Suitability of different tests for characterization of the dimpled concrete-to-concrete interface

Short title:

Tests to characterize the dimpled interface

Authors: **Đorđe Čairović,** dorde.cairovic@vut.cz, Brno University of Technology, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Veveří 331/95, Brno, Czech Republic

Albert de la Fuente, albert.de.la.fuente@upc.edu, UPC BarcelonaTech, Construction Engineering, C/Jordi Girona Salgado, 1-3, C1-202c, Barcelona, ES 08034

Martin Zlámal, zlamal.m@fce.vutbr.cz, Brno University of Technology, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Veveří 331/95, Brno, Czech Republic

Jakub Venclovský, venclovsky.j@fce.vutbr.cz, Brno University of Technology, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Veveří 331/95, Brno, Czech Republic

František Girgle, girgle.f@fce.vutbr.cz, Brno University of Technology, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Veveří 331/95, Brno, Czech Republic

Ondřej Januš, janus.o@fce.vutbr.cz, Brno University of Technology, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Veveří 331/95, Brno, Czech Republic

Petr Štěpánek, stepanek.p@fce.vutbr.cz, Brno University of Technology, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Veveří 331/95, Brno, Czech Republic

Synopsis

The main aim of this study was to assess suitability of different existing test setups for the mechanical characterization of a dimpled-interface obtained by casting concrete against dimpled HDPE membrane. Even though this type of interface roughening is widely used, especially for monolithic connections between precast elements, to the best of the authors' knowledge there is no research providing any data regarding its roughness parameters, tension and shear strength, nor its failure modes.

To this end, a two-fold objective was established for this research: 1) to identify and analyse, from a technical standpoint, the available test configurations for characterizing the mechanical performance of interfaces, and 2) to perform an extensive experimental programme devoted to characterising the mechanical performance of a dimpled HDPE membrane – cast concrete interface.

The suitability of each test for reproducing the expected stress state and the actual resistance mechanism were analysed. Moreover, comparison between tension and shear tests, including its main advantages and disadvantaged are also presented.

Keywords

Concrete-to-concrete interface, dimpled interface, interface shear strength, interface tensile strength, test setups, precast structures

1 INTRODUCTION

The strength of the interface between two concrete layers cast at different times can be a governing mechanical parameter in both strengthening and structural repairs of existing structures and precast concrete structures. The most common examples of the latter include connections between precast elements (column-to-footing connection, see Figure 1), precast beams and slabs with additional topping or precast concrete girders with cast-in-situ slabs.

In order to ensure the monolithic behaviour of the different elements, superficial roughening methods are used. Frequently, the surface is intentionally left-as-cast, deep-grooved before the hardening of concrete or cast against shaped formwork, creating shear keys (i.e. an indented interface). This approach also includes the use of a “dimpled surface”, which is obtained by casting concrete against a HDPE (High-Density PolyEthylene) membrane with diagonally oriented dimples that are 8mm in height. A few researchers, for example (Mohamad, et al., 2015), have investigated indented surfaces as defined in the design codes (Model Code 2010, 2013; EN 1992-1-1, 2008). However, even though dimpled surfaces are widely used (especially for monolithic connections between precast elements), to the best of the authors’ knowledge there is no research providing any data regarding their roughness parameters, tension and shear strength, nor their failure modes. Hence, the main aim of this experimental programme was to characterize the mechanical performance of this type of surface using appropriate test setups.

To some extent, the interface strength parameters derived from experimental characterization depend on the test configuration. This is caused by sensitivity to the interaction between shear and normal stresses (Saldanha, Júlio, Dias-da-Costa, & Santos, 2013), uneven stress distribution (Santos, PhD Thesis: Assessment of the Shear Strength between Concrete Layers, 2009), unavoidable bending (Mohamad, et al., 2015), load deviation eccentricities (Garbacz, Courard, & Bissonnette, 2013) or other test imperfections. Furthermore, during over 50 years of research, a variety of different tests have been developed. The main reasons for this include the need to allow the assessment of shear reinforcement crossing the interface, the need to determine characteristics in the laboratory and onsite, and the desire to represent certain stress-states in real structures. The ability of the most commonly used tests to reproduce the actual resistance mechanism is analysed in Section 2, including their main positive aspects and drawbacks. The analysis was followed by the selection of six different test setups for the aforementioned experimental programme, based upon the produced stress-state, and the robustness and representativeness of the results.

Furthermore, the extensive experimental programme allowed mutual comparison between those test setups. Similar studies have already been performed (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005; Zanotti & Randl, 2019); nonetheless, indented or dimpled interfaces, which can be characterized as surfaces with an irregular roughness profile, were not included in those studies.

2 AVAILABLE TEST SETUPS – LITERATURE OVERVIEW

Many different test setups for the assessment of the shear behaviour of the concrete-to-concrete interface can be found in the literature. (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005) defined three different test categories based on the stress-state of the interface: tension stress, “pure” shear stress (direct shear tests) and a combination of shear and compression stress. In contrast, (Chmielewska, 2005) separated the tests into categories based on the test setup: direct tension, bending, splitting and shearing.

Some of the commonly used tests are briefly described below, including their main advantages and disadvantages.

2.1 BENDING TESTS

Bending tests are commonly used by many authors to assess the bond strength of the concrete-to-concrete interface. Stress distribution along the interface is complex since it depends on the shape and orientation of the interface plane. Usually, a small interfacial area is tested compared to the size of the specimen. Several tests have been developed over the years by different authors, some of which are presented in Figure 2.

