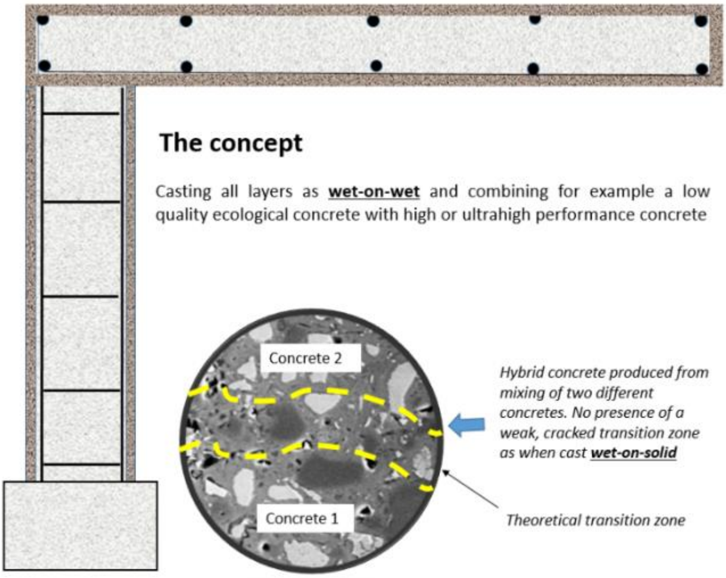
MID-TERM REPORT

HYBRID CONCRETE



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Building Materials

LULEÅ TEKNISKA UNIVERSITET

HYBRID CONCRETE

by

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MID-TERM REPORT

Luleå, APRIL 2023

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Klaudja Telhaj

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SUMMARY

The amount of CO_2 related to Portland cement can be reduced by its partial replacement in concrete with secondary cementitious binders; limestone, blast furnace slag or fly ash or by a full replacement with alternative cements. Both variants bring certain limitations but also advantages. Such concretes may show a slower strength development or worse durability. The worse durability can be related to more porous microstructure, formation of phases that are less stable and more prone to interact with for example chlorides or CO_2.

One of the solutions enabling to produce durable structures, that have also lower CO_2 footprint, and are cost effective is to combine different types of concretes in one element. This concept has been used for decades but as casting wet-on-dry, while very little has been done for the wet-on-wet technology. The results collected so far indicate that the concepts of using moving plate and dissolving meshes to cast two types of concretes at the same time are feasible.

All concretes produced using the moving plate method showed excellent bond and mechanical performances. No cracks, higher porosity, or increased formation of Portlandite were observed in any of the studied combinations. The dissolving mesh concept is still at the very beginning, but the results showed its big potential and several benefits in comparison to the moving plate method. Tests will be continued in the second part of this PhD study where technology for casting full size elements will be designed and verified.

Key words: hybrid concrete, interfacial transition zone, porosity, bond strength

SAMMANFATTNING

Mängden CO_2 relaterad till Portlandcement kan minskas genom delvis ersättning i betong med sekundära cementbindemedel; kalksten, masugnsslagg eller flygaska eller genom fullständig ersättning med alternativa cement. Båda varianterna medför vissa begränsningar men också fördelar. Sådana betongar kan visa en långsammare styrkeutveckling eller sämre hållbarhet. Den sämre hållbarheten kan vara relaterad till en mer porös mikrostruktur, bildning av faser som är mindre stabila och mer benägna att interagera med exempelvis klorider eller CO_2.

En av lösningarna som gör det möjligt att producera hållbara strukturer med lägre koldioxidavtryck och till lägre kostnad är att kombinera olika typer av betong i en och samma element. Detta koncept har använts i årtionden men vanligtvis genom att gjuta våt-på-torr, medan mycket lite har gjorts för tekniken våt-på-våt. Resultaten som hittills har samlats in indikerar att koncepten att använda rörliga plattor och upplösande nät för att gjuta två typer av betong samtidigt är genomförbara.

Alla betongar som producerats med hjälp av metoden med rörliga plattor visade utmärkt bindning och mekanisk prestanda. Inga sprickor, högre porositet eller ökad bildning av Portlandit observerades i någon av de undersökta kombinationerna. Konceptet med upplösande nät är fortfarande i sin linda, men resultaten visade dess stora potential och flera fördelar jämfört med metoden med rörliga plattor. Tester kommer att fortsätta i den andra delen av denna doktorsavhandling, där teknologi för att gjuta fullskaleelement kommer att utformas och verifieras

Nyckelord: hybrid betong, gränsskikt, porositet, bindningsstyrka

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1 INTRUDUCTION

Concrete has been a popular building material for many years because of its strength and ability to withstand wars and natural disasters. It is also preferred for its affordability and ease of production. The use of concrete has increased significantly, with 30 billion tonnes being used annually worldwide, which is three times more per capita than 40 years ago (York & Europe, 2021). Large production of concrete faces two major challenges: significant consumption of raw materials and major CO_2 emission, mainly from cement production, (Skogsindustrierna & Fossil Free Sweden, 2019).

Unfortunately, the production of Portland cement clinker in large volumes leads to significant CO_2 emissions, estimated to be as high as 5-8% of total global human-caused emissions (Gartner, 2004). The carbon-intensive nature of cement production is due to the use of fossil fuels to heat a mixture of limestone and clay to over 1,400 °C in a kiln. This process releases about 600 kilograms of carbon dioxide per tonne of cement produced. Therefore, reducing the carbon footprint of concrete will require addressing the carbon intensity of cement production.

As a result, using hybrid concrete where the composition, microstructure, and properties vary gradually and continuously over the volume of the material might help in reduction of the CO_2 footprint. Hybrid concrete can be created by varying the mix composition of the concrete within the produced element. This can be achieved by changing types and ratios of concretes ingredients such as aggregates, cement, water, or admixtures.

By tailoring the composition of the concrete to local needs, hybrid concrete can achieve multiple objectives simultaneously. For example, the concrete can be made stronger, more durable, and more resistant to cracking in areas where the stresses are highest, while in other areas it can be made lightweight, resistant to thermal stresses, or acoustically insulating, depending on the requirements of the application, (Fehling, 2014; Kodur et al., 2020). Hybrid concrete can also be used to optimize the use of materials and reduce costs. By using the right mix composition only where it is needed, the overall amount of expensive or environmentally harmful materials used in a structure can be reduced, while still meeting the required performance criteria.

1.1 Aim and objectives

The project aims at creating a novel technology, including materials and production process, enabling manufacture of such hybrid structures where two different types of concretes can be cast simultaneously in predefined locations.

This research is focused on the production technology of the hybrid concrete using two or more concrete mixes casted simultaneously. The objectives of this study were as follows:

- Enabling the use of materials with low CO_2 footprint such as secondary cementitious materials.
- Producing concrete elements having good mechanical properties.
- Design a production technology for casting hybrid elements which have a long-life span and sustainability.

1.2 Research questions

The following research questions were formulated for this PhD project:

RQ1 – How does the rheology of the concrete mixes affect the bond line?

RQ2 – How does the interfacial transition zone formed in the hybrid differ from ITZ formed between binder matrix and aggregates?

RQ3 – What are processes controlling formation of the hybrid transition zone?

RQ4 – How does the hybrid transition zone affect performances of the hybrid concretes, including strength and durability?

RQ5 – Could hybrid concrete enable usage of larger amount of industrial or other wastes without sacrificing the mechanical properties and durability of the element.

1.3 Scientific approach

The research work started with the literature review to acquire the essential understanding of hybrid concrete and casting methods used for its production. The aim was to compare two types of casting methods used to produce the hybrid concrete, i.e., wet-on-hard, and wet-on-wet. The following factors were studied, fresh properties of the concretes, types of concretes, properties of interfacial transition zone formed in both methods. Based on the performed analysis, the knowledge gab was identified and used to refine the research program for this study.

As a result, the main emphasis of this research was directed towards wet-on-wet casting method of the hybrid concrete with respect to both, material properties and full-scale applications. The research program included experimental verification of effects related to fresh concrete properties, types of concretes used and formation of the bonding line. The project focus on study two methods enabling casting of two concretes, i.e., lifting plates and dissolving mesh. The interface transition zone formed between two casted concretes in the hybrid concrete was investigated. The focus was on chemical bond formed in the wet-on-wet casting and mechanical properties of the bond. Based on the acquired results obtained from small samples testing a half scale laboratory investigation was done.

1.4 Limitations

The following limitations of the current studies can be listed:

- The secondary cementitious material used in this study was limited to blast furnace slag due to its good availability in Sweden.
- The experimental study focused only on the wet-on-wet method, where the outer and the inner layers had the same

thickness in small specimens. The effect of the thickness of the layer needs further investigations.

- The study in this part was limited only to mechanical properties of the hybrid concrete determined on small and half scale samples. Large scale specimen should be tested, to understand the behavior of hybrid concrete.

1.5 Chapter overview

The report consists of six chapters which are briefly described below:

Chapter 1: Describes the amin, scope and limitation of the project.

Chapter 2: Contains theory background of hybrid concrete.

Chapter 3: Briefly describes materials and methods used in this study.

Chapter 4*:* Presents results and discussions related to the experimental work.

Chapter 5: Summarises main conclusions.

Chapter 6: Indicates further research for this Ph.D. project.

1.6 List of appended publications

The following publications are included in this mid-term report:

I. Hybrid interfacial transition zone formed between wet-on-wet casted concrete – Microstructure and Mechanical properties.

   a. Klaudja Telhaj, Hans Hedlund, Andrzej Cwirzen

   b. *Materials* **2022**, *15*(19), 6511;

   c. https://doi.org/10.3390/ma15196511

II. Interfacial transition zone formed on wet - on wet cast between ultra - high performance fiber reinforcement concrete - blast furnace slag concrete, (sciencesconf.org: synercrete23:437423)

   a. Klaudja Telhaj, Andrzej Cwirzen **(Accepted)**

III. Mechanical properties of hybrid ultra – high performance concrete – normal strength concrete elements in fresh – on – fresh casting

   a. Klaudja Telhaj, Hans Hedlund, Andrzej Cwirzen

   b. ACI Spring Convention 2023

IV. Hybrid Concrete – production technology and bond properties **(Draft)**

2 LITERATURE REVIEW

This chapter describe and classifies methods to manufacture hybrid concrete. Possible applications and properties of interfacial transition zone formed between layered concrete are discussed.

