

# Effect of interface moisture content on the interlayer bond strength

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**Abstract.** Reducing carbon dioxide emissions in concrete construction is a global priority. One potential solution is functionally graded concrete, where concretes with different properties are used within a single structural element to reduce environmental impact. For functionally graded members with horizontal concrete layers, the mechanical performance of the interface zones is critical for structural behaviour. Factors such as the casting technique, concrete grade, substrate surface texture, time delay between layer deposition and moisture content all influence the interlayer properties. While studies have explored these factors, the impact of interface moisture on bond strength remains inconclusive. This research evaluates the relationship between the interface surface moisture and interlayer bond strength. Splitting tensile tests were conducted on 40 fresh-on-fresh cast layered specimens with low-slump or high-slump concrete mixes. The substrate surface moisture was controlled by drying or adding a known volume of water. In the low-slump mixes a high surface moisture content led to a 10 % reduction in bond strength, likely due to the formation of a weaker transition layer. In high-slump mixes, moisture removal resulted in 11 % reduction, potentially due to surface drying and smoothing. These findings highlight the importance of optimising interface moisture conditions to ensure adequate interlayer bonding in functionally graded concrete.

## 1 Introduction

Functional grading seeks to optimise the utilisation of concrete, and consequently cement, by varying properties throughout the volume, either in one or multiple directions to meet specific requirements. Gradation can be achieved through continuous grading or layering methods. This study focuses on functionally layered concrete, with a particular emphasis on the challenges posed by the interlayer interface during casting. The interfacial bond between adjacent layers is influenced by several factors, including casting techniques, concrete grade, the properties of the individual layers, substrate surface texture, the time delay between pours, and moisture content. Numerous researchers have investigated the effects of these parameters on interfacial bond strength, as summarised in Table 1.

The observations listed in Table 1 highlight the varied effects of interface moisture content (MC) on interlayer bond strength. While it is widely believed that pre-wetting the substrate surface enhances bond strength, the literature shows mixed results. In contrast, studies on fresh-on-fresh cast 3D-printed concrete, indicate that higher surface moisture can enhance bond strength. However, 3D-printed concrete does not fully represent the characteristics of traditional fresh-on-fresh cast concrete due to its unique layer deposition process and material properties.

This paper, therefore, focuses specifically on fresh-on-fresh cast interfaces aiming to clarify the role of interface moisture content in interlayer bonding. The

following section provides a detailed discussion of the underlying reasons for the contradictory observations regarding the effect of surface moisture on interlayer bond strength.

**Table 1.** Key parameters influencing interlayer bond strength.

Parameter	Literature	Findings
Concrete grade	[1 - 4]	Shear bond strength increases with increasing substrate strength
Pour delay	[5, 6]	Longer pour delays weaken interfacial bond strength due to cold joint formation
Surface roughness	[3, 7, 8]	Shear bond strength improves with increased surface roughness due to higher shear friction and mechanical interlock
Surface moisture	[9, 10]	Fresh-on-hardened: saturated surface dry (SSD) substrates showed higher bond strength
	[1, 11]	Fresh-on-hardened: SSD substrates resulted in considerably lower bond strength compared to dry substrates.
	[12 - 14]	3D printed concrete: higher surface moisture enhances bond strength

## 2 Interface surface moisture

Moisture content at the interlayer interface significantly affects bond strength. This section explores how casting methods and varying moisture conditions influence interfacial bond strength.

### 2.1 Fresh-on-hardened cast concrete

Studies on fresh-on-hardened cast specimens suggest that a dry, hardened substrate may absorb water from the freshly poured concrete, leaving unhydrated cement at the interface. This can lead to excessive shrinkage and delamination, ultimately reducing the bond strength. Hence, in concrete practice, pre-wetting the hardened substrate to a saturated surface dry (SSD) condition is observed to improve interface bond strength [9, 10].

In this context, Beushausen et al. [1] investigated the effect of substrate moisture conditions on interface bond strength, comparing dry and saturated surface dry substrates. They found that the SSD substrate resulted in considerably lower bond strength compared to the dry substrate. The adsorption of overlay material into the substrate was observed to facilitate mechanical interlocking between the two layers. In contrast, moisture-filled pores in SSD substrates prevented the interlocking mechanism from developing to its full potential. Consequently, they concluded that pre-wetting the substrate surface provides no added benefit and, in some cases, may negatively affect bond strength.

