Journal of Structural Engineering & Applied Mechanics
2021 Volume 4 Issue 1 Pages 046-056
https://doi.org/10.31462/jseam.2021.01046056
www.goldenlightpublish.com

RESEARCH ARTICLE

A preliminary study on the development of the normal concrete-UHPC composite beam via wet casting

Çağlar Yalçınkaya*

Dokuz Eylül University, Department of Civil Engineering, İzmir, Turkey

Abstract

Ultra-high-performance concrete (UHPC) is an innovative cementitious composite containing steel fiber reinforcement that can improve the behavior of structural elements thanks to its high strength and improved ductility properties. The mix design that provides these superior properties of UHPC also makes it a high-cost material. For this reason, the use of UHPC in parts where it contributes more significantly to the performance of the structural elements will lower down the costs and reduce the negative environmental effects caused by high cement content. In this preliminary study, the production of normal concrete (NC)-UHPC reinforced concrete (RC) composite beams by wet-on-wet casting was investigated by producing mini-RC beams. In the production of mini-RC beams, normal mortar (NM) and self-compacting mortar (SCM) mixtures were used to represent an NC. The results showed that in the production of NC-UHPC composite beams, the mixtures should have different rheological properties depending on the order of the layers. Increasing the total thickness of the UHPC layer enhanced the initial and yield stiffnesses as well as the peak loads. UHPC layer with thicknesses of 15 mm in tension zone, 30 mm in tension zone, and 15+15 mm in tension+compression zone led to the load-carrying capacity increment ratios of 20%, 34.6%, and 24.3%, respectively. However, increasing the thickness of the UHPC layer in the composite beams, especially more than 15 mm, reduced the ductility ratio and energy absorption capacity. Optimizing the tensile reinforcement ratio in UHPC layers can overcome the drawbacks in the ductility.

Keywords

UHPC; Composite beam; Wet-on-wet casting; Functionally graded concrete

Received: 24 January 2021; Accepted: 16 February 2021

ISSN: 2630-5763 (online)

1. Introduction

Composite structural members produced by combining the advantageous properties of different materials are used in structural engineering. Among these composite members, the most widely used one is reinforced concrete (RC), which is a combination of concrete and steel material. Steel reinforcements are placed into the mold prepared in the case of traditional RC systems and a selected class of concrete is poured into this mold. During this process, only one type of concrete mixture is used. In functionally graded concretes (FGC), different types of cement-based materials are used in different parts of the composite body depending on the loading condition, the weight to be lightened, or the external durability conditions. With the increase in the use of high-performance concrete and other special concrete types, the number of studies carried out on this innovative system has been gradually increasing. Besides, adverse

* Corresponding author
Email: caglar.yalcinkaya@deu.edu.tr

environmental effects can be minimized by using these special concretes containing high cement dosage in only the required parts of the structural members.

Torelli et al. [1] has shown that material saving of up to 40% is possible by employing FGC. The authors set the following design goals for FGC: (1) reduction of cement dosage in the selected areas to meet the desired strength; (2) controlling the post-cracking behavior of concrete using the high-quality materials only in the zones that determine cracking behavior; (3) the use of material with low permeability and multiple-cracking ability in the exposed surfaces of RC members to prevent the ingress of harmful ions and associated rebar corrosion; (4) minimizing cracks associated with the heat of hydration in mass structures by grading the cement content of the material; (5) reducing the element weight by providing a positional change in density; (6) the use of heat-insulating layers to reduce energy consumption and associated carbon emissions. Maalej et al. [2] investigated the use of fiber-reinforced cement-based ductile composite, which exhibits multiple cracking and deformation hardening behaviors under bending loads, by embedding the longitudinal tensile reinforcement in the ductile composite. Normal concrete was used in the other parts of the beam. The results showed that the beam containing FGC exhibited significantly higher reinforcement corrosion resistance compared to the conventional RC beam. Besides, the cracking tendency in the concrete cover induced by rebar corrosion was reduced. Chan et al. [3] examined the relationships between the mechanical properties, contribution to CO_2 emission, and cost of FGCs containing steel fiber and recycled aggregate. Test results showed that the mechanical performance of FGC was inferior to fiber reinforced concrete, but superior to fiber-reinforced recycled aggregate concrete. It was stated that the developed FGCs could be used in applications requiring lower loading capacity such as parking lots and bicycle lanes. Moghadam and Omidinasab [4] showed that fibers positioned inhomogeneously in FGC boards can improve the bending performance effectively. The authors noted that the more fibers in the tensile zone that carries more stress in FGC systems, the better the bending performance compared to the conventional system. In another study, the authors compared the behavior of the FGC slabs under the effects of the projectile and drop weight impacts with conventional slabs [5]. The study revealed that the slabs containing FGC had lower penetration depths and less destroyed volume under the projectile impact and had higher failure strength and energy absorption under the drop weight impact in comparison with the traditional slabs which were entirely reinforced. The studies carried out at both material and structural member scale have shown that, with the FGC technique, cheaper, lighter, higher performance, more durable, and more environmentally friendly structural composite elements can be produced [6–10].