2.1 Hybrid concrete

Hybrid concrete elements can be classified into two main categories based on the order in which the casting is done: wet-on-hardened and wet-on-wet. In the wet-on-hardened method, new layers of concrete are added only when the previous layers have already set and hardened. In contrast, in the wet-on-wet method, different concrete mixes are combined and cast simultaneously, so that they set and harden at the same time. The choice between the two techniques depends on the specific needs of the construction project, including design requirements, construction specifications, and timeline.

2.1.1 Wet-on-hardened casting

Concrete structures worldwide are often exposed to severe environment condition, and they need to be properly maintained to preferably extend their lifetime. Repairing and strengthening of existing structures is one of the most common methods used for the rehabilitation of damaged or deteriorated concrete structures. One of the methods often used to retrofit or repair existing structures is wet–on–hard casting. Wet–on–hard casting consists of pouring a fresh over layer on existing concrete structure. The fresh overlays are suitable for structures with large surface areas such as slabs, pavements, bridge deck, walls, columns, and tunnels, where it can be either poured or sprayed. Examples of wet-on-hardened casting include the application of ultra-high-performance concrete (UHPC) to extend the lifetime of deteriorated concrete structures. This could be done either by restoring a smooth sound surface or adding more material to improve its load bearing capacity, stiffness, and cracking resistance, (Bruhwiler, E., 2008). An example of a bridge pier after rehabilitation is shown in **Figure 1**. Another application of wet-on-hardened casting is used for casting on site connections between precast elements, **Figure 2.** When concrete is used to connect precast elements, high-strength mixes are usually adopted to meet the local durability and strength requirements, (Graybeal, 2010, 2014).

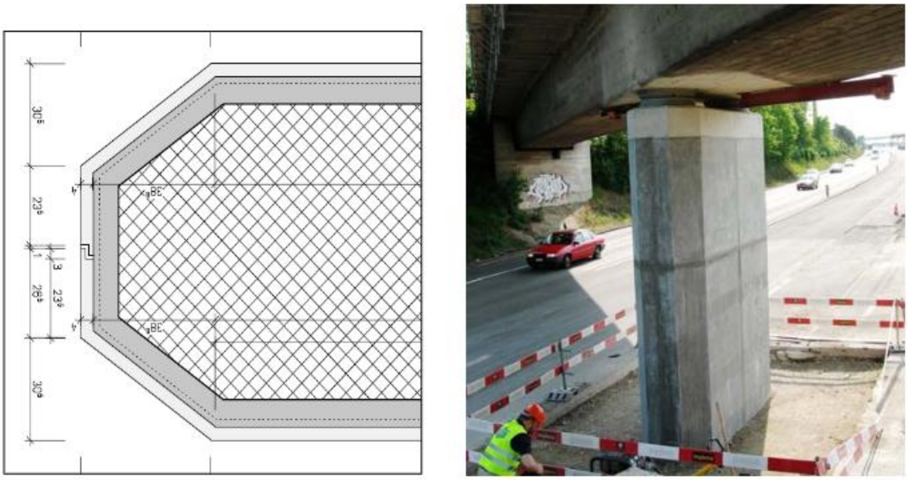


Figure 1 *Schematic representation of a bridge pier cross section cast wet-on-hard and general view after rehabilitation,* (Bruhwiler, E., 2008).

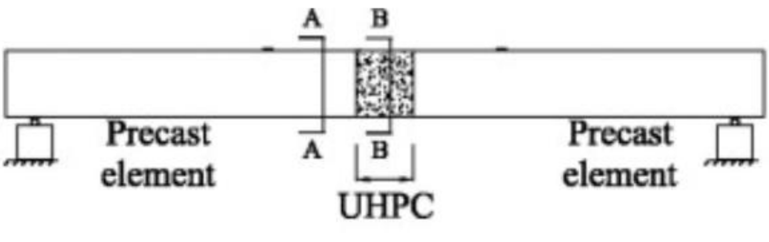


Figure 2 *Typical connection of two precast bridge deck elements.* (Maya et al., 2013)

Wet-on-hardened casting has some advantages over wet-on-wet casting, e.g., better control of the layer geometry, no need to cast different types of concretes at the same time. However, it may slow down production speed, which could limit its adoption in precast construction plants.

There are several limitations of this method. It is generally required to guarantee a good bond between layers and ensure full a composite interaction. The interfacial transition zone formed between new- and old- layers determined the durability of hybrid structure. The quality of the bond depends on both, substrate preparation and overlay placement procedure. In this respect, the quality of the workmanship and cleanliness of the older hardened concrete surface when the fresher mix is poured is of major importance, (Yin et al., 2017).

A further limitation factor is also the drying shrinkage. This is because the overlay is bonded directly to the existing concrete substrate, so any shrinkage that occurs in the overlay can cause stresses to develop in the substrate. To mitigate this effect, it is important to carefully control the mix design and curing conditions of the overlay to minimize the drying shrinkage. Additionally, reinforcement and support should be provided to help distribute any stresses that develops and prevent cracking or any other forms of damage. (Theiner & Hofstetter, 2012)

2.1.2 Wet-on-wet casting

Wet-on-wet method consist of casting two types of concretes simultaneously in the same element. Two casting arrangements are generally used, i.e., horizontally, and vertically layered.

Horizontal arrangement

Horizontal layering is a process of constructing reinforced concrete structures by placing multiple layers of fresh concrete horizontally on top of each other, with each layer typically separated by a layer of reinforcing steel. This process is often used in the construction of floors, roofs, and walls.

While horizontal layering may share some similarities with conventional casting processes, such as the use of fresh concrete and reinforcing steel, there are several key differences. One of the main differences is that horizontal layering involves the use of several types of concrete, each with its own unique characteristics and properties. This introduces additional compatibility constraints, as the fresh and hardened states of each mix must be compatible with the other mixes being used.

In a conventional casting process, typically only one mix of concrete is used for the entire structure. This simplifies the technology and allows for a greater control of properties of the finished product. However, the horizontal layering offers several advantages over the conventional casting processes, such as greater flexibility in design or faster construction.

An advantage of this casting method compared to the wet-on-hard is a possibility to achieve a good interlayer bond. However, strain incompatibilities are expected to arise due to differences in drying shrinkages of the two casted mixes. Furthermore, a major challenge in the wet-on-wet casting is to control the flow of concrete mixes. It may lead to undesired interface intermixing, which may affect the properties of the cast element. (Brault & Lees, 2020a; Torelli & Lees, 2020). For example, when a stiff mix is placed on top of a fluid mix, the weight of the stiff mix can cause it to sink into the fluid mix, creating uneven bond line between the two. On the other hand, if a stiff mix is placed on the bottom and a fluid mix on top, the weight of the fluid mix cannot push down on the stiff mix, creating a more even bond line (***Figure 3***).

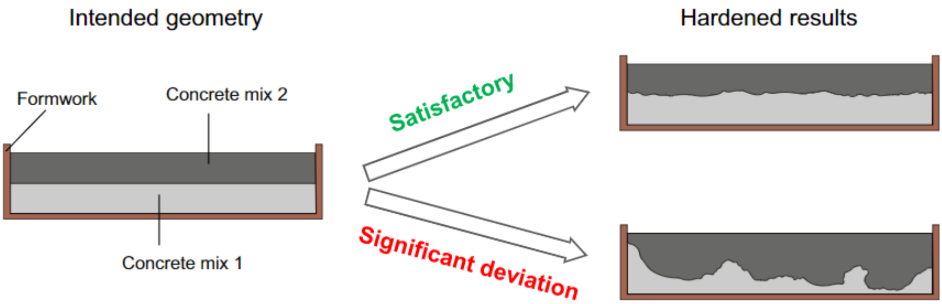


__Figure 3__ Schematic representation of the interface bond line formed between two cast concrete in wet-on-wet method. (Brault & Lees, 2020a)

Yalcinkaya has conducted a preliminary study on hybrid concrete with a combination of the UHPC – steel reinforcement concrete with normal mortar (NM) and self – compacting mortar (SCM). (Yalçınkaya, 2021) To prevent the deformation of the horizontally layers, the UHPC mix was designed to have a plastic consistency. Other researchers added a break between casting the first and the second layer. (Maalej & Li, 1995; Roesler et al., 2007)

Another drawback of using fresh-on-fresh casting method is that it may require the utilization of several concrete mixers to pour multiple concrete mixes in a restricted timeframe. This can cause difficulties in managing the construction process due to the sensitivity of material sourcing and delivery time, as well as necessitate a more intricate arrangement of the construction plant.

Vertical arrangement

Wet-on-wet casting methods to cast vertically elements are in the initial stages. These generally rely on movable plates to separate vertically layers before casting. However, the deformation of bond line may occur when the movable plates are lifted, while the mixes are still in their fresh states.

This method was used to cast hybrid concrete as a combination of ultra-high strength mortar (UHS) with normal strength concrete (NSC). Portland cement was replaced with 70 wt.% GGBFS in NSC. Simultaneous casting of hybrid concrete was performed in a standard 100 × 100 × 500 mm steel mold with a temporary steel plate placed vertically in the middle, perpendicular to the longitudinal axis of the mold. After pouring both types of concrete, the steel plate was removed (Cwirzen et al., 2008). The objective of this study was to determine the bond strength formed between two materials.

