

# INFLUENCE OF CONCRETE DENSITY AND STRENGTH ON THE BOND STRENGTH OF COMPOSITE MEMBERS

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## Abstract

The present paper addresses the influence of both material density and strength in the adhesion between concrete layers cast at different ages. A Normal Density Concrete (NDC), a LightWeight Aggregate Concrete (LWAC) and an Ultra High Durability Concrete (UHDC) were considered. The latter is characterized by presenting enhanced durability properties. Nevertheless, the production of the UHDC presents both economical and environmental disadvantages. In order to minimize the impact of its use and, simultaneously, take advantage of its properties, it is proposed to use it only in the cover layer of structural members, being the bulk produced in ordinary concrete.

An experimental study was conducted to characterize the adhesion between UHDC/NDC and UHDC/LWAC by means of the *Modified Slant Shear Test* (M-SST). This new bond test was developed by the authors to always ensure adhesive failures in composite specimens. Two different surface conditions were selected for the interface: *i*) smooth surface, as-cast against steel formwork; and *ii*) surface obtained by casting against a plastic wavy formwork. Experimental results are discussed and conclusions are drawn.

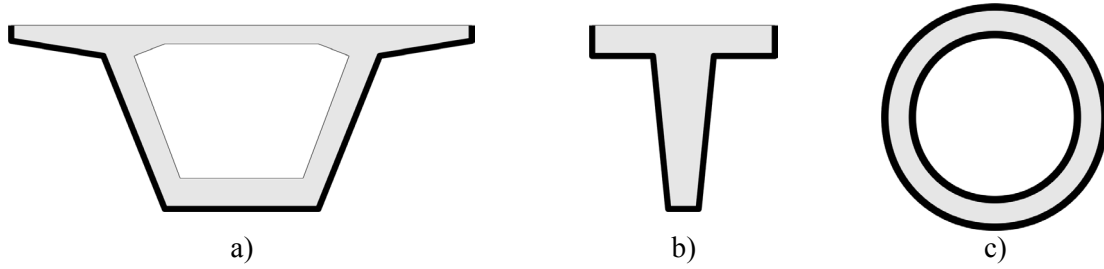
**Keywords:** Adhesion, Bond, Concrete, Interface, Ultra High Durability Concrete (UHDC)

## 1 Introduction

In 2008, following previous works conducted by the authors (Júlio, *et al.* 2004; Júlio *et al.* 2006; Santos *et al.*, 2007), a research project called ‘Intelligent Super Skin’ (ISS project) was launched to develop a new concept for reinforced concrete (RC) members. The main objective of this project was to increase the durability of RC members by adding a concrete cover (Fig. 1) of Ultra High Durability Concrete (UHDC). This solution leads to more durable members, maintaining economical and environmental costs. It is important to refer that this solution has already been adopted in a bridge in Switzerland, where a UHPFRC (Ultra High Performance Fibre Reinforced Concrete) cover was used (Brühwiler and Denarié, 2008).

This solution can be used both in new and existing structures. In the first case the concrete cover can be pre-casted and used as the formwork for the RC members. In the second case the deteriorated concrete must be removed and then the UHDC can be directly applied.

However in order to achieve this goal it is essential to ensure the monolithic behaviour between the cover made of UHDC and the bulk made of normal density concrete (NDC) or LightWeight Aggregate Concrete (LWAC). Therefore this study aims to verify if it is possible to use the combination of this innovative material (UHDC) with NDC and LWAC, i.e., to ensure sufficient interface bond strength.



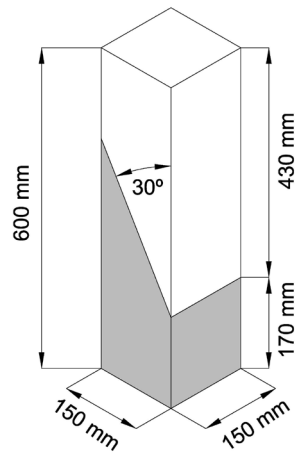
**Fig. 1** Possible applications of composite members in UHDC/NDC and UHDC/LWAC: a) Hollow box section; b) T beam; and c) Manhole for sewer systems. (cover layer in UHDC represented as thick black line)

## 2 Experimental investigation

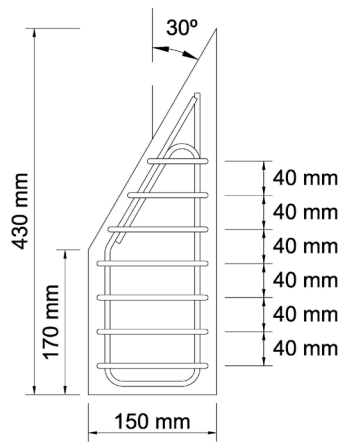
### 2.1 Modified Slant Shear Test (M-SST)