The functionally grading operation can be performed in two ways: pouring a fresh mixture over a hardened layer that was already cast and cured or pouring the different fresh mixtures layer by layer simultaneously at very short intervals. These two techniques can be named fresh-on-hardened casting and fresh-on-fresh casting, respectively [1]. The fresh-on-fresh casting technique is also called wet-on-wet casting. It is aimed that the structural or non-structural elements produced by both casting techniques behave monolithically under service loads. However, in the case of fresh-on-hardened casting, there is a need for additional precautions to provide monolithic behavior between the old layer and the freshly casted layer. Pouring fresh concrete on hardened ones is a frequently used and familiar production technique in structural engineering applications. Pouring concrete as a cover on bridge decks and pouring concrete/mortar on the joints between the prefabricated elements are examples of this usage. However, the formation of the cold joint, which is an inevitable phenomenon observed as a result of pouring concrete on a hardened layer, has an adverse effect on structural performance. Besides, the fact that freshly poured concrete exhibits a steep early-age shrinkage whereas the hardened layer under the freshly poured one has already exhibited its ultimate shrinkage, causes the formation of shrinkage-induced cracks between the layers. To ensure the bond strength between the layers, there are requirements such as roughening the hardened surface or the use of adherence increasing admixtures. Additional operations such as epoxy bonding or anchorage applications are required for cement-based composites to be manufactured prefabricated and assembled after hardening [11,12]. Casting of different fresh mixtures layer by layer consecutively in the FGC technique prevents the problems listed above, the increase in labor requirement, and additional costs. However, there is still a need for experimental studies to reveal the detailed procedures of the production, and clarify the mechanical performance of the structural elements.

Ultra high-performance concrete (UHPC) is a cement-based composite, usually reinforced with steel fibers, having a high binder content (≥ 700 kg/m^3) and very low water to cement ratio (≤0.25) [13]. Due to its high compressive strength (≥ 150 MPa) and superior performance under bending loads, it can reduce the element dimensions while improving the mechanical performance of the structural elements. Besides, due to its extremely low porosity and permeability values, it is many times more resistant to environmental effects and penetration of harmful ions compared to conventional concrete [14]. As a result of its enhanced tensile properties and energy absorption capacity, UHPC can significantly improve the structural performance of RC members such as beams and slabs subjected to the bending loads [15]. However, its high cost limits the use of UHPC in structural elements [16]. In this preliminary study, the production of a normal concrete-UHPC composite RC beam by implementing the wet-on-wet casting method was investigated on the mini-RC beams. It was aimed to reduce the amount of UHPC, which is an expensive material, by using it only in tensile or tensile + compression zones of the beams, and to identify key features for large scale production.

2. Experimental

2.1. Materials

UHPC, normal mortar (NM) and self-compacting mortar (SCM) mixtures have been formulated within the scope of this study. The aim of using two different mortar mixtures in addition to UHPC is discussed under the section of results and discussion. Portland cement (CEM I 42.5 R) produced by Denizli cement (OYAK cement Group) was used in the mixtures. Densified silica fume used in UHPC formulation was obtained at BASF company. Some chemical and physical properties of Portland cement and silica fume are given in Table 1. The aggregate phase of UHPC was composed of 30% 0–0.4 mm and 70% 0.5–1 mm quartz by weight. In the case of NM and SCM mixtures, crushed limestone sand (0–5 mm) was used as the main aggregate phase. Besides, 0–0.4 mm quartz aggregate was used as filler. The specific gravity and water absorption of limestone sand were 2.62 and 1%, respectively. These values for quartz aggregate were 2.65 and 0.12%, respectively.

Table 1. Chemical composition and selected properties of cementitious materials

Chemical composition (wt %)	Portland cement	Silica fume
CaO	61.85	0.49
SiO_2	19.1	92.26
Al_2O_3	4.40	0.89
Fe_2O_3	3.96	1.97
MgO	2.05	0.96
Na_2O	0.27	0.42
K_2O	0.70	1.31
SO_3	3.72	0.33
Cl^-	0.0004	0.09
Loss on ignition	1.82	-
Free CaO	0.50	-
Physical properties		
Strength activity index-28d (%)	-	95
Fineness (m^2/kg)	369	20000
Specific gravity	3.12	2.2

A high-range water-reducing superplasticizer based on polycarboxylic ether polymer having a specific gravity of 1.1 was used to adjust the slump-flow value of UHPC and SCM mixtures. Brass-coated micro steel fibers having a length of 13 mm and a diameter of 0.2 mm were incorporated into the UHPC mixture. The specific gravity, aspect ratio, and tensile strength of micro steel fibers were 7.17, 65, and 2750 MPa, respectively.

