticles included in the cement mortar of the overlay in concrete floors on the level of its pull-off adhesion f_b between the overlay and concrete substrate, as well as on its functional parameters.

7. Conclusions

The aim of this article was to briefly introduce readers to the problem of the adhesion between overlays and substrates in concrete floors and to illustrate the current state of knowledge on the subject. The recently used non-destructive and semi-destructive testing methods and the parameters useful for characterizing the adhesion between overlays and substrates in concrete floors, as well as methods useful for characterizing the functional properties of the overlays were presented. The literature survey, with special emphasis on the critical review of the current research results and research gaps, was presented. On this basis, future research directions were highlighted. Specific conclusions and research gaps are listed as follows:

1. Additional research should be carried out in order to assess the influence of modifying a mortar overlay using other nanoparticles on the pull-off adhesion f_b between the overlay and the concrete substrate. The functional and mechanical properties (such as abrasion resistance, flexural strength, compressive strength, subsurface tensile strength) of the overlay should be taken into consideration together with the values of pull-off adhesion f_b . Julio et al. [130] and Ghazy and Bassuoni [131] used SiO₂ and Al₂O₃ nanoparticles to increase the shear bond strength between concrete layers. However, there is still a lack of wider research in this field.
2. Additional research should be carried out in order to better understand the mechanism of adhesion between an overlay modified with different types of nanoparticles and the concrete substrate on a micro- and nanoscale of observation. The samples taken from the interphase zone between the overlay and the substrate, together with the sample from the subsurface zone of the overlay, should be examined in order to understand and confirm the influence of the addition of

nanoparticles on the adhesion and functional and mechanical parameters. The scanning electron microscopy (SEM) method can be especially suitable for this purpose.

3. Nanoparticles could be successfully used to reduce the porosity of the cementitious material of the overlay in the near surface zone of the mortar overlay, together with proper treatment of the surface of the concrete substrate, to increase the pull-off adhesion f_b between these layers. The studies carried out by Sadowski and Stefaniuk [50,53] reported that while decreasing the fraction and number of pores in the near surface zone of the overlay mortar, and increasing these values in the near surface zone of the concrete substrate, the pull-off adhesion f_b between these layers increases.

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