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UHPC overlay as sustainable solution to preserve old concrete structures

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Abstract. Concrete structures exposed to harsh environments, especially including bridges, harbor structures are often suffered from durability problems. Typical external signs include surface deterioration, cracking caused by for example sulphate attack, frost action or reinforcement corrosion. All are strongly linked to the porous microstructure of the binder matrix and chemical decomposition of certain phases. Full replacement of deteriorated concrete structures is costly and can be troublesome for their users. The increasing demand to reduce the carbon footprint and to prolong the service life of concrete structures adds yet another argument to restore the existing structures. One alternative is to use very dense Ultra-High-Performance concrete (UHPC) as an external protective coating. The goal of this study was to determine the interfacial bonding characteristics between a damaged normal concrete (NC) and the applied thin layer of the UHPC. To curb the CO_2 emission, UHPC is produced by substituting 50 wt% of Portland cement with a fine limestone powder. Fresh and hardened properties, shrinkage and frost durability have been evaluated. Mechanical properties were determined on a full-scale hybrid element using ultrasonic pulse velocity (UPV) and bond test (pull-off test). The results showed a significant increase of mechanical properties. Despite the applied thin layer of UHPC and volumetric restrain from the substrate normal concrete (NC) only limited surface shrinkage cracks were observed. The bond test and UPV showed good excellent values.

Keyword. Ultra-high-performance concrete (UHPC), Normal concrete (NC), Shrinkage, Frost durability, Ultrasonic pulse velocity (UPV), Bond test (pull-off)

1 Introduction

With growing infrastructure and urbanization concrete is widely used as construction material. Its mechanical and durable properties exhibit outstanding performance when in exposed to ambient conditions. But on exposure to harsh environment, it exhibits adverse effect due to its porous microstructure and deleterious chemical change in the binder matrix. The structures located along the coast, such as road bridges, piers and harbors, and offshore structures are mainly affected and raises durability related issues.

One such case can be observed in places having natural freezing and thawing, causing structures to freeze and expand the concrete volume by up to 9%. Followed by permanent damages occurring from the formed stresses and strain on the pore walls of the concrete to promote cracks and surface scaling. To prevent such durable related issue and to avoid the complete replacement of the entire element, a novel ultra-high-performance concrete (UHPC) can be used as a jacket or a shield to protect the substrate normal concrete, [1]. The essential qualities are its high compressive strength (>150 MPa), tensile strength (>8 MPa), increased flowability, and highly dense microstructure and also its extreme low permeability, [2–9]. The major drawback of UHPC is the use of high amount binder about 1100-1300 kg/m^3 significantly increase the CO_2 footprint, [10][11]. However, because of the low moisture content resulting from an extremely low w/b ratio, major portion of binder content is left unhydrated and can be replaced from very inexpensive locally available limestone powder as filler, [10]. Additionally, since UHPC applied as an overlay layer around old concrete it further significantly reduces the cost and achieve broader use of it in many applications.

Interfacial transitional zone between the UHPC overlay and the substrate concrete is very crucial when exposed to varied weather conditions. The prime factors affecting the bond is the degree of substrate roughness, moisture content, w/c ratio, [12–14]. Several research studies showed that 70% of the substrate surface is occupied with the coarse aggregate and it promote the initial bonding between the layer through the interlock mechanism, [15].

