

A review of research into the interface properties of ultra-high performance concrete and normal concrete

ABSTRACT: Ultra-high performance concrete (UHPC) is an emerging ultra-high performance cementitious fibre reinforcement material that has been widely used in the reinforcement of concrete structures. In this paper, the mechanical properties and durability of the interface between UHPC and ordinary concrete (NC) are compared and analysed in terms of the influencing factors, mechanical properties and durability of the UHPC-NC interface. The results show that the mechanical and durability properties of the UHPC-NC interface are excellent and significantly better than those of the NC-NC interface and that UHPC fibres and interface treatment have a significant impact on the interface bonding performance. The results of the research on the mechanical and durability properties of the UHPC-NC interface are summarised, and the research on the properties of the UHPC-NC interface is presented.

Keywords: ultra-high performance concrete; interface; mechanical properties; durability; reinforcement

1. INTRODUCTION

Normal concrete (NC) is widely used in modern civil engineering structures as a traditional material with excellent performance. However, with the increase in service life, under the increasing load, and long-term physical, chemical and biological effects, concrete structures around the world are commonly damaged or destroyed to varying degrees, resulting in a gradual decrease in the load-bearing capacity of the structure. Even collapse, which seriously affects the safety and durability of concrete structures. The development of efficient, durable and cost-effective repair and strengthening techniques for concrete structures is a challenge for civil engineers given a large amount of maintenance and

strengthening work involved [1]. UHPC is a new type of cementitious composite material with high toughness, excellent structural reliability, high durability and ultra-high strength made from cement, admixtures, aggregates, fibres, admixtures, water etc. Table 1 gives a comparison of the main performance indicators of UHPC with HPC and ordinary concrete. A number of current studies and engineering applications have shown UHPC to be a promising reinforcement repair material for damaged reinforced concrete structures, as shown in Figure 1. "Innovation-driven development" has become the consensus of the whole society. In the field of cementitious materials and their applications, ultra-high performance concrete (UHPC), as an

advanced cementitious material, provides a source of innovation and space for industry-friendly, lightweight and durable engineering structures; the requirements of low-carbon, green, sustainable and high-quality development also promote the

application of UHPC in engineering construction. The application of UHPC in engineering construction is also being driven by the requirements of low-carbon, green, sustainable and high-quality development.

Table. 1 Comparison of the main performance indicators of UHPC with HPC and ordinary concrete

Type of concrete		UHPC	HPC	NC
Mechanical properties	Compressive strength (MPa)	170~230	60~100	20~50
	Bending and tensile strength (MPa)	30~60	6~10	2~5
	Modulus of elasticity (GPa)	40~60	30~40	30~40
	Rupture energy (kJ/m ²)	20~40	0.14	0.12
Durability	Chloride ion diffusion coefficient (10 ⁻¹² m ² /s)	0.02	0.6	1.1
	Carbonation depth (mm)	0	2	10
	Freeze-thaw spalling (g/cm ²)	7	900	>1000
	Water absorption properties (kg/m ²)	0.2	0.4	2.7
	Abrasion factor	1.3	2.8	4.0



Fig. 1 Example of UHPC reinforcement

UHPC is a very advanced cement-based building material. It is characterised by an ultra-compact matrix with very low permeability and excellent tensile and compression resistance. The development of high-performance concrete has its origins in research carried out by Older, Brunauer and Yudenfreud in the early 1970s. They investigated high-strength cement pastes with water-to-cement ratios between 0.2 and 0.3, characterised by low porosity and high compressive strengths of up to 200 MPa. Compared to high-strength concrete,

ultra-high-strength concrete with compressive strengths of up to 250 MPa exhibited remarkable performance in terms of physical and mechanical properties and durability. With these new types of concrete, lightweight buildings can be constructed with or without classical steel reinforcement. Beams with large openings, bridges, thin coverings and high structures are just some of the possible applications of these super-performance concretes. Highly trafficked bridges have been built in France, the Netherlands and Germany, as well as in

Sherbrooke, Canada and Korea. 2006 saw the development of the American Association of State Highway and Transportation Officials (AASHTO) Code of Practice for Load and Resistance Factor Design (LRFD) Bridge Design, which establishes guidelines for the design of UHPC slab systems, specifying material properties and structural performance by analysing the load carrying capacity of elements such as bridge slabs. Interim calculation recommendations have been published in France and Germany. Some of the first notable applications of UHPC in Canada, Europe and Asia demonstrate the advantages of this new technology in terms of cost, sustainability and operational behaviour.