Further experiments by Beushausen et al. [11] evaluated four substrate moisture conditions: SSD (24 hours in tank), SSD (30 minutes in tank), dry, and oven-dried. The results confirmed that pre-wetting the substrate does not enhance bond strength. Microstructural analysis of the SSD interface revealed an increased water-cement ratio and higher porosity in the overlay transition zone. Conversely, the dry substrate condition exhibited a low-porosity interface with a higher amount of unhydrated cement. Overall, the researchers concluded that the effect of substrate moisture condition on bond strength was negligible, regardless of the substrate's absorption properties.

### 2.2 Fresh-on-fresh cast 3D printed concrete

3D printing of concrete falls under the fresh-on-fresh cast category, where layers are deposited while the underlying layer is still fresh, ensuring better cohesion and minimising the formation of weak interfaces.

Several studies on 3D-printed concrete have observed the significant influence of surface moisture on interlayer strength. Sanjayan et al. [12] investigated the effect of time delay combined with surface moisture content on interlayer bond strength, concluding that surfaces with low moisture content lack the workability needed to develop a strong bond, and higher surface moisture leads to better bond strength. Similarly, Marchment et al. [13] emphasised that maintaining surface moisture is critical, as insufficient moisture reduces the degree of hydration and weakens the bond.

Weng et al. [14] also found that higher surface moisture improves bond strength.

### 2.3 Discussion and research gap

Studies on fresh-on-hardened casting have shown that the effect of moisture content (MC) on bond strength is not straightforward. While pre-wetting the substrate can prevent water absorption from the overlay, it may also lead to higher porosity and a weaker interface in certain conditions. Studies on 3D-printed concrete have similarly highlighted the role of MC in interlayer bonding, revealing that higher surface moisture generally improves strength. However, detailed studies on fresh-on-fresh casting, apart from applications like self-compacting concrete (SCC), are limited.

Although 3D-printed concrete (3DPC) resembles fresh-on-fresh casting, there are notable differences, such as the use of distinct mix designs with varying slumps. These variations introduce challenges, including differences in moisture availability at the interface. This could affect bond strength. However, in fresh-on-fresh casting of functionally graded concrete, excess moisture at the interface may form a thin, weak layer of cement paste, a phenomenon not commonly observed in 3DPC.

Given these complexities, a better understanding of the effect of moisture on interfacial bond strength in fresh-on-fresh casting scenarios is of interest.

## 3 Experimental programme

In particular, the influence of two distinct mix designs, one with a lower slump (drier mix) and one with a higher slump (wetter mix) and modifying the interface moisture content were explored.

### 3.1 Selection of experimental method

Several experimental methods are commonly used to evaluate the interfacial bond strength between adjacent concrete layers. These include direct tensile tests (DTT) [1, 11], direct shear tests (DST)[12, 13], wedge-splitting tests [6], and splitting tensile tests (SpTT)[14]. Each has its own advantages and limitations.

The direct tensile test (DTT) directly measures the tensile bond strength and offers closer predictions of the actual tensile performance due to minimal interference from aggregate interlock. However, it is a time-consuming method as glue failure is common, requiring repeated tests. Additionally, the availability of testing caps restricts the number of specimens that can be tested at the same time, affecting the precision of results. Achieving consistent interfacial failure can be challenging, as failure may occur in the weakest layer or junction. While notching can help localise failure to the interface, it may also introduce artificial stress concentrations that interfere with the natural failure mechanism. However, inducing interfacial failure is essential for obtaining quantitative measurements of actual bond strength between concrete layers.

The direct shear test (DST) assesses the shear strength of the interface. However, aggregate interlock crossing the interface often dominates the test results, which can obscure the effect of specific parameters, such as moisture content, on interfacial bond strength.

The wedge-splitting test provides a clear interfacial failure due to the inclusion of a notch, which ensures the stress is concentrated at the interface. While this makes it an effective method for isolating interfacial bond behaviour, the preparation of specimens is labour-intensive and time-consuming, limiting the number of samples that can be tested in a practical timeframe.

The splitting tensile test (SpTT), in contrast, is efficient and allows for testing a large number of specimens. While it tends to slightly overestimate the actual tensile strength and may be influenced by minor surface profile variations, it suits parametric studies. Its efficiency and reliability make it advantageous for exploring the relationship between specific parameters, such as surface moisture and interfacial bond strength.

Considering these factors, the splitting tensile test was selected for this study as it provides a practical balance between accuracy, efficiency, and the ability to isolate the effect of surface moisture on interfacial bond strength.