The monolithic behaviour between the bulk and the UHDC cover is assured by adhesion, since there is no reinforcement crossing the interface and normal stress is not supposed to be applied to the UHDC cover. Therefore, the most appropriate test was selected to assess the bond strength in shear due to this mechanism, the Modified Slant Shear Test (M-SST) (Saldanha *et al.*, 2012). This is a modified version of the Slant Shear Test (Kriegh, 1976; Tabor, 1978), proposed by the authors, which was designed to achieve adhesive failures (interface debonding), by introducing reinforcement at both halves. With this test, cohesive failures (crushing of the weakest concrete) are avoided and the actual bond strength of the interface is assessed, instead of a lower bound based on the weakest concrete compressive strength.

The M-SST specimen is a prism with a  $150 \times 150 \text{ mm}^2$  cross section, a total height of 600 mm and an interface angle of  $30^\circ$  to the vertical (Fig. 2). The reinforcement of both halves, presented in Fig. 3, is composed by 6 mm stirrups spaced of 40 mm, which are held in place using the longitudinal reinforcement. In the experimental study herein described, steel reinforcement with a yield stress of 400 MPa and a 10 mm concrete cover were adopted.



**Fig. 2** M-SST Geometry



**Fig. 3** M-SST Reinforcement

The average interface strength, in shear and in compression, can be determined, respectively, by dividing the tangential and the normal components of the failure load by the interface area (Eq. 1 and 2).

$$\tau = \frac{P \sin \alpha \cos \alpha}{b^2} \quad (1)$$

$$\sigma = \frac{P \sin^2 \alpha}{b^2} \quad (2)$$

where ' $\tau$ ' is the average shear stress at the interface; ' $\sigma$ ' is the average normal stress at the interface; ' $P$ ' is the compressive load; ' $\alpha$ ' is the interface angle with the vertical; and ' $b$ ' is the cross section width.

## 2.2 Concrete mixtures

Three concrete mixtures were designed. NDC and LWAC, corresponding to the bulk of the concrete member, were designed to achieve a compressive strength in the range of the values adopted in current solutions, and also considerably lower than the UHDC. Compared to the NDC and LWAC, the UHDC presents a significantly different structure, characterized by a low water/cement ratio and an ultra compact matrix (Ghafari *et al.*, 2012a and Ghafari *et al.*, 2012b). This leads to a reduced permeability and, therefore, to an enhanced behaviour regarding durability. Moreover, the behaviour of the UHDC, mainly the tensile strength, can be significantly improved due to fibres addition.

The design of all mixtures was based on the absolute volume expression (Júlio *et al.*, 2006). The constituents for each one are presented in Table 1. The compressive strength of each concrete type was assessed according to NP EN 12390-3 (2009). The average (AVG), the standard deviation (STD) and the coefficient of variation (COV) are presented for each set in Table 2. For NDC and LWAC, 150 mm cubic specimens were adopted, while the UHDC was tested using 100 mm cubic specimens.

**Table 1**  
**Constituents for the NDC, LWAC and UHDC mixtures**

Constituents (kg/m <sup>3</sup> )		Concrete Types		
Description	Type	NDC	LWAC	UHDC
Cement	Portland Type II 32.5 R	320	–	–
	Portland Type II 42.5 R	–	360	–
	Portland Type II 52.5 R	–	–	730
Aggregates	Fine sand	421	272	983
	Medium sand	181	634	–
	Fine limestone	369	–	–
	Coarse limestone	861	–	–
	Coarse lightweight expanded clay	–	512	–
Additions	Filler	–	–	219
	Silica Fumes	–	–	146
Water		174	158	200
Commercial admixture		1.6	1.8	40.2