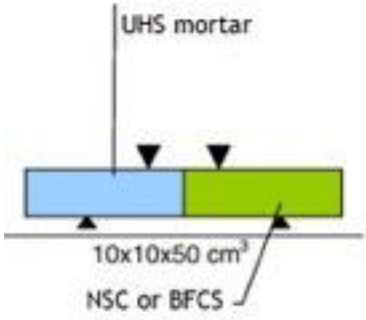


Figure 4 *A schematic representation of the vertical arrangement and the loading schemes,* (Cwirzen et al., 2008).

Torelli & Lee has adopted a similar concept to cast small scale prism of vertically layers with different mixes. The acrylic glass plate was used as moveable plate to separate the different mixes during casting. After finishing with casting the plate was removed and then two mixes came into contact. The aim of this study was to identify the effect of fresh properties of the materials in the stability of the bond layer, (Torelli & Lees, 2019).

When casting vertical layers, concrete flow in the fresh state can significantly affect the final geometry of the layers, just as it does with horizontally layered elements. To control the flow of fresh layers, it is essential to choose appropriate concrete mixes and avoid vibration-induced flow during the process. The integrity and characteristics of the interface between layers also depend on the process and the extent of intermixing, which can affect the local fracture properties and the effectiveness of the bond between different materials.

2.1.3 Interfacial transition zone in hybrid concrete

The interfacial transition zone (ITZ) plays a critical role in determining the performance and service life of a hybrid concrete structure.

The interfacial transition zone in *wet-on-hardened* casting method is formed between the fresh overlay and the substrate. The properties of ITZ depend on several factors, including the compatibility of repair material with existing concrete substrate, preparation, and cleaning of substrate surface prior to repair, and the method of application of repair material. On the other hand, the ITZ in the *wet-on-wet* casting method is formed between two fresh concrete mixes. The quality of ITZ depends on chemical bonding between layers and the compatibility of concrete used mixes.

There are several testing methods that are used to determine the bond strength of the hybrid concrete (***Figure 5***). (Tayeh et al., 2013) studied the performance of bond strength between NSC substrate and UHPC that was used as a repair material. Tests included the application of an indirect tensile stresses and a combination of compressive and shear stresses using tensile splitting test and slant shear test method. Several surface preparations methods were used, i.e., no roughness (AC), sand blasted (SB), wire brushed (WB), with drilled holes (DH) and groove preparation (GR) were applied on the NSC substrate. The NSC portion of the sample was saturated for 10 min and dried to create the saturated surface dry (SSD) condition. The measured tensile strength showed a good bond with the most failures occurring on the NSC side. The highest bond strength was observed on sample with the SB surface preparation, while the weakest in samples with the AC surface preparation on both tensile splitting and slant shear test.

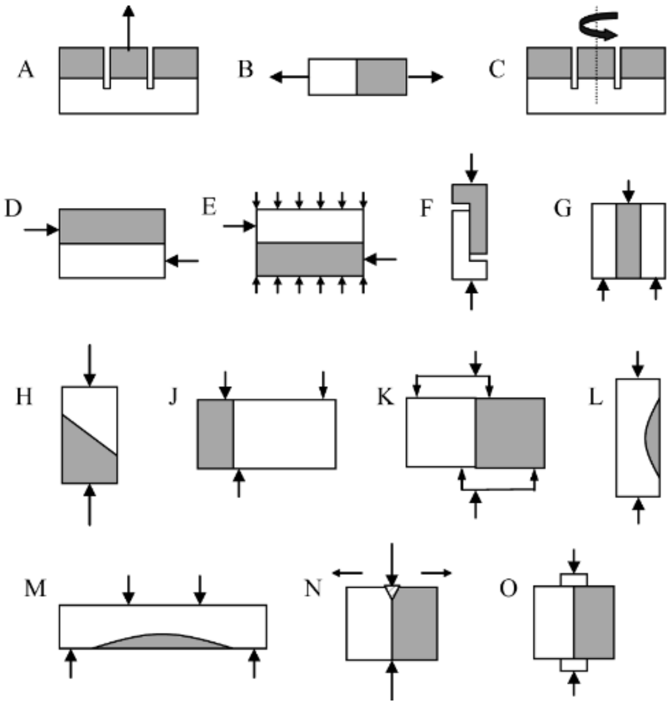


***Figure 5** Various test method used to determine bond strength.* (Silfwerbrand et al., 2011)

(Carbonell Muñoz et al., 2014) studied the performance of the interfacial bond strength between dry and SSD normal strength concrete and UHPC using different surface preparation such as slightly brushed, sandblasted, grooved, and rough. The surface roughness was measured. Three different tests, i.e., tensile splitting, pull off, and slant shear test were used to evaluate the bond strength of the hybrid concrete. In the beginning of the tensile splitting test, a large number of hybrid samples that were cast against a dry surface preparation have failed during their preparation. Therefore, they used the SSD surface preparation before placing the fresh layer of UHPC in all remaining tests. The results indicated that both the saturated concrete substrate and the exposure to freeze – thaw cycles showed an improvement in the bond strength. However, the effect of the surface roughness on the bond strength was not evaluated since the failure did not take place on the interface. Previous study on the wet-on-wet method also focused on mechanical properties and bond strength. (Pratama et al., 2019; Rydval et al., 2017) In a study conducted by L. Hussein, the flexural strength of hybrid concrete made of UHPFRC and NC/HSC, cast horizontally using the wet-on-wet method, was investigated. The addition of fibers to the bottom UHPFRC layer increased the flexural strength. A splitting test was conducted to evaluate the bond strength between UHPFRC and NC/HSC, and the bond failure occurred along the interface. The bond strength between wet-on-wet casted layers was significantly higher than the reference beams made of NC and HSC. (Hussein & Amleh, 2015).

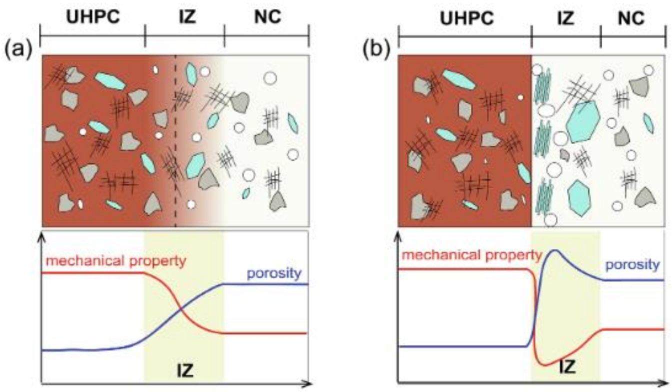


***Figure 6** Schematic diagram a) wet-on-wet cast interface b) wet-on-hard interface*. (Liu et al., 2022)

Vertically layer of hybrid concrete (UHPC-NC) was cast in wet-on-hard and wet-on-wet method. A comparison between the interfacial transition zone formed in each casting method was studied by Liu (Liu et al., 2022). The test results showed that the ITZ formed in the wet-on-hard method had higher porosity and higher degree of hydration, resulting in poor local mechanical properties compared to the NC interior. On the other hand, the ITZ formed in the wet-on-wet method showed a gradual change of porosity, anhydrous cement particle content, and mechanical properties, resulting in a smooth transition zone for UHPC and NC, **(Figure 6).**

3 METHODOLOGY

In this chapter, materials and methods are described. Interface transition zone characterization formed between two types of concretes casted simultaneously and casting technology used for production of the hybrid elements are explained.

3.1 Materials

Portland cement type CEM I 42.5N (Anläggningscement) produced by “Cementa” (Skövde, Sweden) is the main cementitious binder used for all the mixes in this study. In the blast furnace slag concrete 50 wt.% by cement weight is replaced with BFS, type Mmerit provided by SweCem (Helsingborg Sweden). The max aggregate size used in blast furnace slag concrete (BFSC) and high-performance concrete (HPC) was 8 mm and in the SCC 16 mm. Additionally, in the HPC mix was addedcontained also condensed micro-silica type 920D from Elkem (Oslo, Norway) and bleeding stabilizer type “MasterMatrix 101” from BASF AB (Rosersberg, Germany). TIn the UHPC mix contained was addedalso the condensed micro-silica 920D from Elkem (Oslo, Norway), limestone powder “Nordkalk Limus 40” from Nordkalk AB, Norquartz 45 from Sibelco Nordic (Lillesand, Norway) as well as micro sand B15 (150 μm) and B35 (350 μm) provided by Baskarpsand AB (Habo, Sweden). A polycarboxylate-based superplasticizer type “MasterGlenium ACE 30” from BASF (Rosersberg, Germany) was added to the mixes of BFSC, HPC UPHC and UHPFRC. In the SCC a superplasticizer type "MasterAir 105” from BASF (Rosersberg, Germany) is used. The chemical composition of the dry materials used is shown in Error! Reference source not found..

Eight different types of concrete mixes were used in this study, as show in **Table 2**. Including two normal concretes (N1, N2), tow concretes containing BFS (C1, C2), one high performance concrete (H1) and two types of UHPC concretes with and without still fibres

(U1, U2). The amount of binder varied from 400 to 664 kg/m^3. Fresh concretes properties were determined using slump and slump-flow methods and the obtained results are shown in **Table 2**.

Table 1*. Chemical composition of the used materials used.*

	CEM I 42.5N	**BFS**	**Silica fume**	**Quarts**	**Sand (B15, B35)**
CaO	63,30	30,3	1	99,6	-
SiO_2	21,20	34	≥85	-	90,5
Al_2O_3	3,40	11,6	1	0,25	4,9
Fe_2O_3	4,12	0,291	1	0,02	0,5
MgO	2,20	12,1	1	-	-
Na_2O	0,18	0,531	0,5	-	1,2
K_2O	0,56	0,811	1,2	-	2
SO_3	2,70	-	2	-	-
Cl	<0,01	-	0,3	-	-
LOI	2,50	-0,9	4	0,15	-

These concretes were combined into hybrids in several combinations shown and were combined in various ways as shown in **Table 3**. Ultra-high-performance concrete with and without fibres, high performance concrete and normal strength concrete is used as an outer layer of hybrid concrete where the inner layer consisted of normal strength concrete, self-compacting concrete, and blast furnace slag concrete. The summery of mix compositions is shown in **Table 2**.