(Ohama, Demura, Nagao, & Ogi, 1986) tested the adhesive properties of polymer-modified mortars using different test setups. Among others, an adhesion test in flexure was performed according to JIS A 1172 (JIS A 1172, 1995) (Method of test for strength of polymer-modified mortar). (Abu-Tair, Rigden, & Burley, 1996) developed a modified setup suitable for characterising the tensile bond strength of thin repair layers (20-25mm) or repair material placed between two halves of a substrate concrete specimen. (Wall, N.G., & B.R., 1986) performed flexure tests, with bond planes at 45° and 60° relative to the horizontal axis, in accordance with (ASTM C78, 2018). Compared to, e.g. the slant shear test, the flexure test is characterized by low sensitivity to surface roughness, and a large scatter of results has been reported by authors. (Kunieda, Kurihara, Uchida, & Rokugo, 2000) investigated bond properties at joint interfaces in concrete structures through four-point bending tests on notched specimens. They concluded that fracture energy was the most sensitive parameter for the evaluation of bond properties. (Kamada & Li, 2000) designed a test setup to induce a defect in the form of an interfacial crack between the repair material and the base concrete by introducing a T-shaped notch. Also, in contrast to the other tests mentioned here, the orientation of the interface plan is horizontal. The authors of the test observed similar behaviour occurring regardless of the surface preparation, meaning that this test is rather insensitive to differences in the roughness of the interface surface. Finally, (Luković, Schlangen, Y., & Šavija, 2013) performed three-point bending tests on small-scale composite beams and concluded that interface roughness does not increase the bearing capacity of members, but increases their monolithic behaviour and reduces the probability of debonding.

2.2 TENSION TESTS

Two sub-categories of tension tests can be defined based on the mechanism for stress transfer to the interface: direct or indirect.

2.2.1 Direct tension tests

In these types of tests (Figure 3), the interface is subjected to pure tension. Therefore, the pure tensile strength of the interface can be obtained without the effects of friction caused by external compressive forces.

The direct tension test, which is defined by (ASTM C1404, 1998), is probably the most difficult test to perform in this category (Zanotti & Randl, 2019). Precise alignment in the axis of loading is essential. Deviations can cause bending, thus leading to a large scatter of results.

The Pull-Off test is a standardized test (EN 1542, 1999) and, according to many authors (Courard, Lenaers, Michel, & Garbacz, 2011; Zanotti & Randl, 2019; Silfwerbrand, 2003; Austin, Robins, & Pan, 1995), it should be used for the evaluation of the tension bond strength between substrate concrete and either repair materials or a concrete overlay. One of the greatest advantages of this test is that it can be also performed in-situ, and thus its use is not limited to laboratory conditions. The main disadvantage is that it involves drilling of cores, which can cause unwanted damage to both the interface and the surrounding concrete layers. The latter type of damage can cause a large scatter of results and/or failure outside of the Interface Transition Zone (ITZ – a high-porosity zone in close proximity to the interface). Among others, (Austin, Robins, & Pan, 1995) investigated this test setup in detail, including the effects of drilling depth, shrinkage and material mismatch, by means of numerical analysis and an extensive experimental programme.

The Twist-Off test, also known as the Friction-transfer test or Torque test, was introduced by (Silfwerbrand, 2003) and later used by, e.g. (Naderi, 2007) to fill the gap in the range of available tests by developing a test configuration that induces shear stress at the interface and can be used *in-situ*. Instead of applying tensile force, like in the Push-Off test, torsional moment is applied at the top. Shear stress can be assessed by assuming the material exhibits linear elastic behaviour. Even though this test should be categorized as a direct shear test, it was included in this section because of its evident similarity to the abovementioned Pull-Off test setup.

2.2.2 Indirect tension tests (Splitting tests)

In splitting tension tests (Figure 4), failure occurs due to indirect tension. This test is a modified version of the Brazilian splitting test, as defined by e.g. (EN 14488-4, 2005), with the only modification being that the specimen is cast in two layers, creating an interface in-between. It can be used on both cubic and cylinder-shaped specimens.

This test is very simple to perform (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005), and the formwork used is the same as that used for standard compression tests. (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005) performed this test to obtain a comparison with direct and slant shear tests. Even though the coefficient of variation of the former was reported to be rather low (9% in average), it was stated that this test fails to represent the stress pattern that can be found in real structures.

2.3 SHEAR TESTS

Due to the significant differences between them, and in order to guarantee a better description, shear tests have been divided into three sub-categories: Push-Off, Direct Shear and Slant shear tests.

2.3.1 Push-off tests

This test configuration (Figure 5) is mainly used to characterize the shear strength of reinforced interfaces. In fact, test configurations in this category uniquely allow the use of shear reinforcement that crosses the interface, either perpendicularly or inclined.

The main advantage of the Push-Off test (Fig. 4a) is that normal stress perpendicular to the interface can be applied. (Mohamad, et al., 2015) tested 60 specimens, considered different normal loads perpendicular to the interface, and proposed an empirical expression to calculate the coefficients of cohesion and friction, based on interface roughness. (Randl, 2013) enhanced this test configuration to minimize the effects of unwanted bending. The study included a total of 83 specimens with and without shear reinforcement.

As for the L-type test, the main disadvantage is the small interfacial area compared to the size of the specimen. One of the first design expressions to predict interface shear strength was proposed in 1960 by Anderson (Anderson, 1960) based on experimental results obtained using this test. In the following years, many authors (Mattock and Hawkins (1972) (Mattock & Hawkins, Shear transfer in reinforced concrete - Recent research, 1972), Mattock et al. (1976) (Mattock, Li, & Wang, Shear transfer in lightweight reinforced concrete, 1976) and (Walraven, 1980)) adopted the test. Later, (Júlio, Dias-da-Costa, Branco, & Alfaiate, 2010) conducted an experiment on L-type specimens (Figure 5c) with or without shear reinforcement crossing the interface. They reported that this setup is less sensitive to changes in surface roughness.

In order to minimize work-intensity in comparison with the L-type test, a simplified small-scale test setup was proposed and referred to as the Z-type test (Figure 5b, see (Čairović, Girgle, Kostiha, Kadlec, & Štěpánek, 2016)). 150 mm-sided cubes were proposed as specimens so that standard cube formwork can be used. After the casting of the substrate layer (and surface treatment if needed), the overlay was cast in the same manner as with the Push-Off test. Afterwards, inclined 3 mm-thick notches were made using a concrete slicer. The resulting area of the interface subjected to shear stress was therefore 30x150mm. During testing, the specimen was simply subjected to compression load using a hydraulic press. Although this test procedure is easy to carry out, it has to be stated that large scatter of the results was observed (the CoV was up to 20%).

2.3.2 Direct shear tests

Direct shear tests (Figure 6) are interface strength tests with a simple configuration. They are easy to perform and highly efficient (see Section 2.4.)