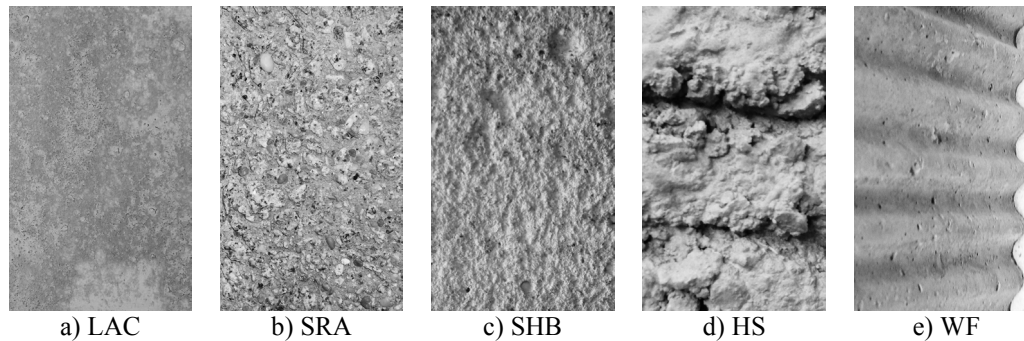
**Table 2**  
**Compressive strength**

Test	Concrete type	Compressive strength (MPa)	AVG (MPa)	STD (MPa)	COV (%)
Preliminary Tests	NDC (substrate concrete)	40.97	40.17	0.79	1.95
		39.40			
		40.15			
	NDC (added concrete)	36.96	36.94	0.04	0.12
		36.97			
		36.89			
Final Tests	NDC	43.12	41.83	1.46	3.48
		40.25			
		42.12			
	LWAC	47.55	45.68	2.05	4.50
		46.00			
		43.48			
	UHDC	102.12	102.63	1.65	1.61
		101.29			
		104.47			

### 2.3 Surface preparation

In order to select the most appropriate surface treatments to use, a preliminary study was made using NDC on both halves of the M-SST specimen.

Five surface treatments were considered in this study: *i*) left-as-cast against steel formwork (LAC), to serve as reference, Fig. 4a); *ii*) surface prepared using a retarding admixture (SRA), which was applied on the formwork before casting and washed away after demolding, Fig. 4b); *iii*) surface prepared by shot-blasting (SHB), Fig. 4c); *iv*) surface prepared by hand-scrubbing (HS), similar to raking, Fig. 4d); and *v*) surface obtained by casting against a plastic wavy formwork (WF), Fig. 4e).



**Fig. 4** Surface condition

Three specimens of the M-SST were produced for each surface condition of the interface. After placing the reinforcement inside the moulds and casting the substrate concrete, the specimens were stored during 28 days under the existing conditions in the laboratory with the temperature and relative humidity in the range of 13-24°C and 30-95%, respectively. During this period, the interface surfaces were prepared as described. The surface roughness was measured using the 2D-Laser Roughness Analyser (2D-LRA) method (Santos and Júlio, 2008), previously developed by the authors to characterize the texture of concrete surfaces. Ten measurements were made for each surface condition in order to obtain the surface profiles and, subsequently, to determine the roughness parameters (Santos and Júlio, 2010).

Subsequently, the specimens were cleaned with compressed air and placed again inside the moulds to cast the concrete overlay. After demolding, the M-SST specimens were stored for another 28 days, under the same curing conditions. Afterwards, the specimens were tested under compression.

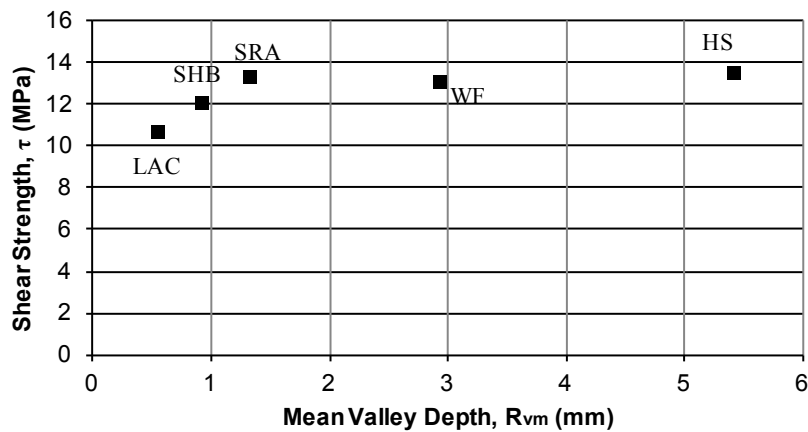
The interface shear and normal strength obtained for each specimen is given in Table 3, as well as the Mean Valley Depth ( $R_{vm}$ ) for each surface condition (See Saldanha *et al.*, 2011). The average (AVG), the standard deviation (STD) and the coefficient of variation (COV) are presented for each set. This roughness parameter was determined to verify that different interface surfaces were obtained with each preparation method, Fig. 5.

Analysing the results, it can be concluded that the LAC surface presents the lowest value of shear strength, as expected. Furthermore, it can be seen that the remaining surface conditions lead to slightly higher values of the interface shear strength, in spite of the significantly different roughness.

Based on the observations of this preliminary study, it was decided to select the following two surface conditions for the production of the UHDC/NDC and UHDC/LWAC composite specimens: LAC and WF. The LAC surface treatment was chosen, since it was the treatment that led to the lowest value of the interface shear strength. Even though the WF surface condition is not the one that leads to the highest interface shear strength, it was selected due to its uniformity and, therefore, less variability of results.