Table 2. *Mix proportion of the mixes. (NSC - N1, N2; BFSC - C1, C2; HPC - H1; UHPC – U1; UHPFRC- U2;), Slump: S- slump, SF- Slump flow*

Ingredient (kg/m³)	N1	N2	C1	C2	H1	U1	U2
Cement (Cem I 42,5N)	400	360	200	200	447	680	664
BFS			200	200			
Silica Fume 920D					29	136	132.8
Limestone filler						680	664
Quartz filler			92	92	91	68	66.4
Sand – B15	358	337	92	92	91	238	232.4
Sand – B35						238	232.4
Aggregate 0-4	1254	1179	1106	1106	547		
Aggregate 4-8	179	168	553	553	1095		
Steel fibers 7mm							66.4
Steel fibers 13 mm							99.6
PCE - superplasticizer	3	0.9	3	3	14.3	34	33.2
VAM- bleeding stabilizer					4.76		
Air (%)	2	2	2	2	2	4	4
w/c	0.45	0.65	0.45	0.4	0.3	0.3	0.3
Workability (slump) mm	30 (S)	25 (S)	340 (SF)	380 (SF)	610 (SF)	720 (SF)	620 (SF)

Note: Self compacting concrete is a mix design developed from a concrete distributor which do not allow to publish the mix design.

Table 3. Used combination of concretes

Inner layer →	**NSC (N1) (w/c= 0.45)**	**NSC(N2) (w/c= 0.65)**	**BFSC(C1) (w/c= 0.45)**	**BFSC(C2) (w/c=0.4)**	**SCC (S1) (w/c= 0.45)**
Outer layer ↓					
NSC(N1) (w/c= 0.45)				N1C2	
HPC (H1) (w/c=0.3)			H1C1		H1S1
UHPC (U1) (w/c= 0.3)	U1N1	U1N2	U1C1	U1C2	U1S1
UHPFRC (U2) (w/c= 0.3)	U2N1	U2N2			

3.2 Methods

3.2.1 Mixing

The mixing procedure varied depending on the produced concrete type and was done with two types of mixers, i.e., 72 litres Pan mixer type Zyklos and 8-liter “Hobart” mixer, Error! Reference source not found.. The mixing sequence for NSC, BFSC, HPC and SCC consisted of 3 minutes of dry mixing, followed by addition of water and superplasticizer, and mixing for another 2 minutes. UHPC and UHPFC were dry mixed for 5 min, followed by additional 5 minutes of mixing after addition of water with superplasticizer. 7- and 13-mm long steel fibres were added to the UHPFC mix and mixing continued for another 5 minutes. The total mixing time varied between 10 to 15 min.

a) b)

Figure 7. *Mixing equipment, a) 8 – litter “Hobart” mixer, b) Zyklos pan mixer.*

3.2.2 Sample preparation

- **Test beams and cubes**

Test beams and cubes were prepared in two arrangements. The first consisted of 500×100×100 mm beam that was cast with two concretes that were separated by a vertical plate placed in the middle of the beam. The plate was removed after casting vertically simulating the lifting plate method to be tested in this project. The casting second arrangement of the 500×100×100 mm beam consisted of casting in two horizontal layers. This arrangement simulated casting of slabs. The third type of small size specimens produced in this project were 100×100×100 mm cubes that were either casted fully with one or two types of concretes in a vertical arrangement, **Figure 8.**

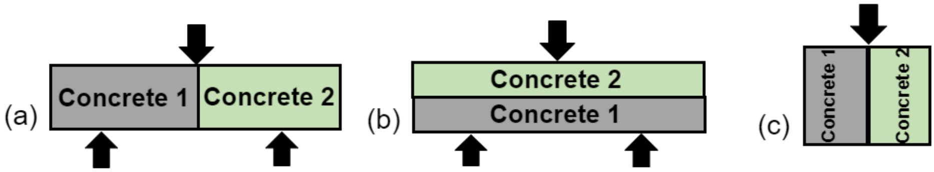


***Figure 8** Used test specimen: a) beam with vertical arrangement, b) beam with horizontal arrangement of layers, c) cube with vertical arrangements.* (Telhaj et al., 2022)

Another set of beams with dimension of 40×40×160 mm and cubes with dimension of 50×50×50 mm was used for testing a concept of dissolving membrane. The membrane was placed in the middle of the beam and two types of concretes were cast simultaneously. The arrangement of the dissolving membrane is shown in **Figure 9**.

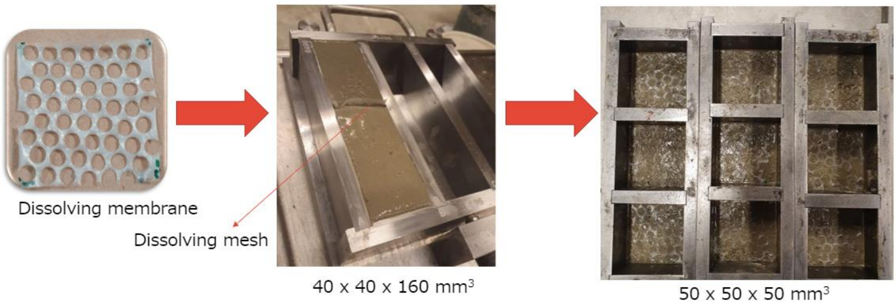


***Figure 9** Casting procedure used to prepare small samples to test performance of the dissolving mesh.*

- **Half-scale columns**

Half scale columns were made using plywood-formwork shown in **Figure 10.** Formwork for column having dimensions of 400×400×800 mm. The moving plates in this set up were made from Plexiglas. Their position in the form work was ensured with machined rails. During casting the 4 plates were lifted once the two concretes filled spaces on both sides.

Figure 10 *Formwork preparation before casting with reinforcement and moving plates installed.*

3.2.3 Casting

The fresh-on-fresh casting method is used here to cast all possible planned combinations of the hybrid elements. The two concrete mixes were almost nearly at the same prepared at the same time and left stationary until placing in the formwork occurred. Moulds were marked to define the length in vertical arrangement and the height in the horizontal arrangement. In all small-scale lab test, UHPC is used as an outer layer, which occupied half of the element and NSC, BFSC are used as an inner layer which also occupied half of the element. The vertical arrangement consisted of two concretes poured simultaneously against a removable plastic lifting plate or a dissolving membrane. The plate was removed after the completion of pouring but when the dissolving membrane was used, it stayed in the middle. The horizontal arrangement was cast in two layers without using any separating plate. No vibration was used after the plate removal. In the horizontal arrangement no vibration was used at all to prevent the undesirable intermixing in the interface.

The fresh-on-fresh casting method was used also for the half scale elements. The hybrid concrete columns were composed of a 50-mm thick column– external layer of ultra-high-performance concrete (H1) or high-performance concrete (U1) and a 300-mm wide "internal column" made of self-compacting concrete of blast furnace slag concrete (C1). The inner column had the dimensions of 300×300×800 mm and the outer column had the dimension of 400×400×800 mm as it shown in **Figure 10**. The mixes were cast approximately at the same time and left stationary until pouring in the formwork occurred. To prevent the deformation of the removable plate from the concrete pressure during pouring the concrete the pouring of two types of the concretes was done simultaneously. A compaction with a rod was applied after 1/3 of filling with concrete when combination of UHPC/HPC with SCC was done before removing the plates. In the other combination of UHPC/HPC with BFSC (U1/H1 + C1) an internal vibration rod was used to compact before the plates were removed. The removal of plates has taken place after the whole pouring was finished.

3.2.4 Microstructure and chemical composition

- **SEM and EDS**

The microstructure was analysed using digital light microscope Dino-Lite and Scanning Electron Microscope (SEM) – type Jeol JSM-IT100 *(JOEL Ltd., Tokyo, Japan)* coupled with energy-dispersive spectrometry (EDS) from *Bruker (Bruker Corporation, Billerica, MA, USA),* Figure 11. All tests were performed 28 days after casting. Samples were cored and stored in isopropanol for 5 days to stop the hydration process. Later samples were followed by storage in a desiccator for several days. The following step included and impregnation under vacuum with a low viscosity epoxy resin. After curing samples were grinded and polished using *Struers CitoVac* and *Labosystem*. Polishing was done using diamond sprays having particles sizes of 9, 3 and 1 µm.