This study can be evaluated as a pilot study that examines the production method of the composite RC beams via wet casting. Therefore, mini-RC beams were produced by employing galvanized steel wires as rebars. In mini-RC beams, galvanized steel wires had a diameter of 4.0 mm and 2.5 mm for longitudinal reinforcements and stirrups, respectively. The tensile strength of the steel wires declared by the manufacturer was 500 ± 100 MPa.

2.2. Mix proportions

Three different mixtures were used in the production of mini-RC beams via FGC technique. UHPC, NM, and SCM mixtures were designed to meet the different requirements arisen during the production of mini- RC beams. UHPC mixture was used as a high-strength and ductile layer to increase the flexural performance of the beams whereas one of the other mixtures (NM or SCM) was chosen depending on the rheological requirements for filling the remaining volume with low-cost material. Mix proportions are given in Table 2. The aggregate phase of UHPC was composed of only quartz aggregates. Silica fume was used to improve mechanical properties. Micro steel fiber reinforced (2% by volume) UHPC mixture had a water to binder ratio of 0.16. On the other hand, the aggregate phase of SCM was mostly composed of crushed limestone aggregate. The need for inert filler was met with the fine quartz aggregate (0–0.4 mm) concerning the powder type design approach. By subtracting the superplasticizer from the mix proportions of SCM, the NM mixture which had a plastic consistency was obtained. UHPC and NM are mixtures having a plastic consistency that require vibration during placement. On the other hand, SCM can fill the mold under its weight without the need for compaction energy.

2.3. Production of mini-RC beams

UHPC layers were used in three different combinations in the production of mini-RC beams utilizing the FGC technique. For this purpose, the molds with a cross-section of 6×10 cm^2 and a length of 60 cm were used to represent an RC beam having a rectangular cross-section with a width-to-height ratio of 0.6. The reinforcement details of the beams are shown in Fig. 1. The tensile reinforcement ratio was 0.0066. The depth of the concrete cover was ~0.5 cm. The rebar diameters and their placement were chosen to represent a real-scale RC beam. However, a detailed calculation was not made due to the size effect and the properties of the wire reinforcement that differ from the real-size rebars. It was aimed to simulate the real-size production, to estimate the mechanical response of the beams, and to observe whether delamination develops between the layers. The mini-RC beams were produced via wet-on-wet casting in the layer order given in Fig. 2.

Table 2. Mix proportions

Materials (kg/m^3)	Mixtures		
	UHPC	SCM	NM
Water	200	237	237
Portland cement	1000	500	500
Silica fume	250	-	-
Crushed limestone aggregate (0–5 mm)	-	1322	1328
Quartz aggregate (0.5–1 mm)	536	-	-
Quartz aggregate (0–0.4 mm)	230	200	201
Micro steel fiber	143.4	-	-
Superplasticizer	32	2.2	-
Design parameters			
Water/cement ratio	0.20	0.50	0.50
Water/binder ratio	0.16	0.50	0.50
Flow diameter (mm)*	150	250	150

*Flow table test for UHPC and NM according to TS EN 1015-3 [17], slump-flow test by using the same mini-cone for SCM.

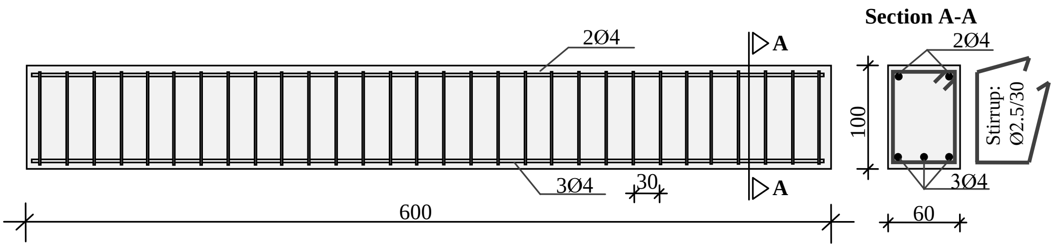


Fig. 1. Reinforcement details of mini-RC beams (dimensions in mm)

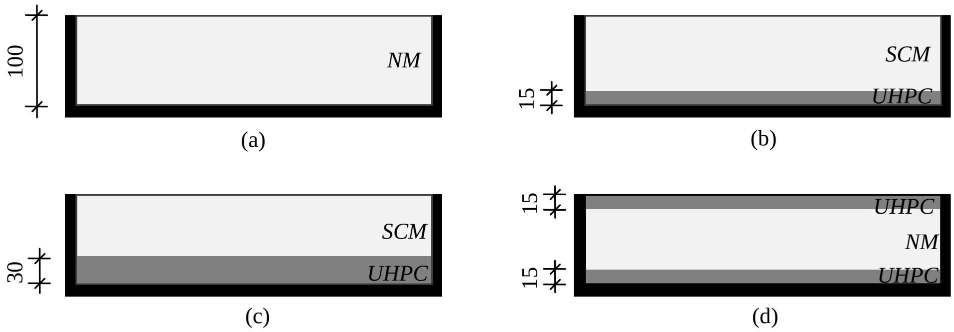


Fig. 2. The longitudinal sections of the beams; control beam without UHPC (a), composite beam-1 and 2: 15 mm (b) and 30 mm (c) UHPC layer in the tension zone, composite beam-3: 15 mm UHPC layers in tension + compression zones (d)