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However, during freezing and thawing a fine layer of moisture might develop in the interface and cause expansion during freezing and delamination. But optimized mix composition play an important role in retaining its durability. Natural fine sands and mixed mineral ultra-fines were used to replace pulverized quartz and silica fumes in the UHPC, indicating that it had a high freeze–thaw resistance, [16][17]. Furthermore, the steel fibers extended the frost durability by decreased mass loss rates, [16].
The primary aim of this research was to study the interfacial bond behavior between the deteriorated normal strength concrete substrate (NC) and fresh overlay concrete (UHPC). This is achieved by quantitative analysis of the hybrid element using ultrasonic pulse velocity (UPV), bond strength (pull-off test)

2 Materials and methods

Ordinary Portland cement (OPC) CEM I 42.5N – SR identified as Anläggningscement and Portland-Fly Ash cement CEM II/A-V 52.5N identified as Bascement from Cementa were used to produce ultra-high-performance concrete (UHPC) and self-compacting normal concrete (NC) respectively. In the hybrid element UHPC represents external protecting layer to strengthen the deteriorated substrate normal strength concrete. The thickness of UHPC overlay layer was limited to 30 mm. The designed UHPC and normal concrete gained a strength over 150 MPa and 50 MPa respectively after 28 days of curing. Detailed mix composition and the used materials for UHPC and NC are shown in Table 1.

Table 1. Mix composition – Normal concrete and UHPC

Materials		**Normal concrete (Kg/m^3)**	**UHPC (Kg/m^3)**
Portland Cement (CEM I 42.5N-SR)		-	651
Portland-Fly Ash Cement (CEM II/A-V 52.5N)		340	-
Silica Fume 920D		-	130
Limestone powder		-	651
Dolomit filler – KM200		160	-
Quartz filler		-	65
Sand - B15		-	228
Sand - B35		-	228
Fine aggregate (0-4) mm		1021	-
Coarse aggregate (8-16) mm		802	-
Superplasticizer	MasterGlenium ACE 30	-	32.6
	MasterGlenium SKY 823	3.4	-
Steel fibers 6mm		-	65
Steel fibers 13mm			98
w/c		0.55	0.33
Water		187	192

Since UHPC layer was the exposed surface in hybrid concrete element (UHPC+NC), only the UHPC was evaluated for shrinkage and freeze-thaw (F-T) durability. The autogenous and drying shrinkage measurements were carried out on a cylindrical specimen with a diameter of 100 mm and a height of 200 mm. The test was started by gluing a pair of steel studs to a 1-day-old specimen, positioned in a line measuring roughly 100 mm in length, Figure 1. Subsequently after a span of 30 min, few specimens were wrapped with foil for autogenous shrinkage and others were exposed to the atmosphere for drying shrinkage, Figure 1. Manually operated electronic strain gauge DEMEC type (Mayes Instruments) was used to measure the difference in strain levels, Figure 1. Measurements were registered every day for a period of 28 days. Similarly, to determine the frost durability, surface scaling test was performed on UHPC concrete of dimension 150*150*50 mm3 exposed to 56 cycles of F-T (freeze-thaw) following SS-EN 13 72 44:2005 standard, Figure 2. Before being placed for frost test, the UHPC samples were water cured for 28 days.

Fig. 1. UHPC – Autogenous and drying shrinkage test setup

Fig. 2. UHPC – Freeze-Thaw durability surface scaling test setup

Furthermore, internal fractures and or delamination and the interfacial bond strength between the UHPC layer and substrate normal concrete of hybrid element of dimension 300*300*2500 mm were determined using ultrasonic pulse velocity (UPV) and pull-off test respectively. SS-EN 12504-4:2004 standard was followed to determine the internal fractures using Pundit Lab ultrasonic instrument with exponential transducers of 54 kHz frequency, direct transmission method and having a path length of 300 mm,

[18]. For every 200 mm three consecutive reading were noted on each node, Figure 3a.
ASTM C1583 standard was used to analyze the interfacial bond strength between the UHPC overlay layer and substrate normal concrete, [19]. The test was carried out with a commercially available "Proceq dy-216" instrument and a 50 mm aluminum disc at a loading rate of 35 kPa/s. Figure 3b, depicts the performed test locations and the sample failure mode.