Magnification of 55x was used for the digital microscope and 150x, 1000x and 4000x for the SEM. The SEM images were captured in a backscattered electron mode (BSE). SEM-EDS spot analysis was performed at 4000x magnification in locations that were assumed to be predominantly occupied by the CSH phases, based on the grey levels of BSE images. The Ca/Si atomic ratio was determined at various distances from the ITZ that was localized based visually observations done with the digital microscope. The SEM acceleration voltage was 15 kV, the electron beam current was 50 mA, and the chamber vacuum was 30Pa. 50,000 counts per each analysis were used for the SEM-EDS.

a) b)

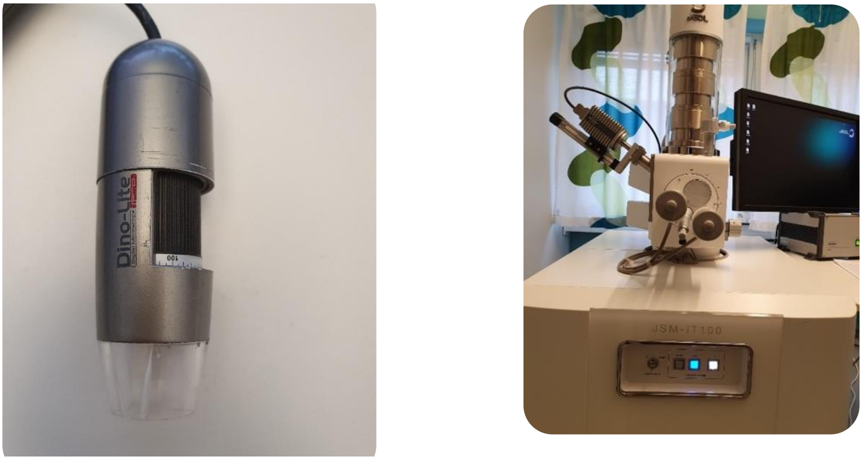


Figure 11. *Characterization of microstructure and chemical composition, a) optical microscope, b) Scanning Electron Microscope (SEM).*

3.2.5 Ultrasound pulse velocity

A pundit PL-200 *(Proceq, Zurich Switzerland)* with exponential transducers at 54 kHz was used. The 400×400×800 mm column elements were tested. The transmission time for each specimen was measured after 28 days from casting. Three different areas of the column were analysed outer layer, interface line and inner layer. The pulse velocity was determined as follows: (ASTM C597-16)

$$V = L/t \quad (1)$$

Where:
V- is the pulse velocity, (m/s);
L- is the distance between centres of transducers faces, (m);
t- is the transit time, (s).

a)

b)

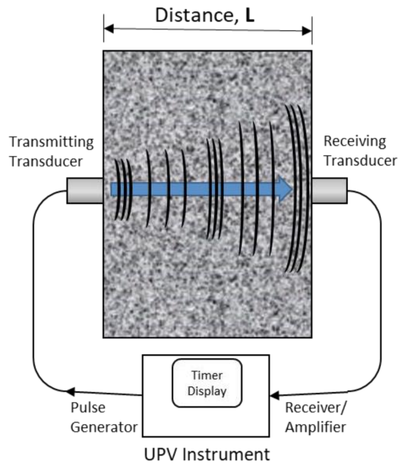


Figure 12 *a) UPV device, b) UPV measurement set up used.*

3.2.6 Mechanical properties testing

The bond strength of the hybrid concrete elements was determined by flexural, compressive strength and pull-out off tests.

28 days compressive and flexural strength measurements were performed on 10x10x10 cm samples following the *SS-EN 12390-3* “Testing hardened concrete- part 3: Compressive strength of test specimens” (Ics, 2020a). The 28-days flexural strength was determined on 500x100x100 cm beams following the *SS-EN12390-5* “Testing hardened concrete – Part 5: Flexural strength of test specimens” (Ics, 2020b).

The pull-out off test was done according to the *ASTM C 1538*. A “Proceq dy – 216” *(Proceq, Zurich Switzerland)* with 50 mm aluminium disc at a loading rate of 35kPa/s was used to perform the test. 70 mm deep core, including the outer layer of 50 mm and 20 mm of the inner layer was drilled in the column to perform the test. The bond strength (tensile strength) was calculating using the equation:

$$\sigma = \frac{F}{A_0} \quad (2)$$

where σ- tensile strength (MPa), F- failure load (kN), A_0- surface of the core (mm^2). Bond failure mode were classified in four types by visual observation as described in ASTM C 1538.

Table 4. Bond failure modes in pull off test

Bond Failure
Failure in substrate
Bond failure at concrete/ overlay interface
Failure in overlay/ or repair material
Bond failure at epoxy/ overlay interface

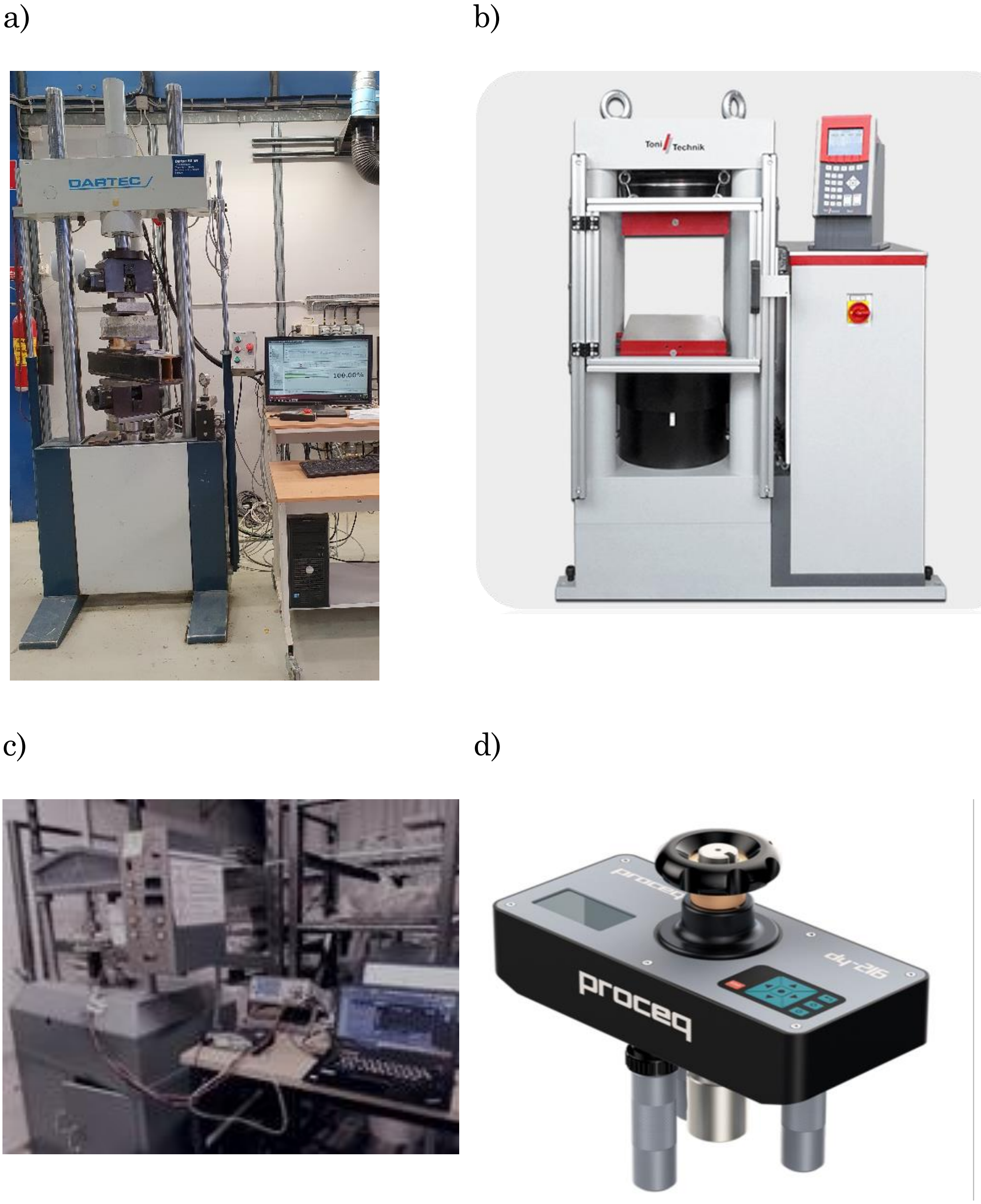


Figure 13 *a), c) Flexural strength equipment b) compressive strength equipment, d) pull off test equipment.*

4 RESULTS AND DISCUSSIONS

In this chapter, the results related to of the mechanical properties and microstructure of the hybrid concrete element are discussed. The first part focuses on the production of the small hybrid elements and their mechanical and microstructural properties. The second part describe the production technology of large-scale elements and their mechanical properties.

4.1 Test results – small hybrid element samples

4.1.1 Lifting plates

As described earlier, while casting vertical layers, a temporary plate was placed in the mould to separate the two types of concrete during their casting. Shortly after casting the plate was removed to enable a wet-on-wet connection. Generally, the visual examination of the produced samples after their demoulding did not reveal any signs of intermixing. This trend was observed even when the casted concretes had a very different workability, for example, fluid-like UPHC and a rather stiff NSC. In all investigated cases the interface appeared as a nearly straight line. Similar results, when casting wet-on-wet, have been observed by others, (Brault & Lees, 2020b; Torelli & Lees, 2019).

The situation became significantly more complex when the two layers were casted horizontally to simulate the production of slabs or beams. Here, the fluid UHPC concrete has been cast first, followed by the placement of a stiffer NC concrete, **Figure 14.** The visual examination of the lateral surfaces after demoulding showed a large variability of the thickness of each layer. The stiffer NSC concrete penetrated down through the fluid-like UHPC by up to 30 cm and pushed it up at different locations. The decrease of the ultimate thickness of the external layer made of a durable UHPC, even possibly to a nearly zero value, could lead to serious durability problems, e.g., corrosion of reinforcement. This could occur if only the external layer is designed to resist exposure to the environmental factors. While the internal layer has a sufficient load-bearing capacity but at the same time an insufficient durability. In another setup, a casting of the fluid-like UHPC on the top of already cast stiffer NSC concrete has been simulated, **Figure 14**. In that case, the UHPC did not tend to penetrate the NC concrete, which resulted in the formation of a nearly straight-line interface. These results indicate a possibly demanding technological problem of placing horizontal layers of two types of concretes having high workability.