A total of four types of specimens were produced: the control beam produced by using only NM, composite beam-1 and 2 containing a UHPC layer with a thickness of 15 and 30 mm in the tension zone in sequence, and composite beam-3 containing 15 mm thick UHPC layers in both compression and tension zones. In the mini-RC beams produced with the FGC technique, NM or SCM mixture was chosen for the remaining volume depending on the rheological requirements. These requirements are discussed under the "results and discussion" section. Note that NM and SCM mixtures have similar mix proportions except for superplasticizer dosages.

The mixtures were prepared through Hobart mixers. Mix procedure of the mortars and UHPC was ended simultaneously. The mixtures were casted consecutively to avoid cold joint formation due to the premature densification of the UHPC casting surface called elephant skin formation [18]. UHPC and NM mixtures were cast in the mold by means of a vibrating table. SCM mixture, on the other hand, was poured onto the freshly casted UHPC layer under its weight without the need for compaction energy. The fresh state requirements for a successful wet-on-wet casting that determines the production method of the beams given in Fig. 2 are discussed in the section of results and discussion.

2.4. *Curing and mechanical testing of the specimens*

Steam curing application was preferred for the composite beams to represent the prefabrication process. First, the mortar specimens and mini-RC beams were kept sealed in the mold at 20 ° C for the first 24 hours. Then, the molds were removed and the specimens were placed in a steam curing cabinet. Automatic heating was initiated to increase the temperature from 20°C to 70°C in 6 hours. The specimens were cured at 70 °C for 72 hours to bring the mixtures to their ultimate mechanical properties. Following a gradual cooling period of the specimens, mechanical tests of the mixtures were performed in accordance with the specifications of TS EN 196-1 [19]. A three-point bending test was applied to determine the flexural strength. The simply-supported specimens were loaded from their mid-span. Note that the load-mid-span deflection graph of the UHPC mixture was obtained by an electromechanical closed-loop testing system. A compressive strength test was applied to the two pieces left from the flexural test at a loading rate of 2400 N/s. Three specimens for flexural strength and six specimens for compressive strength were tested for each mixture.

Mini-RC beams with the dimensions of 6×10×60 cm^3 were subjected to a three-point bending test by using an electromechanical closed-loop testing system at a support opening of 54 cm. The load-midpoint deflection curves were obtained by testing with a displacement-controlled press in the bending test. The loading was conducted under the deflection control with a rate of 1 mm/min. The loading was carried out in the direction that the UHPC layer would be located in the tension/compression zone of the beam. There were longitudinal reinforcements of 3Ø4, and 2Ø4 in the tension and compression zones, respectively (Fig. 1).

3. Results and discussion

3.1. Evaluation of production technique

During the trial castings, it was observed that there were some fresh state requirements to able to pour a different type of concrete on the underlying concrete layer successfully. In the case of self-compacting mixtures, the underlying concrete layer must have a sufficiently higher fresh unit weight than the upper one. Within the scope of the study, a rheological measurement was not taken by a rheometer. However, it can be said that the high thixotropy level of the underlying layer will facilitate the bearing of the upper layer and increase the risk of cold joint formation as a side effect. In this study, UHPC was designed in a plastic consistency that needs compaction energy because it needs very high dosages of superplasticizer when designed as a self-compacting mixture [20]. In this case, the UHPC mixture was simply placed on the bottom layer applying 15 s of external vibration. The higher viscosity and the unit weight of the UHPC compared to the SCM mixture featured the combination of UHPC+SCM as a very practical and successful production method among the others. The casting stage of UHPC+SCM composite beams can be seen in Fig. 3.

In the case where UHPC that had a plastic consistency was used in sandwich form both in tension and compression zones, a stiff mixture with high viscosity such as NM mixture had to be used at the midsection too. Since the SCM mixture had a much lower viscosity and fresh unit weight compared to the UHPC, it could not resist the weight of UHPC as a separate layer in case a UHPC mixture with a stiff plastic consistency was poured on it. A similar issue was also reported in a previous study [21].