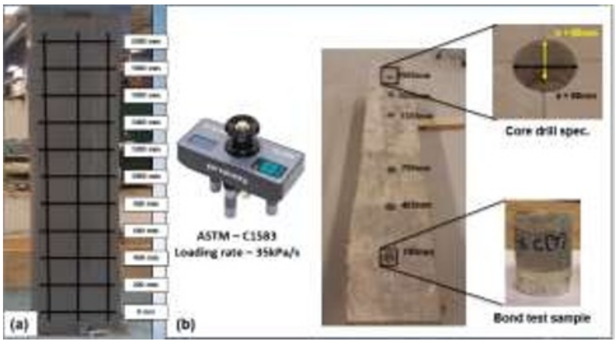

Fig. 3. Test setup on composite column (a) Ultrasonic pulse velocity (UPV) test nodes; (b) Pull-off test location and sample failure mode.

3 Results and Discussion

3.1 Shrinkage and Freeze-Thaw

Figure 4 shows the drying and autogenous shrinkage of Ultra-high-performance concrete (UHPC) and total shrinkage of reference OPC concrete registered for a period of 28 days. Autogenous shrinkage, by definition, is a volumetric change that occurs in a closed system due to the chemical reaction during hydration and subsequent self-desiccation immediately after initial setting time rather than due to external force, [20][21][22][23]. In classical UHPC mix with high binder concentration and water-to-binder ratio lower than (0.4) display higher level of autogenous shrinkage compared to ordinary Portland cement based normal concrete, [24]. This is mainly due to the high portion of binder is left unreacted because of insufficient internal moisture and subsequently lead to rapid self-desiccation, [24]. Furthermore, by replacing a portion of cement with SCM will clearly lower the production costs and CO_2 emissions, but it may enhance autogenous shrinkage from hydration and pozzolanic activity, resulting in a faster depletion of used water, [25][20]. However, in the present research considering all the factors, with the use of inert quartz and limestone powder autogenous shrinkage of UHPC was limited and showed similar to the ref. OPC concrete. Wu et. al (2017) evaluated similar where limestone powder had very negligible influence on the autogenous and drying shrinkage due to its inert behavior and subsequently enhanced the properties by filling the pore space, [20]. Furthermore, the designed UHPC had relatively lower drying shrinkage compared to the ref. OPC concrete, Figure 4. The incorporation of a large volume of inert limestone filler (calcium carbonate) restored the voids and released the entrapped water from the matrix, resulting in improved internal relative humidity, decreased capillary stresses, and enhanced hydration products, [26][27–29][30]. Figure 5 shows the cumulative surface scaling of UHPC exposed to 28 F-T cycles. Compared to reference concrete, UHPC had significantly lower surface scaling. The very dense microstructure of UHPC caused by the reduced w/b ratio and incorporation of reactive materials such as silica fume, as well as the employed steel fibers, decreased pore size and their volume and therefore improved freeze-thaw resistance, [16].