The Bi-surface test (Figure 6c) was introduced by (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005). Its main advantage is that loads are applied symmetrically, unlike in the case of the single shear plane test (Figure 6a). According to the authors, the proposed configuration leads to a shear stress state representative of the expected stress state of interfaces in real structures. A comparison between the interface shear strength obtained by bi-surface shear and tension tests (pull-off and splitting tests) was presented. Nonetheless, it is uncertain as to what extent shear strength is affected by friction caused by normal stresses acting at the interface.

2.3.3 Slant shear tests

The Slant Shear Test (SLT) (Figure 7), also known as the Arizona slant shear test, was first proposed by (Kriegh, 1976). It is widely used and its application is described in several international standards (e.g. EN 12615, 1999). The interface is simultaneously loaded in shear and compression, allowing the assessment of friction.

Interface strength depends on both friction and adhesion and, hence, it has been found that it is insufficient to employ a unique test if one wishes to characterize this strength with the required representativeness. Therefore, some authors (Zanotti & Randl, 2019; Saldanha, Júlio, Dias-da-Costa, & Santos, 2013) have performed tests with two different angles. If a linear relation (the constant value of the coefficient of friction) is considered, part of the interface failure envelope in compression can be obtained, including interface shear strength.

Several researchers have reported monolithic failures of specimens to be frequent, even with an angle of 30° between the interface and loading axis. To ensure adhesive failure occurs, (Saldanha, Júlio, Dias-da-Costa, & Santos, 2013) introduced the Modified Slant Shear Test (M-SLT), where both parts of the specimen were reinforced.

Even with those modifications, monolithic failures can occur even for smooth interface surfaces, when lightweight-aggregate concrete is used (Čairović Đ. , Zlámal, Žitt, & Štěpánek, 2018). This type of failure occured due to the low tensile/compressive strength ratio. For that reason, the Confined Slant Shear Test (C-SLT) (Čairović Đ. , Zlámal, Žitt, & Štěpánek, 2018) was proposed (see Figure 7c). Steel square tubes were used to transversely confine the concrete, thus increasing the strength of the monolithic parts. It must be remarked that this test should only be resorted to in those situations when interface roughness is high and adhesive failure cannot be achieved otherwise, since the uneven stress distribution along the interface caused by confinement has to be taken into account. On the other hand, a similar situation can occur with standard tests when there is a noticeable difference in the modulus of elasticity of the substrate and overlay layers (Austin, Robins, & Pan, 1995; Santos & Júlio, Factors Affecting Bond between New and Old Concrete, 2011).

2.4 COMPARISON

When there is no reinforcement crossing the interface, the main contributors to interface shear strength are cohesion and friction. Cohesion represents the chemical bond between two concrete layers, or the bond between the hardened substrate concrete and the overlay when it is cast in a fresh state. Hence, it can be stated that interface strength will depend on the surface properties of the base layer and the chemical and mechanical properties of the overlay concrete. The overall bond strength will be governed by the weakest link in this composite system. Possible failure modes in tension are presented in Figure 8.

An ideal test setup should be simple and easy to use and should provide stable results without large scatter. Table 1 gathers together the most relevant features and capabilities of the abovementioned tests for characterizing the strength capacity of the interface. Besides the stress state on the interface and the fact that different test configurations allow the assessment of either tension or cohesion with or without the effects of friction, other factors can influence the determination of the most proper test setup. For example, if reinforcement crossing the interface (shear dowels) should be included, only the Push-Off or L-type test can be used. If tests have to be performed on site, the Pull-Off and Twist-Off test can be used in the laboratory, and also on site.

Efficiency was defined as the ratio between specimen volume and interfacial area, and characterized as low for values lower than 30%, medium in the range from 30-60%, and high if higher than 60%. The presented coefficients of variation (CoV) are based on the experimental programme carried out within this (and previous (Čairović, Girgle, Kostiha, Kadlec, & Štěpánek, 2016; Čairović Đ. , Zlámal, Žitt, & Štěpánek, 2018)) research, and data available in the literature (Momayez, Ehsani, Ramezanianpour, &

Rajaie, 2005; Zanotti & Randl, 2019; Courard, Piotrowski, & Garbacz, Near-to-surface properties affecting bond strength in concrete repair, 2014; Lin & Chen, 1989).

Some authors have obtained both adhesive and cohesive failures (interface and monolithic concrete failure modes). For example, when performing the Twist-Off test, (Silfwerbrand, 2003) reported only one interface failure out of 58 specimens in total. Slightly better results were obtained for the Pull-Off test, where 11 out of 74 specimens failed along the interface. Especially when interface roughness is higher (i.e. obtained by water-blasting, sandblasting or similar methods), a high percentage of cohesive failures can be expected. (Ohama, Demura, Nagao, & Ogi, 1986) reported about 40% of failures were adhesive when performing bending tests, but that the number was as low as 5-15% for Slant-Shear tests or 15-30% for direct shear tests. (Santos & Júlio, Factors Affecting Bond between New and Old Concrete, 2011) reported an increasing number of Slant-Shear specimens failed monolithically with increasing interface roughness.

3 EXPERIMENTAL PROGRAMME

In order to experimentally obtain a correlation between different test setups and consequently the failure envelope of dimpled interfaces, six different tests were performed: the Splitting tension test (SPL), the Pull-Off test (PLF), the Bi-Surface direct shear test (DRT), the L-Type test (LTP), the simplified Push-Off test (PSH) and the Modified Slant Shear test (M-SLT). The experimental programme involved 39 specimens in total, meaning that six specimens were tested for each test setup, except for the Pull-Off test, where nine specimens were tested.

Special attention was paid to keeping those parameters known to affect interface strength constant: roughness of the interface, material properties, age of specimen (i.e. stresses induced by shrinkage), curing, surface moisture and cleanliness.

3.1 INTERFACE ROUGHNESS

A light HDPE membrane with diagonally oriented 8mm dimples was placed in formwork, leading to the formation of a concrete-concrete interface which was referred to as “dimpled”, as presented in Figure 9.

The surface topography was obtained using 3D optical profilometry (Čairović D. , et al., 2016). A mobile measurement system based on the scanCONTROL 2750-100 laser triangulation profilometer allowed roughness parameters to be obtained with a high accuracy of 50µm. Both 2D and 3D surface texture parameters were established by following the guidelines of (ISO 4287:1997, 1997) and (ISO 13565-1, 1996), respectively, and (ISO 25178-1:2016 - Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 1: Indication of surface texture, 2016) was utilised for areal methods.