For this reason, in the sandwich-type composite RC beams where the stiff consistency UHPC layer is used in both tensile and compression zones, a concrete mixture with increased consistency and viscosity should be used at the midsection. For this purpose, the NM mixture having a conventional consistency stiff enough was obtained by removing the superplasticizer from the formulation of the SCM mixture. After the UHPC was placed in the compression zone utilizing the vibration table, the NM mixture was poured and gently vibrated for the purpose of leveling. The necessary vibration needing for compaction of the midsection was applied together with the freshly poured UHPC layer in the compression zone of the mini-RC beam. Otherwise (in the case of two times vibration of the midsection), segregation and bleeding may occur in the NM mixture. For this reason, after NM was leveled by vibrating for a few seconds, UHPC was poured onto it, then the vibration was applied together for 15 seconds at the last stage. The combination of UHPC+NM+UHPC requires a much more careful production procedure. Besides, it should be investigated whether there is a local increase in the water to cement and air void ratio between the UHPC layer in the compression zone and the NM layer below as a side effect of the production procedure followed.

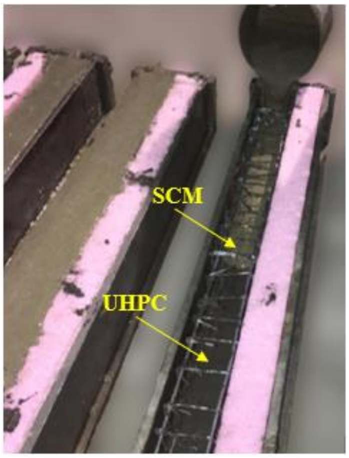


Fig. 3. Pouring SCM onto the freshly placed UHPC layer

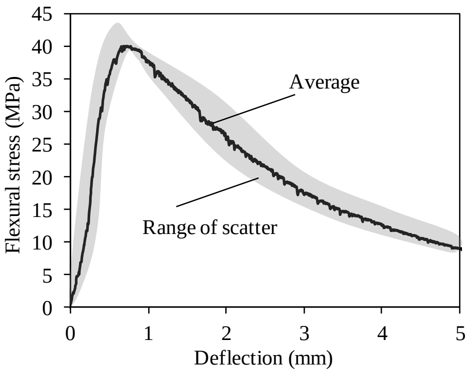


Fig. 4. Flexural stress-deflection graph of the UHPC mixture

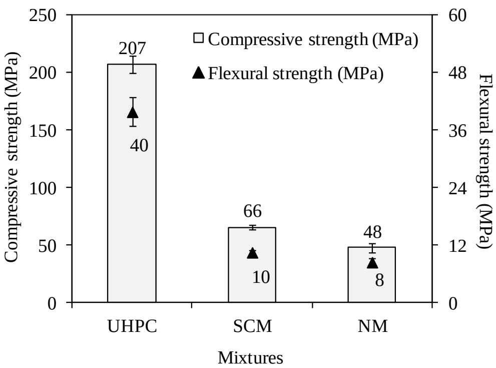


Fig. 5. Mechanical properties of the mixtures

3.2. Mechanical properties of the mixtures

The flexural stress - midspan deflection curve of the UHPC mixture and the mechanical strengths of all mixtures are given in Fig. 4, and Fig.5 in sequence. The UHPC mixture has an average flexural strength of 40 MPa and a significant load-carrying capacity even at high deflection values, thanks to the high fiber reinforcement content. UHPC mixture achieved a compressive strength of 207 MPa. SCM and NM mixtures exhibited an average flexural strength of 10 and 8 MPa, respectively. The compressive strength was obtained as 66 MPa for SCM and 48 MPa for NM. A 37.5% decrease in compressive strength was observed in the NM mixture compared to the SCM mixture as a result of the elimination of self-compacting ability by removing the superplasticizer from the formulation. This can be attributed to an increase in the ratio of entrapped air void in the matrix.

3.3. Flexural behavior of the mini-RC beams

Load - mid-span deflection responses of the beams obtained by the three-point bending test are presented in Fig. 6. Note that the loading was conducted until the rupture of tensile reinforcement. A ductile flexural failure was observed in the under-reinforced mini-RC beams. The yield and ultimate points were obtained following the method recommended by Park [22]. The yield deflection corresponds to the deflection at the intersection of the secant stiffness at 75% of the peak load with the level of peak load (Fig. 7). Besides, the point corresponding to a 20% load reduction from the peak load was identified as the ultimate point (Fig. 7). The calculated yield points were found very close to ones occurring before the ductility plateau of the beams containing the UHPC layer. Experimental values calculated from the load-deflection graphs are given in Table 3.

As can be seen from Table 3, implementing a UHPC layer in the beams increased the first cracking loads more than 2 times. Besides, the initial stiffness values increased with an increase in the thickness of the UHPC layer which has higher strength and stiffness than the conventional cementitious mixtures. At this stage, micro-steel fibers may also reduce the microcracking before the first crack. Yield load and yield stiffness were increased as a result of UHPC layer usage. Starting from the yield point to the peak load, a very limited increase in the load was monitored for the beams containing the UHPC layer. During the tests, a major crack formed at a single point over the mid-span starting from the peak load (Fig. 8). Peak load deflections were importantly reduced as a result of the UHPC application, especially in the case of composite beam-1 and 2. In the case of composite beam-3 containing UHPC layer at the compression zone, a higher deflection at the peak load was recorded compared to that of the beams containing UHPC layer in the only tension zone. UHPC layer application in the compression zone resisted the major crack when it achieved to the compression face. After the peak load, some microcracks started to develop around the loading point in the control beam and composite beam-1 and 2.