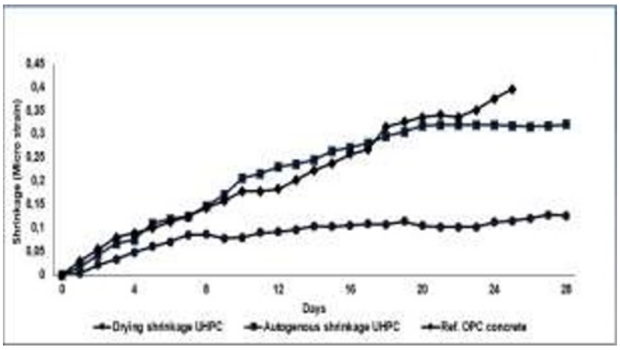

Fig. 4. Shrinkage developed on UHPC and ref. OPC concrete

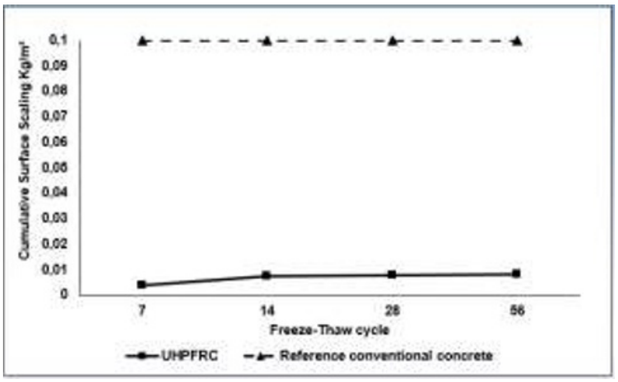

Fig. 5. Cumulative surface scaling of UHPC exposed to 28 F-T cycles.

3.2 Ultrasonic Pulse Velocity (UPV) and Bond test (Pull-off)

The registered transit time and the bond strength between the UHPC overlay and substrate normal concrete of the hybrid element is shown in Figure 6. The pulse velocity ranged between 4600-4700 m/s over the entire length of the element. Despite the 30 mm thickness of the UHPC, the interface was assumed to be adequately bonded because there was no significant difference in transit velocity. Furthermore, because the substrate had a very uneven and rough surface (70% coarse aggregate), the fine-dense and flowable UHPC was able to establish aggregate interlocking mechanism, [31–36]. In addition, unreacted silica fume combines with $Ca(OH)_2$ from the NC substrate over time in the interface zone, resulting in additional C-S-H at the interface and hence improved adhesive strength, [7,37–40]. Similar results were obtained for bond strength and were in line with the UPV measurements. The bond strength was over 2 MPa and had substrate failure mode in every tested location of the hybrid element. As previously stated, bonding is highly influenced by the substrate roughness and moisture, as well as the repair concrete's properties. Several investigations have shown that when numerous layers of concrete are cast at different time intervals (cold cast), as in the current study, poor bonding and delamination occur due to differences in shrinkage between the two layers, [41] [33,42]. Despite casting the overlay after a long period of waiting time, no such delamination or poor bonding were detected in the current study, may be due to the high friction and interlocking between the layers. But surface cracks (limited) were observed as resulting restraint from substrate concrete and very thin layer of UHPC overlay.

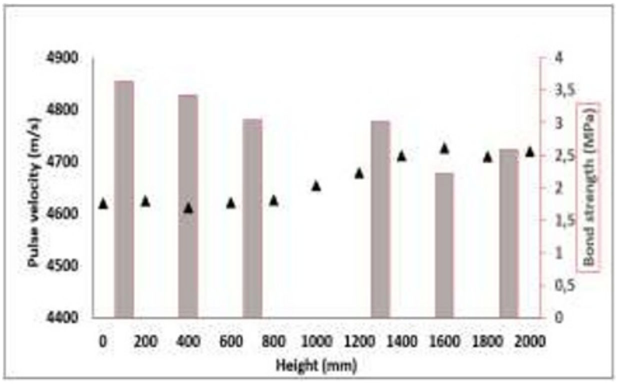

Fig. 6. Ultrasonic Pulse Velocity (UPV) and Pull-off test results on hybrid element (UHPC+NC) at different height.

4 Conclusion

The aim of the study was to determine the interfacial bond characteristic between the two layers (UHPC+NC) of concrete exposed to real weather conditions.

- Partial replacement of cement with limestone powder limited the autogenous and drying shrinkage.
- Dense microstructure of UHPC and incorporation of steel fibers with lower w/b ratio significantly improved the frost resistance.
- On applied tensile force, no delamination was observed between layers and failed under substrate failure mode.
- Rough surface texture of substrate concrete promoted the interfacial friction and interlock mechanism was achieved.
- No significant difference in UPV measurement were observed resulting from highly dense and viscous UHPC adhere the substrate layer.

All data, figures, and the support findings of this study are original. And the authors would like to acknowledge the Swedish Transport Administration (Trafikverket) and the Swedish Agency for Innovation Systems—Vinnova for the funding.

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