It must be remarked that waviness and micro-roughness profile are included in the results. Thus, the presented values (Table 2) represent primary profile parameters (or P-parameters) and the labels R and S are used to distinguish between the profile and areal approach, respectively. Only the surface levelling was performed considering a 1st order polynomial fitted by the least-squares method. This approach prevents errors from being caused by misalignment of the measuring apparatus. Higher-order polynomials should be used with caution because of the tendency to diverge close to the edges of the surface. A similar approach was suggested and used by (Santos & Júlio, Effect of Filtering on Texture Assessment of Concrete Surfaces, 2010) to avoid the results being influenced by filtering and cut-off length. They also reported that micro-roughness was similar for all concrete surfaces, regardless of the treatment. Therefore, the use of F-filters to remove small-roughness components seems to be unnecessary in this field of application.

The texture profile (Figure 10b) used for assessing the roughness parameters was deliberately placed in the middle of the dimples and oriented horizontally (the same orientation was used during the mechanical tests). In this regard, the Average Roughness (R_a) and Root Mean Squared Roughness (R_q) values are slightly higher, which is as expected due to the abovementioned placement of the profile. Still, the values obtained by both the profile and areal method were similar. As for the parameters connected with peaks (and valleys, respectively), the areal method resulted in higher values. This was also expected since it is unlikely that the highest peaks on the whole surface are placed along a single profile line.

Table 2 also includes Skewness (R_{sk}), Kurtosis (R_{ku}) and other statistical parameters of a surface with stratified functional properties (ISO 4287:1997, 1997; ISO 13565-1, 1996; ISO 25178-1:2016 - Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 1: Indication of surface texture, 2016). These can provide further information about topography, but should not be used for the evaluation of surface roughness. For example, with Skewness below zero, the profile height distribution has a deviation above the mean line of the profile. This means that the larger part of the interface is located above the mean profile line. If Kurtosis is lower than 3, it can be concluded that the height distribution is even. Great attention must be paid when comparing these statistical parameters for surfaces with different roughness profiles since unrepresentative (or even incorrect) conclusions can be derived.

When comparing the presented roughness parameters with other data available in the literature, it can be suggested that only “average” parameters be used, namely *Ra* or *Rq*, since more stable results are usually obtained regardless of the approach (areal or profile), filtering and form removal method.

The Sand Patch Test (Kaufmann, 1971) is a widely used method for the classification of surface roughness. In this sense, in (Model Code 2010, 2013) it is suggested that this property be classified into different categories via the test: very smooth, smooth, rough and very rough. The procedure consists in spreading a defined amount of fine glass beads on the surface to be characterized and measuring the diameter of the circle. The parameter obtained by this method is referred to as “peak-to-mean” roughness, or Mean Texture Depth (MTD). This procedure, nonetheless, cannot be used for this type of surface since it would lead to partial filling of the dimples, and the results might thus be unrepresentative. For that reason, the MTD was estimated using equation (1), which is based on previous studies (Čairović, Girgle, Kostiha, Kadlec, & Štěpánek, 2016), and is in agreement with Randl's suggestion (Randl, 2013).

$$MTD \cong {}^{1}\!/_{2} R_z \cong 2 \cdot R_a \cong 4.5\text{mm} \geq 3.0\text{mm} \rightarrow \text{very rough} \tag{1}$$

Therefore, the dimpled surface was characterized according to (Model Code 2010, 2013) as very rough (Table 3), comparable to those obtained by high-pressure water-blasting, or indented surfaces.

Dimples can also be assumed to be shear keys, as defined in Section 6.3.5 of Model Code 2010, with proportions close to the recommended limits.

3.2 MATERIAL PROPERTIES

In order to minimize the effects of material mismatch (especially modulus of elasticity and its effect on uneven stress distribution (Saldanha, Júlio, Dias-da-Costa, & Santos, 2013)), the same concrete mix design was used for both the substrate layer and the overlay. Crushed granite was used as aggregate. The mixture proportions and properties of the hardened concrete are summarized in Table 4-5. The properties of the hardened concrete were obtained at the age of 28 and 35 days for the overlay and substrate layer, respectively (corresponding to the age of the specimens at the time of testing). The specimens were removed from the formwork after 2 days and kept fully saturated under plastic sheets at approximately 20°C for an additional 5 days, following by air-curing in the laboratory until testing. The differences in age and curing conditions lead to a slight mismatch in compressive strength regardless of the fact that the mix design was the same.

3.3 SPECIMEN PREPARATION

(Courard, Piotrowski, & Garbacz, Near-to-surface properties affecting bond strength in concrete repair, 2014; Courard, Lenaers, Michel, & Garbacz, 2011) presented different factors affecting the bond between concrete layers (with different ages), including the degree of influence within a scale of 0-3. Besides material properties and surface roughness, the factors that govern the mechanical response of the interface are stated to be cleanliness, pre-wetting, compaction and curing.

For that reason, all specimens included in this experimental programme were cast at the same time. The overlay was cast 7 days after the substrate layer. Before casting the overlay, the surface was pre-wetted and left to dry in order to achieve optimal saturation, i.e. Saturated Surface Dry (SSD). The surface was kept clean and free of laitance at all times. The direction of casting was always parallel to the interface. During that period, the specimens were kept in formwork covered by plastic sheets.

After the casting of the overlay, the specimens were moist cured for 7 days under the same conditions and then kept in air until testing took place 21 days after. The ages of the substrate and overlay concrete were 35 and 28 days, respectively.

3.4 SPLITTING TENSION TEST

The splitting tension test (SPL) is one of several widely adopted setups for characterizing the tensile strength of cementitious materials. It can be performed on either cubic or cylinder specimens. (Ramey & Strickland, 1984) were the first to propose using this type of test to evaluate interface tensile strength. Afterwards, many authors (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005; Li, Geissert, Frantz, & Stephens, 1999; Zanotti & Randl, 2019; Espeche & León, 2011) adopted the same approach.