### 3.2 Surface moisture measuring techniques

Controlling surface moisture, much like surface roughness, presents significant challenges. Surface moisture can be measured using two primary techniques: contact-based (refer to Figure 1) and non-contact-based (refer to Figure 2) methods. Non-contact techniques are ideal for measuring surface moisture without altering it, whereas contact-based methods are better suited for understanding mix and surface behaviour.

In this study, a novel approach was developed to modify and control the surface moisture. This involved either removing existing moisture from the surface or adding a known volume of water, allowing the creation of distinct surface moisture conditions. This method provided controlled and repeatable scenarios for evaluating the effect of surface moisture on interfacial bond strength.

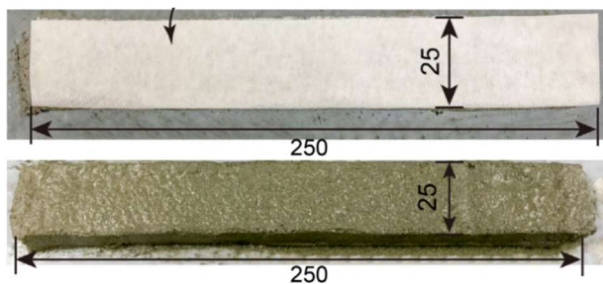


Fig. 1. Surface moisture absorbance using a paper towel [12].

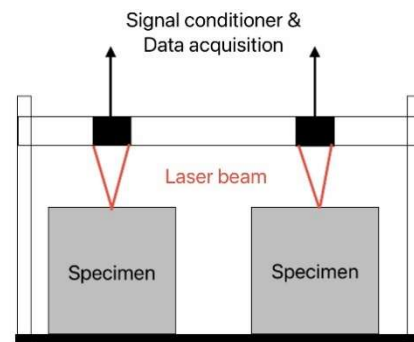


Fig. 2. Non-contact laser set-up to measure settlement [15].

### 3.3 Concrete mix properties

Two concrete mixes, one with low-slump and the other with high-slump, were designed to achieve a similar compressive strength by using the same water-cement ratio. Both mixes consisted of CEM II/A-L 32.5R cement, crushed fine aggregates (fineness modulus = 2.31), uncrushed coarse aggregates (maximum size of 10 mm), and water. To achieve different workability levels, the aggregate-to-binder ratio and fine-to-coarse aggregate ratio were varied between the mixes. The mix proportions for both mixes are presented in Table 2.

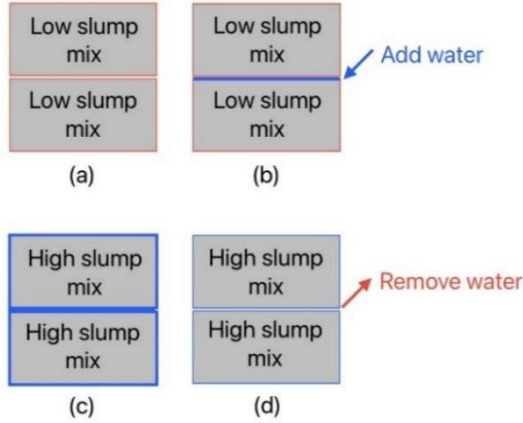
Table 2. Mix proportions.

Component	Low slump mix	High slump mix	Unit
Cement	368	452	kgm <sup>-3</sup>
Water	197	242	kgm <sup>-3</sup>
Fine aggregate	932	981	kgm <sup>-3</sup>
Coarse aggregate	860	627	kgm <sup>-3</sup>
Water/ Cement	0.535	0.535	
Aggregate/ Cement	4.9	3.6	
Fine aggregate/ Coarse aggregate	1.1	1.6	
Obtained slump	10	195	mm

### 3.4 Specimen preparation

Four types of specimens were prepared for the study. For the low-slump mix, two-layered specimens were created, one set with water added to the substrate surface. In these specimens, the substrate surface was trowelled to minimise the effect of the surface profile on bond strength. A total of 15 ml of water was sprayed evenly on the surface to create the 'LL(+W)' specimen type, while the specimens without added water were

designated 'LL(Ref)'. For the high-slump mix, after compacting the substrate layer, excess water on the surface was removed using a sponge covered with a paper towel to create the 'HH(-W)' specimen type, while the specimen with no water removed was labelled 'HH(Ref)'. Water addition and removal on the substrate surface were performed within 20 minutes and then the overlay was poured onto the substrate. A schematic diagram illustrating all four specimen types is shown in Figure 3.