**Table 3**  
**Interface shear and normal strength and Mean Valley Depth ( $R_{vm}$ )**

Surface condition	Interface shear strength				Interface Normal Strength				Mean Valley Depth ( $R_{vm}$ )		
	$\tau$ (MPa)	AVG (MPa)	STD (MPa)	COV (%)	$\tau$ (MPa)	AVG (MPa)	STD (MPa)	COV (%)	AVG (mm)	STD (mm)	COV (%)
LAC	11.24	10.68	2.57	24.06	6.49	6.17	1.48	24.06	0.548	0.395	72.0
	12.93				7.46						
	7.88				4.55						
SRA	13.06	13.32	0.26	1.92	7.54	7.69	0.15	1.92	1.329	0.170	12.8
	13.32				7.69						
	13.57				7.84						
SHB	13.40	12.07	2.28	18.92	7.73	6.97	1.32	19.92	0.921	0.156	17.0
	9.43				5.44						
	13.37				7.72						
HS	13.77	13.51	0.33	2.48	7.95	7.80	0.13	1.76	5.416	2.664	49.2
	13.13				7.58						
	13.62				7.86						
WF	13.10	13.07	0.23	1.77	7.57	7.55	0.13	1.76	2.933	0.075	2.6
	13.29				7.67						
	12.83				7.41						



**Fig.5** Correlation between the Mean Valley Depth ( $R_{vm}$ ) and the interface shear strength

### 3 Composite specimens UHDC/NDC and UHDC/LWAC

Having defined the concrete mixtures and the surface treatments, the composite UHDC/NDC and UHDC/LWAC specimens were produced. For each considered situation three specimens were produced. The same methodology was adopted in the production of the composite specimens, with only one difference. Since the compressive strength of the UHDC was much higher than NDC and LWAC, no reinforcement was used in the concrete halves composed by UHDC.

In Table 4 is presented the interface shear strength obtained for each M-SST specimen, as well as the average (AVG), the standard deviation (STD) and the coefficient of variation (COV) for each set.

**Table 4**  
**Interface shear strength for the M-SST specimens with UHDC/NDC and UHDC/LWAC**

Composite specimen	Surface condition	Interface shear strength (MPa)	AVG (MPa)	STD (MPa)	COV (%)
UHDC/NDC	LAC	8.42	9.58	1.01	10.53
		10.25			
		10.07			
	WF	15.62	15.05	0.55	3.64
		14.53			
14.99					
UHDC/LWAC	LAC	*	5.28	1.43	27.05
		4.27			
		6.29			
	WF	17.67	17.04	0.55	3.22
		16.74			
16.70					

\* Surface debonding occurred before the load test could be executed.

All specimens presented an adhesive failure mode, i.e. interface debonding, Fig. 6a). Nevertheless, it must be stated that a reduced number of specimens, due to the high energy released at the failure moment combined with the UHDC fragile behaviour, exhibited cohesive failure of this overlay, Fig. 6b).



**Fig. 6a)** Adhesive failure



**Fig. 6b)** Overlay failure detail

Analysing the experimental results, given in Table 4, it can be stated that: *i)* an increase in the surface roughness leads to a significant increase in the interface shear strength; *ii)* the WF surface condition presents a lower coefficient of variation in relation to the LAC condition, thus representing a more reliable condition; *iii)* UHDC/LWAC specimens present lower interface shear strength than UHDC/NDC specimens for the LAC surface condition; and *iv)* UHDC/LWAC presents higher interface shear strength than UHDC/NDC for the WF Surface treatment.

## 4 Conclusions

In order to analyse the viability of a new concept to produce RC composite members, consisting in using NDC or LWAC in the bulk and UHDC in the cover, an experimental study was conducted. The 2D-LRA method was used to characterize different roughness conditions and the M-SST adopted to assess the interface shear strength due to adhesion.

Results proved that UHDC could probably be used as a concrete cover of RC members with a NDC or LWAC bulk since high shear strength values were obtained. Nevertheless, further studies are in progress, using full-scale beam specimens, to definitely validate this statement.

This experimental procedure also stretched out the advantages of using the M-SST, since only adhesive failure modes were obtained, despite the differential stiffness and surface roughness. The true interface shear strength was measured and not an estimated value based on a lower bound based on the concrete compressive strength.

The increase of roughness led to the increase of interface shear strength, for both situations, as expected. The results for the LAC surface showed to be significantly lower than the WF treatment for the UHDC/LWAC specimens. The results for the specimens with a WF treatment also presented less variability, both in the preliminary study (NDC/NDC) and in the final tests (UHDC/LWAC and UHDC/NDC). Therefore, it can be concluded that the added concrete must not be casted directly against a LAC surface.

For the LAC surface condition, higher values of the interface shear strength were obtained with UHDC/NDC specimens than with UHDC/LWAC and the opposite was observed for the WF surface condition. Further studies are necessary to investigate in detail the influence of concrete density on the interface shear strength.

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