Splitting tensile strength is usually obtained using Timoshenko's equation (2), which is derived from elasticity theory (Timoshenko & Goodier, 1951).

$$f_{t,i} = \frac{2F}{\pi b \cdot d} \tag{2}$$

Where $f_{t,i}$ is the splitting tensile strength of the interface, *F* is the maximal value of applied force, and *b* and *d* are the dimensions of the interface (i.e. specimen cross-section). Although it is considered not to be relevant in this case, it is worth noting that further analysis needs to be performed in order to evaluate whether equation (2) can be applied if different materials are used, i.e. the effect if modulus mismatch needs to be determined.

Within the scope of this research, six specimens were tested. Cubic specimen geometry was chosen (Figure 11a), with the area of the interface being 150x150mm. The average value obtained for the splitting tensile strength of the interface was 2.1MPa, with a coefficient of variation (CoV) of 7%. A similar scatter of the results was also reported by other authors (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005; Espeche & León, 2011).

The failure mode was in all cases adhesive (Figure 11b), i.e. monolithic failure did not occur. It can also be observed that a significant number of dimples (which are part of the overlay) sheared off. This confirms that part of the failure occurred outside of Interfacial Transition Zone (ITZ). This was probably caused both by the larger area of the dimples (compared to the base area beneath) and the biaxial stress state, or more precisely the vertical compressive stress acting perpendicular to the dimples.

It should be mentioned that the size of the specimen and the test boundary condition can significantly affect the resulting splitting strength determined using the Brazilian test. As was presented by (Rocco, Guinea, Planas, & Elices, 1999), the specimen shape and the width of the bearing strips used to distribute the load during the test are important variables that need to be taken into account. While the width of the wooden strip used in this experimental programme was 10mm and the size of the prismatic specimen was 150mm, the difference between the tensile strength and the experimentally obtained value is below 2%. Even though in this case the difference is insignificant, the authors reported that the splitting strength can vary by up to 35%.

This simple test configuration provided consistent results and can be characterized as a suitable procedure for the evaluation of concrete-concrete interface tensile strength.

3.5 PULL-OFF TEST

The Pull-Off test (PLF) is identified as a direct tension test, and it has lately been suggested by many authors (Silfwerbrand, 2003; Zanotti & Randl, 2019) as being suitable for characterizing the adhesion between different-aged concrete layers.

Nine 50mm-diameter cores, with a depth extending approximately 15mm below the interface, were drilled from a slab specimen. This procedure was suggested by (Austin, Robins, & Pan, 1995) in order to minimize stress concentration along the edges. The thicknesses of the substrate layer and overlay were 100mm and 50mm, respectively. A Proceq DY-2 automated pull-off tester was used. The tensile strength was defined as the ratio between the maximal force and the idealized area of the interface (the area of a circle with a 50mm diameter).

Using this approach, the computed tensile strength of the interface was approximately 2.0MPa. A high CoV of 18% was obtained, though this lay within the same range (from 2.1% for water-blasting up to 20% for jack-hammered surfaces) reported by (Courard, Piotrowski, & Garbacz, Near-to-surface properties affecting bond strength in concrete repair, 2014).

Three different types of failure were observed (Figure 12): adhesive, mixed and cohesive. Adhesive failure (Figure 12a) only occurred for one specimen, and it took place partially outside the ITZ as it did with the Splitting test, with some of the dimples being pulled off. Considering that the surface area of the dimple is much larger than the base area beneath, this type of failure was expected.

Mixed failure occurred for three specimens, and it was always generated via the adhesive failure of approximately 50% of the surface, while the rest of the surface experienced failure of the concrete overlay. The remaining five specimens showed cohesive failure of the overlay concrete in close proximity to the interface. This could be caused by core drilling, which induces micro-cracking and thus lowers the strength of the concrete, and especially of the overlay (Courard, Piotrowski, & Garbacz, Near-to-surface properties affecting bond strength in concrete repair, 2014). The obtained values for both mixed and cohesive failures only fell within the lower bounds of the interfacial tensile strength, ranging between 1.5-2.1MPa.

A high number of undesired cohesive failures were reported by other authors (Zanotti & Randl, 2019; Silfwerbrand, 2003; Courard, Lenaers, Michel, & Garbacz, 2011; Austin, Robins, & Pan, 1995). On the other hand, it must be highlighted that this test (with medium efficiency and low requirements in terms of both time and labour force) is a standardized test method (EN 1542, 1999) which can also be implemented *in-situ*.

3.6 L-TYPE TEST

This type of test was widely used in earlier research (Anderson, 1960; Mattock & Hawkins, Shear transfer in reinforced concrete - Recent research, 1972; Mattock, Li, & Wang, Shear transfer in lightweight reinforced concrete, 1976; Walraven, 1980). The specimen geometry consisted of two L-shaped parts of 300x400mm and 150mm in width, reinforced as described in Figure 13, in order to ensure failure of the interface occurred. During casting, a 10-25mm thick polystyrene slab was placed into the formwork to generate notches separating both parts. The dimensions of the interfacial area were 150x250mm.

The average shear strength of the interface, based on the results from the six tested specimens, was 2.5MPa with an 8% CoV. Typical Load Displacement curves are presented in Figure 14. The shear stress was calculated as the ratio between the maximum applied force over the interfacial area, assuming uniform shear stress distribution. Adhesive failure with shearing of the dimples was observed for all specimens (see Figure 13).

3.7 BI-SURFACE TEST

For the modified direct shear test, which was suggested by (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005) and is referred to as the Bi-Surface test, a 150x150x150mm cubic specimen was used (Figure 15a) with an interfacial area of 150x150mm and an overlay constituting one third of the specimen width.

The average shear strength of the interface obtained by the use of this method on six specimens was 3.2MPa, with a 12% CoV. Only adhesive failure was observed, with all the dimples sheared off. The dependence between applied force and both vertical and horizontal displacements is presented in Figure 16.

If uniform stress distribution is assumed, the obtained values are higher than those gained from the L-type test. This effect can be attributed to the friction caused by compressive stress acting perpendicular to the interface, which can be expected from the specimen geometry and load direction (see Figure 15b).

3.8 PUSH-OFF TEST

While (Randl, 2013) used an optimized setup by including a cantilever capable of counteracting the bending moment caused by load eccentricity, the test performed in this study (see Figure 17) is more similar to the one conducted by (Mohamad, et al., 2015).