When a UHPC-NC composite member is formed by using the UHPC thin-layer reinforcement method to resist external loads, the ability to ensure that the two materials work together is a key issue in achieving effective reinforcement of NC structures. The bonding reliability of the UHPC-NC interface directly affects the crack resistance and ultimate load capacity of the member [2]. Therefore, the study of the bonding performance of the UHPC-NC interface is becoming a hot topic.

This paper takes the UHPC-NC bonding interface as the research object and compares and analyses the mechanical and durability properties of the interface between ultra-high performance concrete (UHPC) and ordinary concrete (NC) from the research results on the factors influencing the bonding of UHPC-NC interface, mechanical properties and durability performance. The current research status and problems are analysed, and an outlook is given on what is still to be studied at the

UHPC-NC interface.

2 . FACTORS INFLUENCING THE BONDING OF THE UHPC-NC INTERFACE

The study of the factors affecting the adhesion properties of the UHPC-NC interface can help to improve the interface adhesion properties. In the literature, it has been found that among many factors such as the amount of fibre incorporated in UHPC, the interface treatment of the old concrete, the moisture content of the old concrete surface, the strength of the old concrete, the curing method, the placement orientation and the age of the concrete, the interface treatment of the fibre incorporated in UHPC and the old concrete is the most important factor affecting the interfacial bonding performance.

2.1 Fibre impact

Within a certain volume rate of steel fibres, the bond strength increased with the increase in the volume rate of steel fibres. Xie Huicai et al [3] in the mortar to join the chaotic, short-cut PAN-based carbon fibres (and the cement weight ratio of 0.5%), the test results show that the maximum shear strength can be increased by 85.6%, pull-out strength increased by 120%, splitting strength increased by 80%. A study by Cheng Hongqiang [4] showed that the addition of steel fibres improved the bonded shear properties of new and old concrete. Steel fibre volume rate of 2.0%, bond shear strength increased by 22.3%, bonding effect is better; steel fibre volume rate of 1.5%, bond splitting strength increased by 14.1%. And Shen Jie's [5] study of the bonding properties of active powder concrete and ordinary concrete, steel fibre dosing of 2.0%,

the bonding splitting strength can reach 99.12%-122.90% of the ordinary concrete itself splitting strength. It was also shown that the bond splitting strength, flexural strength and frost resistance between the bonding surfaces increased as the number of steel fibres was increased.

When UHPC is used in assembled structural joints or to reinforce existing building structures subjected to fire, an important prerequisite for ensuring fire safety is that the concrete does not burst at high temperatures. Peng Zefei [6] showed that an effective measure to improve the resistance of UHPC to high temperature bursting is the incorporation of polymer fibres such as PP fibres, steel fibres also have a certain effect in inhibiting cracking and spalling, again indicating the need for fibre incorporation. In experiments on the effect of fibre incorporation into the repair material on the mechanical properties of the interface, Cristina Z. et al [7] assessed the bond strength by employing bevel shear tests with different slopes. Shear normal stress interaction diagrams and bond strengths were obtained. Repair mortars with different polyvinyl alcohol (PVA) fibre contents and their effect on wet and dry cycles were investigated. The results show that the addition of PVA fibres to the repair can significantly improve the interfacial bond.

In summary, the use of fibres has a positive effect on the interface bonding performance. The fibres have a positive effect on the interfacial bonding performance. The main principles of fibre reinforcement are as follows [8]: ① the shrinkage of UHPC is reduced after the addition of fibres, which effectively reduces the risk of shrinkage stresses and shrinkage cracks; ② the

disordered fibres increase the roughness of the UHPC interface, and the fibres at the junction penetrate the pores of the plain concrete interface, resulting in a higher mechanical bite force; ③ the bridging effect of fibres and fibres during the stressing of the interface effectively (3) The bridging effect of fibres and fibres during the stressing of the interface can effectively inhibit the development of micro-cracks and change the damage pattern of the adhesive surface.