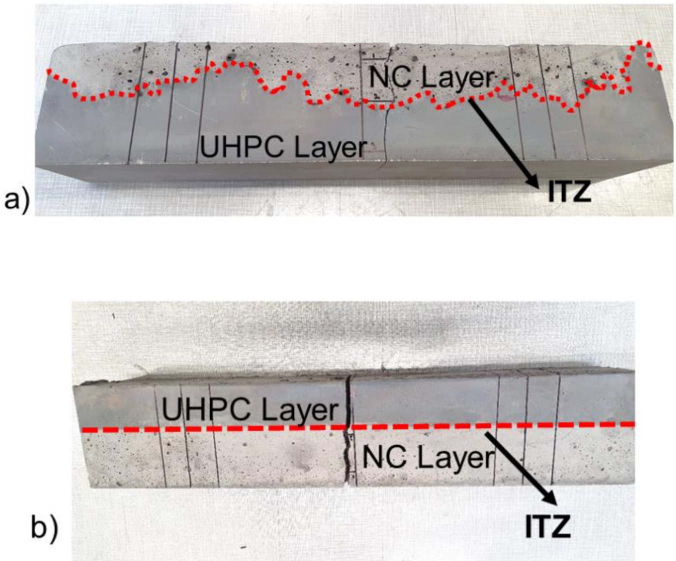


***Figure 14** Horizontal layer of hybrid concrete casted in two different arrangements a) Fluid concrete in the bottom b) Fluid concrete on the top* (Telhaj et al., 2022)

Microstructure properties

The interface transition zone formed in the hybrid concrete elements is the key factor because it determines the mechanical properties and durability of the casted elements. Microstructure and phase composition of the interface transition zone formed between the two casted wet-on-wet concretes on wet-on-wet method was studied. An example of images obtained from the digital light microscope and SEM is shown in **Figure 15**. Different magnifications were used to generally overview the morphology, localize aggregates, and main hydration phases, but especially including the distribution of the C-S-H gel. To study the details in the ITZ formed in the hybrid concrete, SEM images at 1000× magnification have been applied. The investigation focussed on microstructure, phase composition, porosity, and crack formation.

The phase composition of the hybrid ITZ was determined by SEM-EDX. All analyzed spots were localized in areas determined as C-S-H based on their grey levels as seen on the SEM-BSE images. Atomic ratios were calculated and analysed. The results are summarized in **Figure 16**.

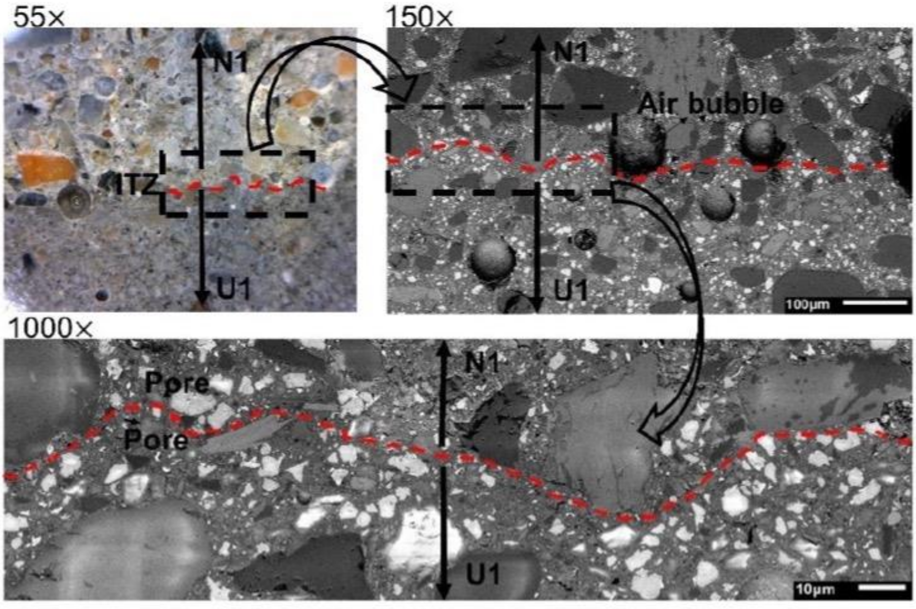
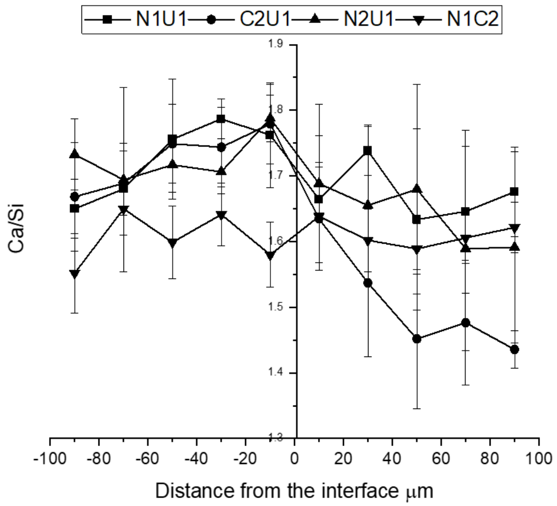


***Figure 15** Transition zone observed in hybrid concretes at 55× magnification (digital light microscope) and at 150× and 1000× magnification (SEM) example of U1N1 mix.* (Telhaj et al., 2022)

a)



b)

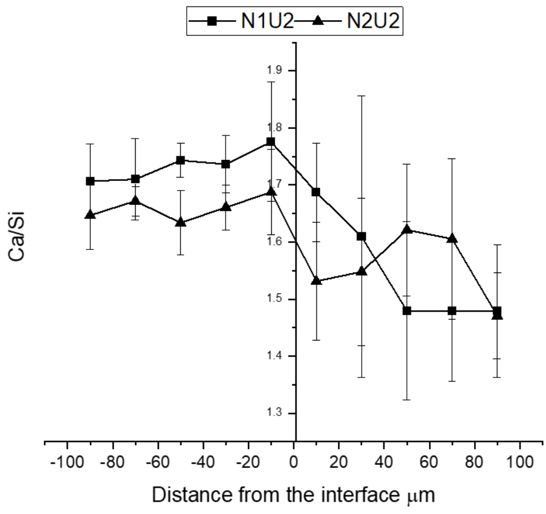


***Figure 16** Average atomic ratio and its corresponding standards deviations of hybrid concrete **(a)** U1N1, U1C2, U1N2, N1C2 **(b)** U2N1, U2N2* (Telhaj et al., 2022)

In the bulk binder matrix, the Ca/Si atomic ratio is typically higher for normal strength concretes (N1 and N2) than for ultra-high-performance concrete mixes (U1 and U2), according to calculations. The observed outcomes can be attributed to the reduction in the formation of Portlandite resulting from the pozzolanic reactions of SF, which leads to the production of C-S-H gel (BENTUR & COHEN, 1987). The Ca/Si distribution in the hybrid transition zone varied significantly between the studied combinations of concretes. However, in general, the ratio tended to increase for the UHPC concretes with a lower water-to-cement ratio closer to the interface. On the contrary, the normal strength concrete having a higher water-to-cement ratio showed mostly no change or only a slight increase. The hybrid system composed of UHPC (U1), and normal strength concrete (N2) had higher Ca/Si atomic ratios closer to the interface and lower values away from it. The created peak corresponded well to the results which have been observed in ITZs formed close to coarse aggregates (Cwirzen & Penttala, 2005; Scrivener, 2004). Similar trends and formations of the Ca/Si ratio peak at the interface have formed for the hybrids composed of the UHPC (U1) and the BFS concrete (C2), as well as for the combination of N1 with U1.

The porosity of the binder matrix was determined directly in the interface zone and in the bulk binder. To obtain the porosity distribution on the interface, the segmentation of the images was done using the ImageJ software. The stitched images at 1000× magnification was dived into strips, having a width of 20-µm. In each strip, three different areas were selected and used to quantify the porosity. The areas were located at a distance from 0 to 100-µm from the interface line. An average porosity value was calculated for each strip and the summarize of the results is shown in the **Figure 17**. In the graph negative X value correspond to porosity values to the inner layer N1, N2, and C2 while positive X values correspond to the outer layer U1-C2.

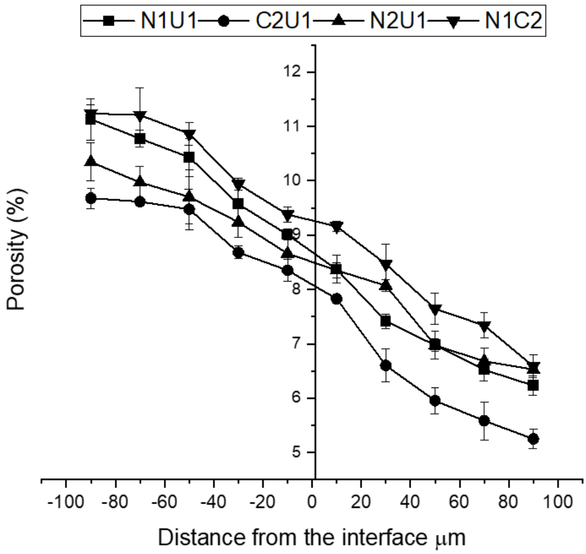


***Figure 17** Average porosity presented as a function of the distance from the ITZ.* (Telhaj et al., 2022)

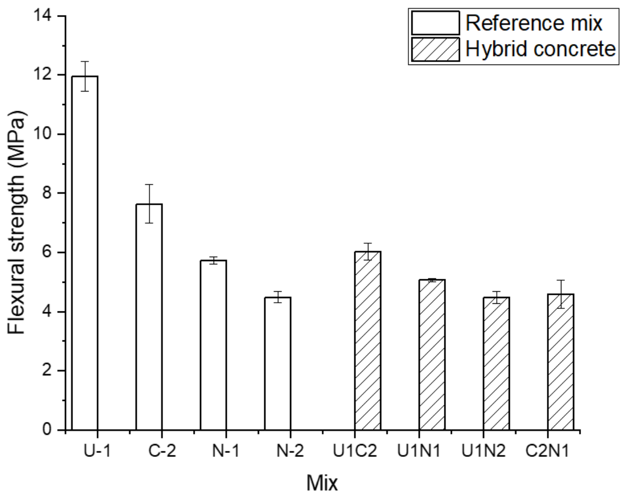
The porosity tended to be higher in the inner layer (N1, N2, C2) compared to the outer layer (U1, C2) of the hybrid concrete, as shown in **Figure 17**. The porosity of UHPC and BFSC in the outer layer tends to decrease. The lower W/C ratio and the presence of the silica fume in the case of the UHPC mix were the main contributing factors. The lower measured porosity of the mix C2 containing 50 wt.% of GGBFS can be related to the latent hydraulic reactions, which densified the microstructure due to the formation of more C-S-H.