The interfacial area was 150x300mm, while the thickness of both concrete layers was 150mm. In total, six specimens were tested. The effects of bending were neglected, and shear stress was calculated assuming uniform distribution. Compressive stress in a range between 0.1-1.0MPa (more precisely 0.1, 0.5 and 1.0MPa) was deliberately applied before loading the specimen in shear, as can be observed in Figure 18. Based on the amount of applied compressive stress, shear resistance ranged between 2.5-4.3MPa, with average values of 3.2MPa and 0.6MPa for shear and compression perpendicular to the interface, respectively. It should be noted that the large scale of the results, caused by different levels of compressive stress, was in fact desired in this case. The scatter of results, which can be defined as deviations from the mean line presented by the linear fit, was in fact rather low, with a CoV of below 9%.

Using the Mohr-Coulomb linear sliding criterion, values could be extrapolated for the coefficients of friction and adhesion. If only the data from this test were used, the coefficient of friction would be 1.4 (corresponding to a friction angle of 55°), while adhesion would reach 2.3MPa.

3.9 SLANT-SHEAR TEST

In order to prevent the specimen from undergoing cohesive failure, the modified test suggested by (Saldanha, Júlio, Dias-da-Costa, & Santos, 2013) was performed, with the main difference being that both halves of the specimen were reinforced as described by the authors (see Figures 7b). The authors also presented a detailed numerical study, confirming that reinforcement will not affect the distribution of stress along the interface, and that shear and normal stress will be distributed uniformly, assuming that the same material was used for both halves of the specimen. The angle between the interfacial plane and the vertical axis α was 30°. The size of the specimen was 150x150x600mm, with a base height of 170mm.

The same adhesive failure mode was observed for all six tested specimens, which is similar to the results from the Push-Off and L-Type tests (see Figure 19b). Average values were computed for shear stress τ (10.4MPa) and compressive stress σ_n (6.0MPa) by assuming uniform stress distribution and using equations (3) and (4).

$$\tau = \frac{F \cdot \sin\alpha \cos\alpha}{b \cdot d} = \frac{1}{2}\frac{F \cdot \sin 2\alpha}{b \cdot d} \tag{3}$$

$$\sigma_n = \frac{F \cdot \sin^2 \alpha}{b \cdot d} \tag{4}$$

Brittle failure was observed for all specimens (see Figure 20) for low shear slip values. This is in accordance with the general behaviour of concrete-to-concrete interfaces without shear reinforcement, as described by (Randl, 2013). A CoV of 12% was assessed. If in addition to the data obtained by the Push-Off test, the average results of the Slant Shear test were used to interpolate the coefficients of friction and adhesion, similar values would be obtained: 1.3 for the friction coefficient (friction angle 53°) and 2.5MPa for adhesion.

4 RESULTS AND DISCUSSION

Adhesive failure modes were mostly observed within the scope of this experimental programme, except for in the case of the Pull-Off test, as was discussed in Section 3.8. Even though these failures were identified as adhesive, they always occurred partially outside the ITZ, i.e. dimples were sheared off. The residual failure surface was therefore composed of a very smooth flat surface together with a somewhat rougher surface under the dimples. Hence, although it should be further investigated, the residual friction angle is expected to be much lower. Also, in most of the cases, only smaller sized pieces of aggregate protruded into the interface, leading to the conclusion that higher resistance and improved behaviour can be achieved if the size of the dimples is larger or at least the same as that of the maximum coarse aggregate size. The latter finding raises the question as to whether the code provisions (EN 1992-1-1, 2008; Model Code 2010, 2013) for dimpled surfaces and the minimal height of the shear keys should be altered to address these assumptions.

With the combination of different test setups used in this research, three interface strength parameters were assessed, namely: tensile strength, shear strength and friction angle, see Figure 21.

The average tensile strengths obtained by the Pull-Off and Splitting test were 2.0MPa and 2.1MPa, respectively. The obtained difference of 5% was in accordance with other data presented in the literature. For example, (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005) obtained a difference of up to 3% for a reference series (using cement mortar without silica fume). For the purpose of this study, a value of 2.0MPa was considered, this being a lower estimate of the interface tensile strength and therefore erring on the side of caution.

Even though two different “pure” shear tests were performed, the value of 2.5MPa obtained by the L-Type test was considered. Bi-Surface shear tests are thought to tend to over-estimate shear strength due to friction caused by normal stresses acting perpendicular to the interface, as was discussed earlier.

Friction was assessed using both the Slant Shear and Push-Off test results. For this purpose, linear regression was assumed and the resulting value of friction angle was 53° (coefficient of friction 1.30), while the pure shear strength of the interface was 2.5MPa, which corresponds to the L-type test results and the adhesive bond coefficient of 0.63.

Based on those results, a modified Mohr-Coulomb failure envelope can be formed (Figure 22), with the originally proposed linear formula in compression and the modified non-linear formula in tension, as suggested by (Shen, Shi, & Barton, 2018) and resorting to equations (6):

$$\tau = c` + \sigma_n \tan \varphi` \qquad (5)$$

$$\varphi` = \varphi - (45° - \varphi)\frac{\sigma_n}{f_t} \qquad (6)$$

$$c` = c + (f_t - c)\left(\frac{\sigma_n}{f_t}\right)^2 \qquad (7)$$

where c’ and φ’ are the adhesion and friction angle functions, respectively.

(Espeche & León, 2011) suggested using Carol’s equation (8) (Carol, Prat, & López, 1997) to define the failure envelope and equations (9)-(10) to predict adhesion based on the interface tensile strength and friction angle. The minimal ratio between the cohesion and tensile strength of the interface was set at √3 for low friction angles. This is in agreement with results obtained by other researchers (see (Espeche & León, 2011; Zanotti & Randl, 2019)) since a ratio of around 2.0 is usually presented in the literature.