**Fig. 3.** Specimen types: (a) LL(Ref); (b) LL(+W); (c) HH(Ref); (d) HH(-W).

### 3.5 Determination of specimen count

To ensure statistical reliability, the total number of specimens was determined based on a 95 % confidence interval (CI). The standard error (SE) from previous studies using the splitting tensile test (SpTT) was analysed to establish an appropriate sample size while minimising the margin of error. The confidence interval formula is given in equation 1:

$$CI = \bar{x} + t \frac{SD}{\sqrt{n}} \quad (1)$$

where,  $\bar{x}$  represents the mean splitting tensile strength,  $t$  is the t-value for a 95 % confidence interval,  $SD$  is the standard deviation of splitting tensile strength measurements, and  $n$  is the number of specimens.

The term  $t \frac{SD}{\sqrt{n}}$  denotes the standard error (SE).

However, absolute standard error alone does not fully capture measurement precision, as variations in mean values across different studies can influence its significance. To address this, the relative standard error (RSE) was considered for comparison. By normalising the SE with respect to the mean splitting tensile strength, the RSE provides a more consistent measure of precision across different datasets. It is calculated using the expression:

$$RSE = \frac{SE}{\bar{x}} \times 100 \% \quad (2)$$

A review of previous studies using SpTT for interfacial bond strength assessment helped determine a suitable specimen count for this study. The comparison is presented in Table 3.

**Table 3.** Comparison of SE and RSE across studies.

Literature	No. of specimens	$\bar{x}$ (MPa)	SE (MPa)	RSE (%)
Peng et al. [3]	3	4.64	2.04	44
Dybel & Kucharska [16]	4	2.06	0.72	35
Weng et al. [14]	5	3.08	0.42	14
Zheng et al. [17]	9	4.27	0.46	11

From this comparison, it is evident that increasing the number of specimens reduces the RSE, leading to improved measurement precision. Based on these findings, a total of 10 specimens for each specimen type were tested to ensure a balance between statistical accuracy and experimental feasibility.

### 3.6 Interface moisture measurements

Contact-based surface moisture measurements were conducted using a paper towel, as demonstrated by Combrink et al. [15], on additional specimens prepared alongside the main specimens. These parallel specimens were specifically used to measure the surface moisture content of the reference specimens, providing a baseline for understanding moisture variations. Table 4 presents the surface moisture content for both the low-slump and high-slump mixes.

**Table 4.** Surface moisture levels.

Mixes	Surface moisture (g/cm <sup>2</sup> )
Low slump substrate	< 0.01
High slump substrate	0.03

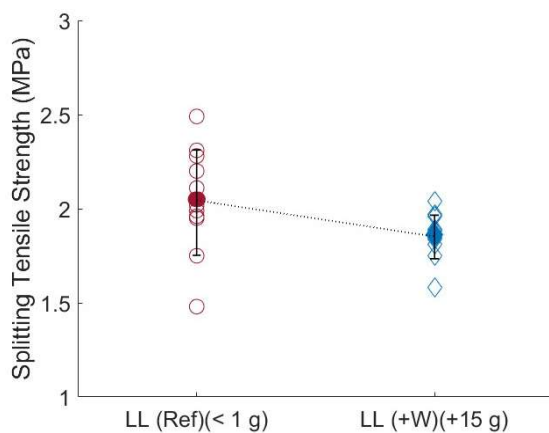
Considering the surface moisture measurements, each specimen, was expected to exhibit specific surface moisture levels after pouring the overlay. For instance, the LL(Ref) specimen had a surface moisture content of less than 0.01 g/cm<sup>2</sup>, corresponding to the moisture present on the substrate before overlaying. In terms of the LL(+W) specimen, 0.15 g/cm<sup>2</sup> of surface moisture was added to the substrate to achieve the intended moisture condition. In relation to the HH(Ref) specimen, the substrate initially contained 0.03 g/cm<sup>2</sup> of surface moisture, and after the overlay was poured, there was an additional 3 g of moisture was introduced from the overlay, given that the surface area was 100 cm<sup>2</sup>, resulting in a total surface moisture level of more than 0.06 g/cm<sup>2</sup>. In contrast, 3 g of moisture were removed from the surface of the HH(-W) specimen. As a result, the HH(-W) specimen contained 3g less moisture than the HH(Ref) specimen.