2.2 Interface treatment

The interface treatment is a very important factor affecting the interfacial bonding performance. Zhang Yang et al [9] evaluated the shear performance and damage modes of the UHPC-NC interface under the treatment of smooth NC surface, chiselling, exposed reinforcement, grooving, drilling and reinforcing by seven sets of tests. It is shown that the UHPC-NC interface has good shear bonding properties and the shear strength of the interface increases with the increase of the roughness of the NC interface, and the UHPC-NC interface with chiselled or grooved NC interface has the best shear bearing capacity. However, it is difficult to manually chisel or grooves the concrete interface in practical engineering, so Chen Debao et al [10] proposed new interface treatment methods such as epoxy resin treatment and high-pressure water gun chiselling to address this problem. By comparing the nominal tensile stress-strain curves of UHPC and the nominal tensile stress-crack width curves of UHPC after different interface treatments, the cracking load and crack distribution of three types of wet joints were analyzed to reveal the stress mechanism of the joints under different interface treatments. The results showed

that the cracking loads of the specimens with epoxy resin treatment, high-pressure water gun chiselled fine aggregate and high-pressure water gun chiselled coarse aggregate were 53.7%, 92.2% and 81.9% of those of the specimens without wet joints, respectively, and the high-pressure water gun interface treatment was superior. The sandblasted NC surface provided the highest quality mechanical bonding when compared with no roughness, wire brush brushing, drilling and grooving.

The bond strength between the NC substrate and the UHPFC is significantly

influenced by the surface treatment of the NC substrate, therefore UHPC-NC requires an appropriate surface treatment to ensure a good bond between the NC substrate and the UHPFC overlay.

Table 2 provides statistics on the UHPC-NC bond performance tests in the literature. The damage mode A is NC damage only; B is interfaced damage only; C is an interface and NC damage; D is UHPC damage only; ✓ indicates that this type of damage mode occurs but no specific values are given in the literature.

Table 2 Results of experimental bonding studies with UHPC-NC

Test method	Percentage of damage patterns/%				Strength/MPa
	A	B	C	D	
Single-sided straight shear test ^[12]	44.4	33.3	22.2		0.8~4.21
Single-sided straight shear test ^[14]	27.8	22.2	0.5		0~3.98
Tilt shear test ^[13]	50.0	50.0			19.77~79.25
Tilt shear test ^[12]	18.2	18.2	63.6		8.55~21.76
Tilt shear test ^[19]	26.67	6.67	66.67		7.38~18.19
Double-sided shear test ^[15]			✓		0.184~3.767
Splitting tensile test ^[19]		6.67	93.33		1.68~4.09

3. UHPC-NC INTERFACIAL BONDING MECHANICAL PROPERTIES

When UHPC was used as the repair reinforcement material, Zhang Xiaochen [12] explored the bonding effect of both cast-in-place and glued methods and assessed the interface bonding performance through straight and diagonal shear tests. It was shown that the addition of shear keys at the interface significantly improved the bond strength of the interface and was superior to treatments such as chiselling and grooving and that the bond strength and stiffness of the diagonal sections with shear keys were substantially increased, which is

recommended for use in repair and strengthening practical projects. The analysis of damage mode, interface bond strength and load-strain characteristics showed that NC was crushed when the interface angle was 0 ° and 15 ° respectively; when the interface angle was 30 ° and 45 ° respectively, the bond interface was damaged by slip and the composite specimen reached the ultimate shear strength; the larger the interface angle, the poorer the bonding performance. The larger the interface angle, the worse the bonding performance and the structure fails to give full play to its deformation performance.

Yang Jun et al [14] designed eight groups of UHPC-NC assemblies containing different depths (t), widths (w) and spacings (d). The tests showed that the keyway treatment significantly enhanced the initial shear stiffness and ultimate shear strength of the UHPC-NC interface. When the depth t is small and $w/t \leq 2$, the keyway part of the post-cast UHPC is subjected to a larger shear load, and the "mixed shear" damage mode appears at the UHPC-NC interface, which can effectively bring into play the bending and tensile properties of UHPC; under the same conditions, when $w/t \geq 4$, the keyway area of the post-cast UHPC Under the same conditions, when $w/t \geq 4$, the area of the post-cast UHPC keyway increases at the interface, and the NC mainly bears the interface shear force. Increasing the keyway spacing d can improve the shear distribution at the interface, and the "dense slotting" method can effectively improve the shear resistance of the interface. Wang De-hong et al [15] studied the bonding performance between post-cast normal concrete (NC) and precast ultra-high performance concrete (UHPC), using UHPC slotting density and post-cast NC strength grade as parameters. The shear strength of the post-cast NC was sheared off as the damage mode of the specimens. The shear strength of the UHPC-NC bond was increased by 19.63% to 48.15% compared to that of the old and new concrete for the same slotted condition. The shear strengths of precast UHPC with slotted densities of 1.33, 2.67 and 4 were 1.398, 1.226 and 1.044 MPa, respectively; both slotted density and post-cast NC strength had significant effects on the shear strength of the UHPC-NC bond. The effect of slotting density on the shear strength of the UHPC-NC bond was much greater than that of the post-cast NC strength.