The authors used experimental results presented by (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005), who evaluated wire-brushed surfaces with estimated profile amplitudes of 3-4mm and 7-8mm for the low-roughness and high-roughness category, respectively. Furthermore, the same approach was suggested by (Zanotti & Randl, 2019) based upon an extensive experimental programme conducted on sandblasted surfaces. Roughness was assessed via the Sand Patch Test, and the resulting MTD was 1.2-1.5mm. Even though the roughness of both the wire-brushed and sandblasted surfaces differed greatly, both roughening methods provided uniform surfaces with regular roughness due to the exposure of the aggregate.

$$\tau = \sqrt{(c - \sigma_n \tan \varphi)^2 - (c - f_t \tan \varphi)^2} \qquad (8)$$

$$c = \left(\frac{2 - \sin \varphi}{\cos \varphi}\right) f_t, \quad for\ \varphi > 30° \qquad (9)$$

$$c = \sqrt{3} f_t, \quad for\ \varphi \leq 30° \qquad (10)$$

Nonetheless, based on the results of this experimental programme, a lower ratio of 1.2 was obtained by comparing the pull-off tension strength to the shear strength obtained by the L-type test. This means that the shear strength of the interface predicted by equation (9) is 3.7MPa, which is more than 50% higher compared to the value of 2.5MPa gained from the L-type test (see Figure 22, series Espeche and León (a)).

Alternatively, the tensile strength of the interface can be obtained provided that shear strength and friction are experimentally obtained. If adhesion were set at 2.5MPa, based on the L-type test results, the tensile strength resulting from equation (9) would be approximately 1.2MPa, which is only 60% of the average value obtained by Pull-Outs. This scenario is also included in Figure 22, as the series Espeche and León (b).

While the surface roughness parameters are comparable with those of the high-roughness surface used by (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005), the roughness profile of the dimpled surface can be characterized as highly irregular. Therefore, it can be concluded that precautions should be taken when using the approach proposed in (Espeche & León, 2011) for surfaces with irregular roughness and indented surfaces since shear strength might be overestimated (and tensile strength thus underestimated).

Although in this case the linear regression (with a determination coefficient R^2 of more than 0.99) fits the experimental data, use of either Carrol's (8) or Shen's equations (5) is advised due to their universality, and the fact that those methods rely on quasi-brittle fracture mechanics behaviour (Carol, Prat, & López, 1997).

5 MODEL CODE 2010 PROVISIONS

(Model Code 2010, 2013) represents a huge milestone in the design of the concrete-to-concrete interface. Based on Randl's suggestions (Randl, 2013), design approaches for ductile and brittle interface behaviour were introduced there, the latter being of more interest in this case.

When comparing experimental results with code (Model Code 2010, 2013) provisions for very rough or indented interfaces, slightly higher values have been obtained, as can be expected. However, it can still be stated that the code provisions provide an adequate estimate of interface strength. The proposed coefficient of friction is 1.0, while the value obtained experimentally using concrete with a compressive strength of more than 50MPa is 1.3. Although it requires further research, this estimation seems reasonable and aligns with other results presented in the literature (Mohamad, et al., 2015; Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005; Zanotti & Randl, 2019). On the other hand, the proposed coefficient of adhesion c_a is 0.50, and this is less conservative since a value of 0.63 was obtained experimentally (assuming mean concrete tensile strength values).

(Randl, 2013) proposed a value of 2.00 for the partial safety factor for the adhesive bond, since it is strongly influenced by cleanliness, surface preparation methods, workmanship and saturation, among other things. This raises the question of whether this value can ensure a reliable safety margin, even if lower-strength concrete is used for either the substrate layer or the overlay. Combined with the failure mode discussed above, revision of the proposed shear key geometry and further research addressing the abovementioned issues are highly advised.

6 CONCLUSION

Within the scope of this research, a comprehensive overview of the state-of-the-art with regard to tests designed to characterize interface strength was presented, including the main advantages, efficiency, adequacy and capabilities of different test setups. Furthermore, the failure envelope of a “dimpled interface” (obtained by casting concrete against an HDPE membrane with diagonally oriented dimples of 8mm in height) was presented based on the results of 6 specific test configurations. Surface roughness was also characterized, including 20 texture parameters obtained by both the areal and profile approach.

The following conclusions can be drawn:

- According to the provisions of *fib* Model Code 2010, the presented dimpled surface can be categorized as very rough or indented. The experimentally obtained coefficient of adhesive bond c_a is 0.6, while the coefficient of friction μ is 1.3, corresponding to a friction angle of approx. 53°. The recommended values for very rough or indented interfaces according to *fib* Model Code 2010 are 0.5 for adhesion and 1.0 for friction, respectively. Even though both values are lower, much more conservative results were obtained for different types of surface preparation (Zanotti & Randl, 2019).

- Failure of the interface occurred partially outside the ITZ, caused by the shearing of the dimples. The presented failure envelope for a dimpled surface is different from the surfaces obtained by, e.g. sandblasting, water-blasting or wire-brushing. The main difference is the ratio between shear and tensile strength; the value of 1.2 is rather low compared to that obtained in other studies. Therefore, caution is suggested when using the approach presented by Espeche and León (Espeche & León, 2011) for representing surfaces with an irregular roughness profile.
- Based on the experimental behaviour of a dimpled surface, namely lower shear strength compared with the predicted values described in Section 4, it is suggested that the geometrical minimal requirements for shear keys proposed for the *fib* Model Code 2010 be revised, especially with regard to maximum coarse aggregate size.
- Both the Splitting and Pull-Off test can be used for the assessment of concrete-to-concrete interface tensile strength. The splitting test tends to slightly overestimate tensile stress, with the differences obtained within this study and reported in the literature being less than 10%. The coefficient of variation CoV and chances of cohesive (monolithic) failure are significantly lower if the Splitting test setup is used.
- Shear strength of the analysed dimpled interface obtained by Bi-Surface test (3.2 MPa) was noticeably higher, comparing to the L-Type test results (2.5MPa), seemingly due to the contribution of friction (unwanted in this characterization). Also, better correspondence between test results and failure envelope was observed for the L-Type test. Therefore, it can

be concluded that this test setup is the most suited for the evaluation of the interface shear strength, regardless the lower efficiency (see Table 1).

- Effects of friction or normal stress acting perpendicular to the interface were assessed using two different test setups: Push-Off and Slant-Shear tests. The obtained values of both the interface strength and the scatter of the results were similar (friction angle 55° and 53°, respectively), this meaning that both tests are suitable for characterization of concrete-to-concrete interfaces.
- It has to be stated that in this experimental programme only one type of dimpled surface was characterized and assessed. Nonetheless, the robust and representative test methodology presented herein can be followed in the future characterization of dimpled and/or highly irregular surfaces.