## 4 Results and discussion

### 4.1 Effect of surface moisture on bond strength

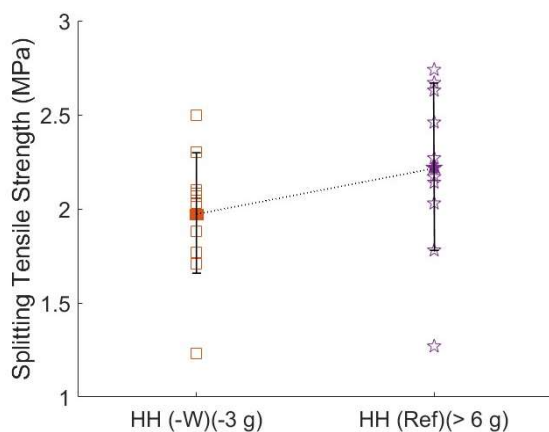
All 40 specimens were tested, and the splitting tensile strength results are presented in Figure 4 and Figure 5. Figure 4 shows the results for LL(Ref) and LL(+W) specimens, while the results for HH(Ref) and HH(-W) specimens are presented in Figure 5.

In Figure 4, a reduction of approximately 10 % in splitting tensile strength is observed when comparing the LL(Ref) to the LL(+W) specimens. This decrease demonstrates the negative impact of excess moisture on the interfacial bond strength between low-slump mixes. The addition of excess water at the interface led to a reduction in bond strength.



**Fig. 4.** Splitting tensile strength of low-low slump specimens.

In Figure 5, the removal of 3 g of water from the substrate surface impacted the interfacial bond strength in the high-slump mixes, resulting in an 11 % reduction. This suggests that moisture removal has a substantial effect on bond strength, even in high-slump mixes with a high internal moisture content. The water removal process may have created a smoother, drier substrate surface, potentially weakening the bond strength. This effect is further discussed in Section 4.3, where failure modes are discussed in detail.



**Fig. 5.** Splitting tensile strength of high-high slump specimens.

### 4.2 Variation of results and comparison with literature

From Figure 4 and Figure 5, it can be observed that the spread of results is considerable across all specimen types, with LL(+W) exhibiting the lowest standard deviation. To assess whether this level of variability aligns with previous research, a comparison with literature was conducted. To quantify the variability in the results, the Relative Standard Deviation (RSD) was calculated as per equation 3:

$$RSD = \frac{SD}{\bar{x}} \times 100 \% \quad (3)$$

The calculated RSD values for all specimens and literature references are summarised in Table 5.

**Table 5.** Results spread comparison with literature.

Specimen/ Literature	SD (MPa)	$\bar{x}$ (MPa)	RSD (%)
LL(Ref)	0.28	2.05	14
LL(+W)	0.12	1.86	7
HH(Ref)	0.45	2.22	20
HH(-W)	0.33	1.97	17
Peng et al. [3]	0.82	4.64	18
Dybel & Kucharska [16]	0.45	2.06	22
Weng et al. [14]	0.34	3.08	11
Zheng et al. [17]	0.6	4.27	14

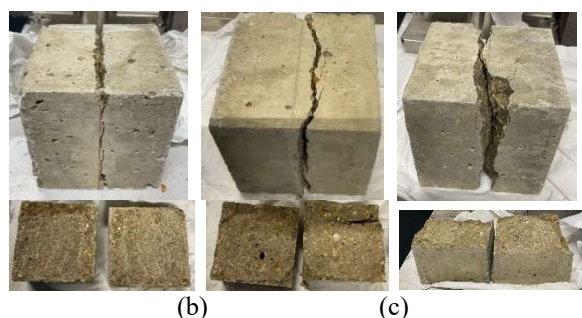
According to Table 5, most studies report an RSD of around 20 %, indicating a considerable spread in the splitting tensile strength results. The present study follows this trend, with the highest RSD reaching 20 %, suggesting that the observed variation is consistent with previous literature. However, while this alignment indicates the expected level of variability in splitting tensile strength results, it is necessary to examine whether such variation is acceptable to accurately evaluate interfacial performance.