None of the studied hybrids showed a visible increase of the porosity directly in the hybrid ITZ. Furthermore, the porosity transitioned smoothly between the two concretes. The same trend was observed in another study where the porosity decreased from NC to UHPC casted wet–on–wet (Liu et al., 2022). Casting wet-on-wet most probably enabled intermixing of both concretes in the transition zone creating a hybrid concrete mix.

Mechanical properties

Mechanical properties of the hybrid concrete small elements were determined based on flexural and compressive strength. The flexural strength was determined for two casting arrangement, i.e., vertical, and horizontal. All tests were performed at the age of 28 days and the size of beam used for this test was 100×100×500-mm. The results of the three-point bending test performed on the vertical arrangement of the hybrid element combination of UHPC without (U1) and with fibres (U2) are shown in **Figure 18.**

a)



b)

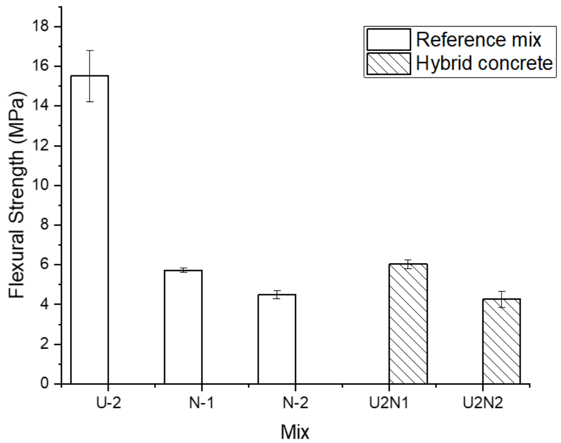


***Figure 18** Three-point bending test results of the hybrid concrete elements casted in the vertical arrangement; a) combination with UHPC (U1), b) combination with UHPFRC (U2)* (Telhaj et al., 2022)

The ultra-high-performance concrete reference beam with and without fibres showed the highest value of the flexural strength respectively 15.5 MPa (U2) and 12 MPa (U1). All the reference beams made from normal strength concretes showed lower bending strengths respectively 7.8 MPa (C2), 6 MPa (N1), and 4.3 MPa (N2). The high flexural strength values of the UHPC can be directly related to the low water-to-binder ratio, better packing density, lower porosity, and the presence of silica fume *(Andrzej Cwirzen, 2004; Cwirzen, 2006; Fehling, 2014; Ghasemzadeh Mosavinejad et al., 2020).*

Due to latent hydraulic and pozzolanic activities of *slag (D. Suresh, 1987; DESTA & JUN., 2018; Samad & Shah, 2017; Yun et al., 2020),* the reference beams containing BFS showed a slightly higher flexural strength. The failure in the three-point bending test of the hybrid concrete elements in the vertical arrangement has always happen in the weaker concrete layer away from the hybrid ITZ, as it shown in **Figure 19.**

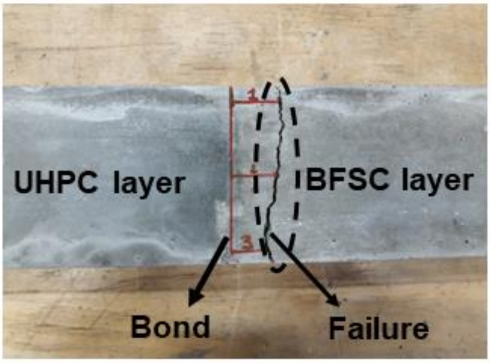


Figure 19 *Failure mode of the vertically layered hybrid concrete element (U1C2) after three-point bending test. (Telhaj et al., 2022)*

The measured flexural strength value of the hybrid concrete elements varied between 6 to 4.3 MPa, which were approximately equally with the value of the reference beam of the normal strength concretes (N1, N2, C2). These results, in combination with SEM-EDX results, further confirmed the formation of the hybrid ITZ, which is denser and stronger than the weaker concrete. Similar results were presented by other researchers from studies focusing on casting hybrid concrete by using the wet–on–wet method. The failure occurred along the interface during the splitting tensile strength test, and the crack propagated into a thin layer of the weaker concrete (NC) *(Hussein & Amleh, 2015; Liu et al., 2022)*.

The average flexural strength of hybrid concrete element arranged horizontally is shown in **Figure 20**. In both cases, the test results showed the highest flexural strength results around 12MPa, which is equally to the flexural strength of the UHPC. This arrangement is done to simulate the production of slabs. In this case, UHPC concrete would provide enhanced protection against environmentally exposure but would also enhance flexural strength.

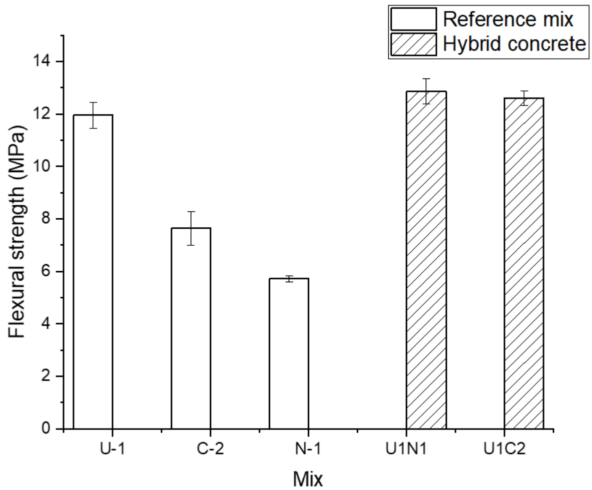
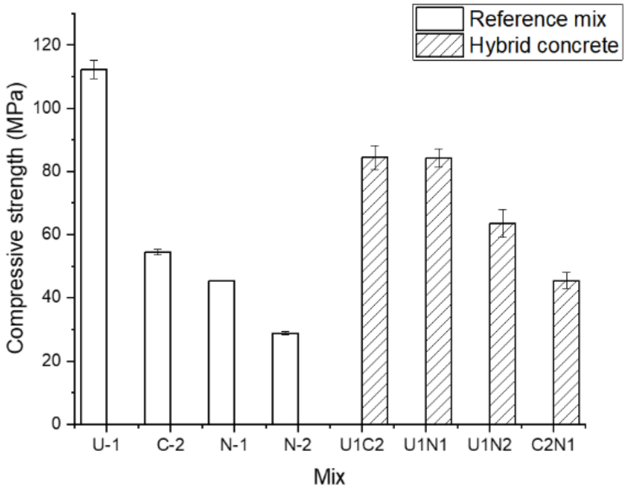


Figure 20 *Average flexural strength results of hybrid concrete elements arrange in horizontal layers. (Telhaj et al., 2022)*

The compressive strength of the hybrid concrete was determined at 28 days using vertically cast cubes. The average compressive strength results of reference and hybrid concrete cubes are shown in **Figure 21.** The highest value of the compressive strength was measured on the UHPC reference cubes respectively 121.2 MPa (U2) and 112.2 MPa (U1). The higher compressive strength of the UHPC can be related to the dense microstructure and lower porosity, *(Fehling, 2014; Ranjan & Iyer, 2013)*. The addition of steel fibres in the UHPC mix (U2) could restrain the initiation of the crack propagation, during the compressive strength which could results in a higher compressive strength. *(Meng & Khayat, 2018; Yang et al., 2022)* The normal strength concretes showed a lower compressive strength compared to the UHPC, respectively 54.5 MPa, 45.5 MPa and 28.8 MPa for C2, N1 and N2 mixes. The hybrid elements cubes showed a higher compressive strength value compared to the normal strength concretes but lower than UHPC.

a)



b)

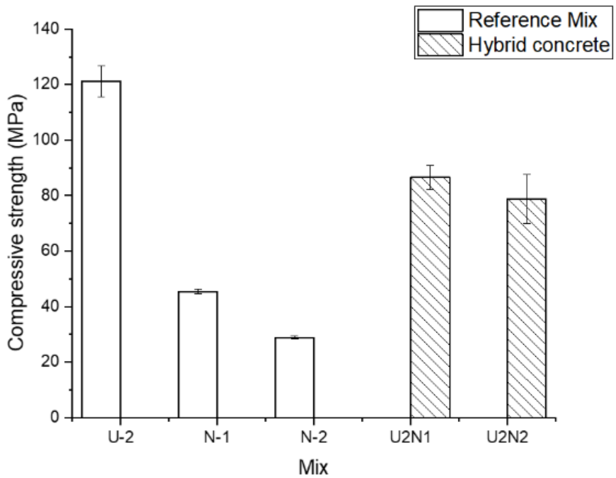


Figure 21 *Average compressive strength results of hybrid concrete elements a) Combination with UHPC (U1), b) combination with UHPFRC (U2) (Telhaj et al., 2022)*

4.1.2 Dissolving mesh

Dissolving mesh is the second studied concept to cast hybrid concrete elements. The set up that was used for testing the concept of dissolving membrane as is shown in **Figure 9.** A vertical arrangement of ultra-high-performance concrete with self-compacting concrete when a dissolving membrane was used as mesh to prevent the undesired intermixing of the casted element. A set of three moulds with having dimensions of 40×40×160 mm was prepared for testing the flexural strength of the hybrid concrete element. These were done in 3, 7 and 28 days after casting. The average flexural strength values are shown in **Figure 22 (a)**.