An extensive numerical programme is currently being carried out to investigate the fracture mechanism in order to shed light on the governing parameters influencing interface strength.

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Table 1 Comparison of different tests for the assessment of interface strength

Category	Test setup / Author	Allows assessment of			Allows dowels	Efficiency		In-situ use	CoV	Work intensity
		tension	cohesion	friction$^{1)}$						
Bending tests	Ohama et al. (Ohama, Demura, Nagao, & Ogi, 1986)	yes	no	no	no	25.0%	low	no	-	low
	Abu-Tair et al. (Abu-Tair, Rigden, & Burley, 1996)	yes	no	no	no	25.0%	low	no	-	low
	Wall et al. (Wall, N.G., & B.R., 1986),	yes	yes	no	no	33.3%	medium	no	-	low
	Kunieda et al. (Kunieda, Kurihara, Uchida, & Rokugo, 2000)	yes	no	no	no	17.5%	low	no	-	medium
	Kamada & Li (Kamada & Li, 2000)	no	yes	no	no	75.0%	high	no	-	medium
Tension tests	Direct tension (ASTM C1404, 1998)	yes	no	no	no	33.3%	medium	no	-	high
	Pull-Off (EN 1542, 1999)	yes	no	no	no	30.7%	medium	yes	18%$^{2)}$	low
	Twist-Off (Naderi, 2007)	no	yes	no	no	30.7%	medium	yes	-	medium
	Splitting test (EN 14488-4, 2005)	yes	no	no	no	66.7%	high	no	7%	low
Shear tests	Push-Off	no	yes	yes	yes	33.3%	medium	no	12%	high
	Z-type	no	yes	no	no	13.3%	low	no	25%	medium
	L-type	no	yes	no	yes	18.2%	low	no	8%	medium

	Direct shear – single plane	no	yes	no	no	66.7%	high	no	-	low
	Direct shear – double plane	no	yes	no	no	33.3%	medium	no	7%4)	low
	Bi-surface shear	no	yes	no5)	no6)	66.7%	high	no	12%3)	low
	Slant shear	no	yes	yes	no	33.3%	medium	no	-	low
	Modified SLT	no	yes	yes	no	33.3%	medium	no	12%	medium
	Confined SLT	no	yes	yes	no	33.3%	medium	no	-	high

Comments:

1) Friction caused by external compressive load, not by clamping forces

2) *Momayez et al.* (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005) reported an average value of 9.8%

3) Similar values of 10.6% and 9.6% have been reported by *Momayez et al.* (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005)

4) Average value reported by *Lin and Chen* (Lin & Chen, 1989), for plain mortar 9%

5) Compressive stress acting perpendicular to the interface is unwanted in this case

6) Even though the authors (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005) stated that dowels could easily be accommodated, it would only be possible if the specimen size was significantly changed.

Table 2 Statistical roughness parameters

Profile Parameters		**Areal Parameters**		units
R_a	2.96	**S_a**	2.36	[mm]
R_q	3.21	**S_q**	2.74	[mm]
R_{pmax}	2.94	**S_{pmax}**	2.72	[mm]
R_{vmax}	-4.91	**S_{vmax}**	-6.02	[mm]
R_t	7.85	**S_t**	8.74	[mm]
R_p	2.9	**S_p**	2.46	[mm]
R_v	-4.73	**S_v**	-5.59	[mm]
R_z	7.63	**S_z**	8.05	[mm]
R_{max}	7.81	**S_{max}**	8.4	[mm]

R_k	0.95	**S_k**	1.57	[mm]
R_{pk}	0.05	**S_{pk}**	0.14	[mm]
R_{vk}	9.76	**S_{vk}**	7.5	[mm]
R_{sk}	-0.56	**S_{sk}**	-0.98	[-]
R_{ku}	1.53	**S_{ku}**	2.37	[-]
M_{r1}	4.43E-04	**S_{mr1}**	2.56E-01	[mm]
M_{r2}	4.48E-01	**S_{mr2}**	3.99E-02	[mm]
V_{vv}	5.96E-02	**V_{vv}**	3.49E-02	[m^3/m^2]
V_{vc}	2.84	**V_{vc}**	1.92	[m^3/m^2]
V_{mp}	1.01E-02	**V_{mp}**	1.17E-02	[m^3/m^2]
V_{mc}	4.69	**V_{mc}**	3.41	[m^3/m^2]

R_a - Average Roughness; R_q - Root Mean Squared Roughness; R_{pmax} - Total peak height; R_{vmax} - Total valley depth; R_t - Total height of the profile; R_p - Total peak height within sampling length; R_v - Total valley depth within sampling length; R_z - Mean Peak-to-Valley height; R_{max} - maximum height of the profile over sampling length; R_k – vertical difference in core section; R_{pk} - Height of protruding peak; R_{vk} – height of protruding valley; R_{sk} – Skewness; R_{ku} – Kurtosis; M_{r1} – material portion of protruding peaks; M_{r2} – material portion of protruding valleys; V_{vv} – void volume of the valley section; V_{vc} – void volume of the core section; V_{mp} – material volume of the peak section; V_{mc} – material volume of the core section

Table 3 Coefficients for very rough surfaces, according to (Model Code 2010, 2013)

Surface Roughness	c_a	c_r	κ_1	κ_2	β_c	μ for f_{ck} ≥ 35MPa
Very Rough * MTD ≥ 3.0mm	0.5	0.2	0.5	0.9	0.5	1.0

* valid also for shear keys

Table 4 Mixture proportions (in kg/m3)

Cement 42.5R	380
Fine aggregate	870
Coarse aggregate 4-8mm	275
Coarse aggregate 8-16mm	713
Max. aggregate size	16
Water	150
Plasticizer admixture	3.4
w/c ratio	0.39

Table 5 Hardened concrete properties (in MPa)

	Substrate	Overlay	Average
Cubic compressive strength $f_{c,\ cube}$	52.5 ± 1.7	56.4 ± 2.3	54.5
Splitting tensile strength f_t	3.8 ± 0.4	4.0 ± 0.1	3.9
Modulus of Elasticity E_c	30.9 ± 0.3	31.3 ± 0.6	31.1