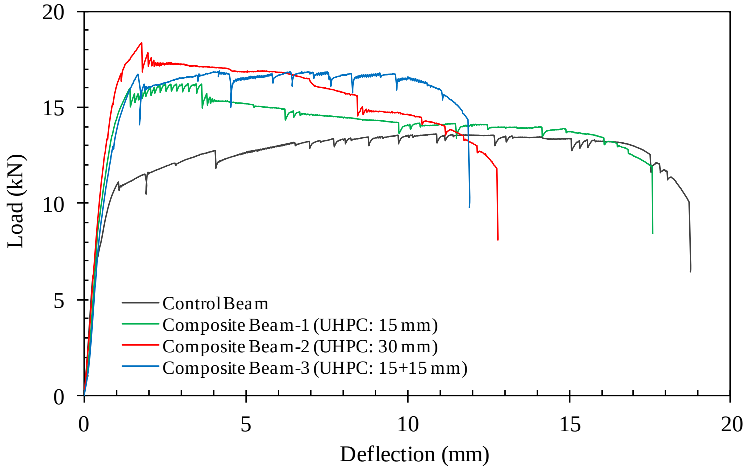


Fig. 6. Load-deflection curves of the mini-RC beams

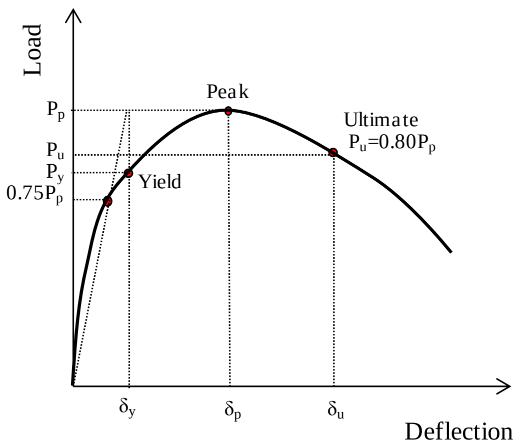


Fig. 7. Definition of yield, peak, and ultimate points

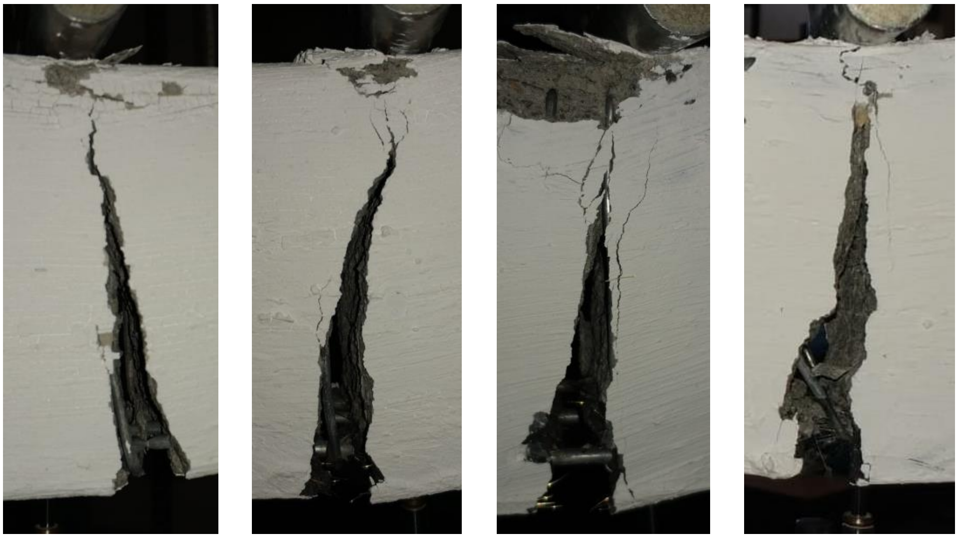
Table 3. Experimental results under flexural loading

	Control Beam	Composite Beam-1	Composite Beam-2	Composite Beam-3
First cracking load-P_{cr} (kN)	6.1	13.3	13.3	13.0
Yield load-P_y (kN)	11.2	14.3	16.4	15.0
Peak load-P_p (kN)	13.6	16.2	18.3	16.9