### 4.3 Failure modes and influence on results

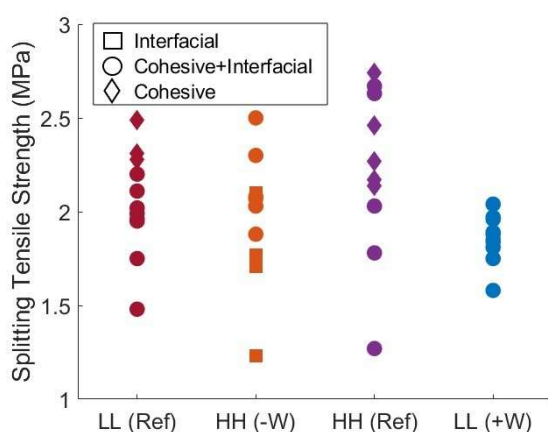
The failure modes observed in the tested specimens were categorised into three types: interfacial failure, cohesive + interfacial failure, and cohesive failure. Interfacial failure occurs entirely at the interface between the substrate and the overlay, indicating weak interfacial bond strength. Cohesive + interfacial failure is a combination of failure at the interface and within the overlay or substrate, suggesting moderate bond strength. Cohesive failure occurs entirely within the overlay or substrate, indicating that the interfacial bond is stronger

than the tensile strength of the material itself. Figure 6 illustrates these failure modes in the tested specimens.

The distribution of failure modes provides valuable insight into the interfacial bond strength. Specimens with higher bond strength tend to exhibit cohesive failures, as the bond surpasses the tensile capacity of the weaker layer. Conversely, specimens with weaker interfacial bond strength predominantly fail at the interface, as the bond cannot withstand the applied stress.



**Fig. 6.** Failure modes: (a) Interfacial failure; (b) Cohesive + interfacial failure; (c) Cohesive failure.



**Fig. 7.** SpTT results indicating different failure modes.

Across the different specimen types, LL(Ref) and HH(Ref) show a mix of cohesive + interfacial failure and cohesive failures which showed parallel cracks in both layers, as illustrated in Figure 7. These specimens did not undergo moisture modification; thus, they maintain a typical bond strength distribution similar to that found in homogeneous concrete cubes. Although LL(+W) did not exhibit interfacial failures, the values observed align with the interfacial failure seen in HH(-W) specimens. The additional moisture at the interface might have prevented cold joint formation but also created a weaker concrete layer with a higher water-cement ratio, leading to cohesive + interfacial failure and reduced strength values.

For HH(-W), the removal of 3 g of water had a notable impact on bond strength, with failure modes similar to those observed with HH(Ref). However, in some instances, pure interfacial failure was observed. This can be attributed to the water removal process, where the use of a sponge likely resulted in a smoother, drier substrate surface. This alteration in surface condition may have induced separation between the layers, thereby weakening the bond at the interface and

leading to pure interfacial failure as shown in Figure 6 (a).

#### 4.4 Further work

To expand upon the findings of this study, future research should consider the effects of mixed-layer moisture variations and how these changes influence interfacial bond strength. It is important to examine how different moisture conditions within both the substrate and overlay layers interact and contribute to overall bond performance. Additionally, varying the rheological properties of the concrete, such as its workability and flow behaviour, should be investigated, as these factors may play a significant role in bond formation at the interface.

### 5 Conclusions

In this study, the effect of surface moisture on the interfacial bond strength was investigated, using splitting tensile tests on 40 specimens. The results highlighted significant variations in bond strength depending on the moisture condition of the substrate surface. The key findings from this study are:

- For the low slump layered mix (LL(+W)), the addition of water to the substrate surface led to a 10% reduction in bond strength compared to the low slump reference specimens (LL(Ref)). This reduction underscores the negative impact of excess moisture on interfacial bond strength in low slump mixes.
- For the high slump mix, water removal from the substrate surface (HH(-W)) resulted in an 11 % reduction in bond strength when compared to high slump reference specimens (HH(Ref)). Despite the high internal moisture content of the high slump mix, moisture removal still impacted the bond strength by altering the substrate surface condition.
- The variability in splitting tensile test results was comparable to previous literature, with relative standard deviation (RSD) values ranging from 7 % to 20 % confirming that the observed variations align with existing research trends, where the RSD falls between 11 % and 21 %.
- Reference specimens (LL(Ref) and HH(Ref)) exhibited stronger bond strength, predominantly failing in cohesive or cohesive + interfacial modes. Moisture-modified specimens demonstrated weaker interfacial bonding, with LL(+W) showing reduced strength due to the formation of a weaker transition layer, while HH(-W) exhibited some pure interfacial failures, likely caused by substrate surface drying and smoothing during the water removal process.

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