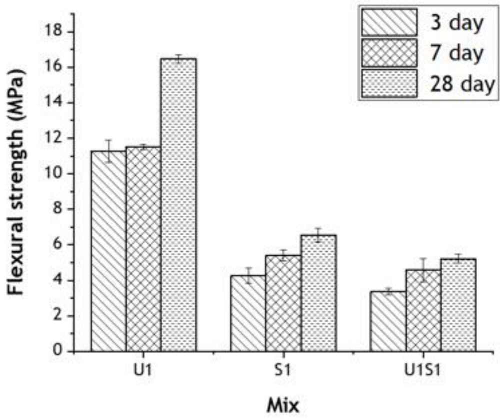
The test results showed that the reference beams and hybrid concrete beams showed the highest flexural strength at 28 days respectively 16.5 MPa (U1), 6.5 MPa (S1) and 5.2 MPa (U1S1). The failure in three-point bending test of the hybrid concrete elements occurred along the interface and the crack propagated into a thin layer of the self-compacting concrete. The measured strength was lower by 20% in comparison with the reference beam of S1.

A set of 3 moulds was prepared for testing the compressive strength of the hybrid elements and their reference cubes. The obtained data are shown in **Figure 22(b)**. The ultra-high-performance concrete showed the highest compressive strength at 28 days of 128 MPa. The self – compacting concrete showed a lower value of compressive strength of 40 MPa compared to UHPC due to high w/c= 0.45 used in the mix design. The hybrid element showed a higher compressive strength 78.7 MPa, which is higher compared to the reference cube of S1. The dissolving membrane did not affect the compressive strength results of the hybrid element.

This part of the test is still ongoing. Optimizing the mix to achieve fully dissolving of the mesh. Large scale elements are going to prepare to test the mechanical properties of the casted element when a dissolving mesh is used.

Determination of the bond strength is still ongoing at the time of preparation this report.

a)



b)

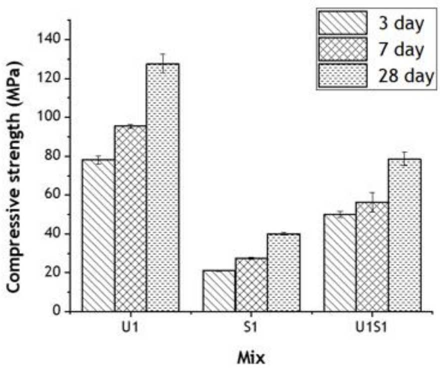


Figure 22 *Mechanical properties of the hybrid concrete casted in vertical arrangement in which a dissolving membrane was to separate these concretes used as a mesh; a) flexural strength, b) compressive strength.*

4.2 Test results – large scale hybrid element samples

4.2.1 Ultrasonic pulse velocity

The transmission time was measured in three different areas, i.e., such as outer layer, interface transition line and inner layer of the hybrid columns. The measurements were performed from the bottom part of column to the upper part. The calculated values of the pulse velocity are shown in **Figure 23**.

The pulse velocity in the outer layer (UHPC) was in the range of 4600 – 4700 m/s. The higher value of the pulse velocity in the UHPC is related to denser microstructure and lower porosity. In the interface line the pulse velocity was respectively, 4600 m/s for U1S1 and 4500 m/s for U1C2. The lower values of the pulse velocity were calculated for the inner layer of the hybrid elements. In both cases, the w/c ratio used in both mixes was 0.45. The transmission time measured in these layers was higher, which indicates a more porous microstructure. The pulse velocity recorded in the interface line was lower than in the outer layer, but higher than the inner layer. This result indicates a denser matrix with lower porosity area, less pores.

There are ongoing tests to investigate porosity in the interface transition zone and in both layers. These results will be correlated to the UPV measurement since porosity, voids or cracks are some of the factors that affect the transmission time.

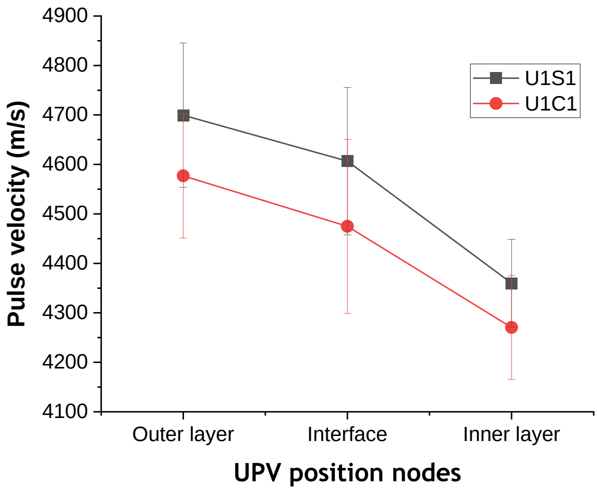


***Figure 23** Ultrasonic pulse velocity (UPV) results in hybrid concrete column*

4.2.2 Bond strength (pull off test)

The bond strength between SCC or BFRC with UPHC as an outer layer in the hybrid element casted wet-on-wet varied 2.5 and 3 MPa, **Figure 24.**

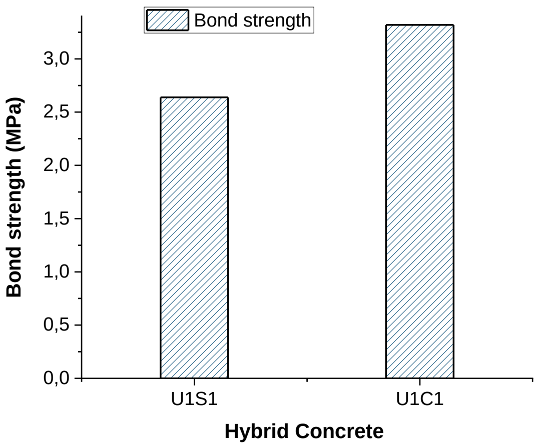


***Figure 24** Bond strength development in hybrid concrete column.*

The failure occurred in the inner layer of the hybrid concrete respectively in the SCC and BFSC, **Figure 25.** The classified failure mode based on ASTM C 1538 is failure at the substrate.

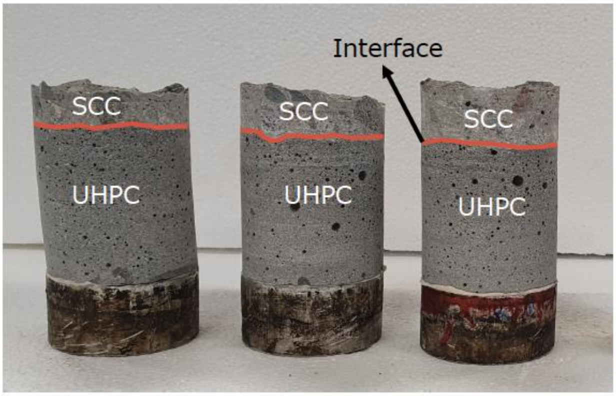


Figure 25 *Failure mode of the test specimen after pull off test.*

In the wet-on-wet method the bond strength is mostly affected by the hydration reaction which takes place on both layers since the casting occurs simultaneously. Furthermore, the concrete mixes used in the hybrid concrete combination has different w/c ratio, respectively 0,3 for the (UHPC) and 0.45 for the (SCC, BFSC), which do not lead to an excessive w/c ratio directly in the interface. The interface transition zone formed in the hybrid concrete showed a higher tensile strength and the failure always occurred in the inner layer.

5 CONCLUSIONS

Hybrid concrete containing two types of concretes have been studied. All samples have been produced using the wet-on-wet method.

The following conclusions related to the research questions have been formulated:

RQ1 – How does the rheology of the concrete mixes affect the bond line?

Different workability of combined concretes can result in an uneven interface leading to a lower mechanical strength especially in the case of horizontally cast layers.

RQ2 – How does the interfacial transition zone formed in the hybrid differ from ITZ formed between binder matrix and aggregates?

The ITZ formed between two different concretes cast as wet-on-wet differed substantially from the regular ITZ known to form around coarse aggregate particles.

The hybrid ITZ could be described as a zone where properties of the two adjacent concretes are intermixed and combined.

The binder matrix microstructure and the phase composition tend to transition gradually within the hybrid ITZ.

RQ3 – What are processes controlling formation of the hybrid transition zone?

Still studied.

RQ4 – How does the hybrid transition zone affect performances of the hybrid concretes, including strength and durability?

The observed gradual transition presumably prevented the formation of microcracks due to differential absolute shrinkage values.

The very dense, homogenous, crack-free hybrid ITZ led to the development of excellent mechanical properties. None of the observed failures occurred in the hybrid ITZ.

RQ3 – Could hybrid concrete enable usage of larger amount of industrial or other wastes without sacrificing the mechanical properties and durability of the element.

The results obtained in this part of the PhD study indicate that hybrid concretes should enable to increase the usage of industrial by products in structures even if they might worsen some performances of the inner part. However, more studies are need especially in durability (to be performed in the second part of this PhD)

6 FUTURE WORK

The primarily experimental results presented in this mid-term report, showed that interface transition zone, which is formed between two different types of concretes casted on wet-on-wet, exhibits excellent mechanical properties. As a result of this study, several new research ideas have emerged for future investigation. These research ideas are summarized below.

- There is need to investigate further the two-production technology used in this project in a large-scale test. How the bond line will be affected from different types of concretes which exhibit different fresh properties.
- The durability of the hybrid elements needs further investigation. An assessment of the sustainability of the element being expose in different environmental exposures is necessary.
- Feasible studies, promoting the implementation of this project in industry and economic consideration needs to be taken into consideration for this further assessment.

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