Table 3. Continued

	Control Beam	Composite Beam-1	Composite Beam-2	Composite Beam-3
Ultimate load-P_u (kN)	10.9	13.0	14.6	14.4
Reinforcement rupture load- P_{rt} (kN)	10.1	12.0	11.8	14.4
First cracking deflection- δ_{cr} (mm)	0.4	0.9	0.7	0.8
Yield deflection- δ_y (mm)	1.1	1.1	1.1	1.1
Deflection at the peak load - δ_p (mm)	10.9	2.5	1.7	4.2
Deflection at the ultimate load - δ_u (mm)	18.4	16.5	8.5	11.9
Deflection at the rupture load - δ_{rt} (mm)	18.8	17.6	12.8	11.9
Initial stiffness-P_{cr}/δ_{cr} (kN/mm)	15.3	16.7	19.0	16.3
Yield stiffness-P_y/δ_y (kN/mm)	10.2	13.0	14.9	13.6
Ductility ratio-δ_u/δ_y	16.7	15.0	7.7	10.8
Energy absorption capacity (kN.mm)	227	225	123	177
Increase in the peak load* (%)	-	20.0	34.6	24.3

*Compared to the control beam



(a) (b) (c) (d)

Fig. 8. Appearances of the control beam (a), composite beam-1 (b), composite beam-2 (c), and composite beam-3 (d) after the three-point bending test

Composite beam-2 having a 30 mm UHPC layer in the tension zone exhibited more obvious crushing at the loading point (Fig. 8c). On the other hand, UHPC in the compressive zone reduced the microcracking that is a signal of crushing the concrete at the loading point (Fig. 8d). UHPC layer in the tensile zone enhanced the bond between plain round rebar - cementitious matrix thereby limiting the rebar slippage under tensile stresses. Apparently, this also contributed to the reduction in the strain capacity of the tested beams under loading. In parallel to this finding, Yoo and Yoon [23] found that UHPC beams could exhibit lower ductility ratios as a result of crack localization that also localized the deformation of longitudinal reinforcement at a single point.

Above all, UHPC layers were importantly increased the load-carrying capacity (Table 3). In the case of composite beam-1, 2, and 3, increment values were found at 20%, 34.6%, and 24.3%, respectively. Increasing the total thickness of the UHPC layers, especially in the tension zone, contributed to the strength markedly. The ultimate load values also increased with the help of the

UHPC layers. However, deflection values at the ultimate load reduced by increasing the thickness of the UHPC layer applied. Marked reductions in the ductility ratio and energy absorption capacity were observed in the case of composite beam-2 and 3. Lowered deflection values at rebar rupture points were observed in the composite beams. This can be evaluated as evidence for hindered slippage of tensile reinforcement in the UHPC matrix. Ultimately, a ductile flexural failure culminated in steel reinforcement rupture was observed in all tested beams (Fig. 8). A previous study showed that UHPC members could be designed for very high levels of deformation, but low reinforcement ratios led to reinforcement rupture at inadequate low deformation values [24]. It was reported in a recent study that unlike traditional RC beams made by NC, increasing the ratio of steel reinforcement enhanced ductility and load capacity of the UHPC beams since the failure in UHPC beams was due to rupture of the steel reinforcement [25]. Besides, Türker et al. [26] showed that using high reinforcement ratios in UHPC beams could provide significant advantages in ductility and flexural moment capacity. Therefore, the layers containing UHPC that has extremely high strength and deformation capacity at material scale can be reached higher ductility levels by increasing the reinforcement ratio.

4. Conclusions

In this study, the production method of a normal concrete-UHPC composite RC beam by implementing the wet-on-wet casting was studied by producing mini RC-beams. To reduce the amount of UHPC as an expensive material, it was used only in tensile or tensile + compression zones of the beams. Major conclusions of this study were as follows:

Depending on the layer order of the normal concrete-UHPC composite beam, different rheological requirements were proposed. Ease of application and its success brings the combination of UHPC+self-compacting mixture to the fore.

Increasing the total thickness of the UHPC layer enhanced the initial and yield stiffnesses as well as the peak and ultimate loads. UHPC layer with thicknesses of 15 mm in tension zone, 30 mm in tension zone, and 15+15 mm in tension+compression zone led to the load-carrying capacity increment ratios of 20%, 34.6%, and 24.3%, respectively.

Increasing the thickness of the UHPC layer in the composite beams developed, especially more than 15 mm, reduced the ductility ratio and energy absorption capacity. In the case of a total thickness of 30 mm, using UHPC layers at both tension and compression zones resulted in a higher ductility ratio and energy absorption capacity compared to using the UHPC layer in only the tension zone. To overcome the drawbacks in the ductility, the tensile reinforcement ratio should be further optimized.

Normal concrete-UHPC structural members in the context of functionally graded materials should be comprehensively investigated to enhance the performance of the structures while reducing the cost and environmental impact of the cementitious composites.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgments

The author thanks Yekzan Arıkan, Ömer Türkmen, Uğur Toprak, and Abdülhamit Demirel for their helps during specimen preparation.

References

[1] Torelli G, Fernández MG, Lees JM (2020) Functionally graded concrete: Design objectives, production techniques and analysis methods for layered and continuously graded elements. Construction and Building Materials 242:118040.

[2] Maalej M, Ahmed SF, Paramasivam P (2003) Corrosion durability and structural response of functionally-graded concrete beams. Journal of Advanced Concrete Technology 1(3):307-316.

[3] Chan R, Liu X, Galobardes I (2020) Parametric study of functionally graded concretes

incorporating steel fibres and recycled aggregates. Construction and Building Materials 242:118186.

[4] Moghadam AS, Omidinasab F (2020) Assessment of hybrid FRSC cementitious composite with emphasis on flexural performance of functionally graded slabs. Construction and Building Materials 250:118904.

[5] Moghadam AS, Omidinasab F, Dalvand A (2020) Experimental investigation of (FRSC) cementitious composite functionally graded slabs under projectile and drop weight impacts. Construction and Building Materials 237:117522.

[6] Li PP, Sluijsmans MJ, Brouwers HJ, Yu QL (2020) Functionally graded ultra-high performance cementitious composite with enhanced impact properties. Composites Part B: Engineering 183:107680.

[7] Ahmed ZY, Bos FP, van Brunschot MC, Salet TA (2020) On-demand additive manufacturing of functionally graded concrete. Virtual and Physical Prototyping 15(2):194-210.

[8] Herrmann M, Sobek W (2017) Functionally graded concrete: Numerical design methods and experimental tests of mass-optimized structural components. Structural Concrete 18(1):54-66.

[9] Roesler J, Paulino G, Gaedicke C, Bordelon A, Park K (2007) Fracture behavior of functionally graded concrete materials for rigid pavements. Transportation Research Record 2037(1):40-49.

[10] Bourada M, Kaci A, Houari MS, Tounsi A (2015) A new simple shear and normal deformations theory for functionally graded beams. Steel and Composite Structures 18(2):409-423.

[11] Sağır EG, Tanarslan HM, Jahangiri R, Yalçınkaya Ç (2019) Farklı kalınlıkta UYPB laminelerin eğilme kapasitesine katkısının incelenmesi. Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi 21(63):1015-1026.

[12] Tanarslan HM, Alver N, Jahangiri R, Yalçınkaya Ç, Yazıcı H (2017) Flexural strengthening of RC beams using UHPFRC laminates: Bonding techniques and rebar addition. Construction and Building Materials 155:45-55.

[13] Yalçınkaya Ç, Sznajder J, Beglarigale A, Sancakoğlu O, Yazıcı H (2014) Abrasion resistance of reactive powder concrete: the influence of water-to-cement ratio and steel micro-fibers. Advanced Materials Letters 5(6):345-351.

[14] Li J, Wu Z, Shi C, Yuan Q, Zhang Z (2020) Durability of ultra-high-performance concrete–A review. Construction and Building Materials 255:119296.

[15] Zhang Y, Zhu Y, Qu S, Kumar A, Shao X (2020) Improvement of flexural and tensile strength of layered-casting UHPC with aligned steel fibers. Construction and Building Materials 251:118893.

[16] Alsalman A, Dang CN, Martí-Vargas JR, Hale WM (2020) Mixture-proportioning of economical UHPC mixtures. Journal of Building Engineering 27:100970.

[17] TS EN 1015–3 (2016) Methods of test for mortar for masonry–Part 3: Determination of consistence of fresh mortar (by flow table).

[18] Yalçınkaya Ç, Çopuroğlu O (2021) Elephant skin formation on UHPC surface: Effects of climatic condition and blast furnace slag content. Construction and Building Materials 268: 121126.

[19] TS EN 196-1 (2009) Methods of testing cement–Part 1: Determination of strength.

[20] Yalçınkaya Ç, Felekoğlu B, Yazıcı H (2020) Influence of aggregate volume on the shrinkage, rheological and mechanical properties of ultra-high-performance concrete. Journal of the Faculty of Engineering and Architecture of Gazi University 35(4): 1701-1718.

[21] Brault A, Lees JM (2020) Wet casting of multiple mix horizontally layered concrete elements. Construction and Building Materials 247:118514.

[22] Park R (1989) Evaluation of ductility of structures and structural assemblages from laboratory testing. Bulletin of the New Zealand Society for Earthquake Engineering 22(3): 155-166.

[23] Yoo DY, Yoon YS (2015) Structural performance of ultra-high-performance concrete beams with different steel fibers. Engineering Structures 102:409-423.

[24] Bandelt MJ, Billington SL (2016) Impact of reinforcement ratio and loading type on the deformation capacity of high-performance fiber-reinforced cementitious composites reinforced with mild steel. Journal of Structural Engineering 142(10): 04016084.

[25] Kadhim MM, Jawdhari A, Peiris A (2021) Development of hybrid UHPC-NC beams: A numerical study. Engineering Structures 233:111893.

[26] Hasgül U, Türker K, Birol T, Yavaş A (2018) Flexural behavior of ultra-high-performance fiber reinforced concrete beams with low and high reinforcement ratios. Structural Concrete 19(6):1577-1590.