To investigate the factors influencing the NC-UHPC interface, Anning et al [16] investigated the effects of interface roughness, interface agent and UHPC steel fibre content on the mechanical properties and freeze-thaw resistance of the NC-UHPC interface. It was shown that: As the roughness of the bond surface increased, the damage mode gradually changed from bond surface damage to ordinary concrete cracking. Moreover, the steel fibre content in the concrete has a certain influence on the bond strength of the interface when using the interface agent, and the splitting strength of the bonded specimens increases with the increase of the steel fibre content.

Xu et al [17] conducted an experimental study on three UHPC-NC beams with different thickness ratios and observed that the final damage of the beams occurred at the interface, indicating that the properties at the UHPC-NC interface had a significant influence on the overall force behaviour of the laminated members; and established a reliable two-dimensional finite element model for UHPC-NC laminated beams, used a local damage gradient model to simulate the damage of UHPC and NC materials The coupled glue and friction model was developed to simulate the damage behaviour of the UHPC-NC interface, and the results obtained from the finite element model are close to the loading test results of the laminated beam. For the finite element analysis of the UHPC-NC interface, Ouyang Na et al [18] established 3D finite element models based on the contact separation model for the tension-dominated member and the compression-shear-dominated member respectively, and proposed cohesion parameters and contact damage-related parameters for the smooth

interface, the medium-rough interface and the rough interface; to verify the validity of the finite element parameters, some literature test finite element models were established and matched with the results. To verify the validity of the finite element parameters, several experimental finite element models were established and compared with the results, which can provide a reference for later finite element calculations.

B.A. TAYEH et al [19] prepared UHPC prismatic bonded specimens with a strength of 170 MPa for oblique shear tests and used SEM/EDS scanning electron microscopy to microscopically examine the bonded transition zone. test damage occurred in the NC structure, and the cast-in-place UHPC-NC bond strength was high sufficient and reliable, and its interfacial strength was even higher than the NC strength. Mohammed K et al [20] carried out an experimental study by examining different surface roughness, maintenance conditions, exposure conditions and testing methods for NC substrates. It was concluded that the maintenance conditions had little effect on the bonding performance, but the NC surface roughness had a significant effect on the bond strength. The highest bond strengths were achieved on NC surfaces treated with sandblasting, except for the double surface shear test, where the highest bond strengths were achieved on drilled surfaces, due to the interlocking effect of the UHPC drilled in the filled NC. All bond strength results also comply with the specification limits for repair/reinforcement applications as defined by the different design codes.

4. UHPC-NC INTERFACE BONDING DURABILITY

4.1 Frost resistance

From the concrete freeze-thaw damage mechanism, it is known that under the action of freeze-thaw cycles, the bond surface freeze-thaw damage mechanism is divided into two aspects [21]: (i) micro-cracks will be generated between the cement stone and aggregate-cement stone bond surface in the old and new concrete, resulting in a decrease in the adhesive force and mechanical bite force on the bond surface, while the structure of the interface agent will become loose and porous from the dense state, and accompanied by micro-cracks ② During the hardening process, the volume shrinkage of the new concrete is restricted by the old concrete, resulting in corresponding shrinkage stress. During the thawing process, water enters these cracked gaps again, and when frozen again, the further expansion of the ice volume leads to new and greater tensile stresses on the cracked surface, resulting in further damage to the bond surface, and so on, eventually leading to macroscopic cracks and causing instability expansion, resulting in freeze-thaw damage.

In the study of the interfacial bond performance of UHPC-NC by Zhang Xiaochen [12], the interfacial bond-slip performance of typical repair parameters under different numbers of freeze-thaw cycles was analyzed, and the regression equations for interfacial bond-slip of different specimens after freeze-thaw cycles were given respectively; the interfacial bond-slip degradation law of each group of specimens was evaluated in terms of interfacial

bond-slip stiffness and rising section slip, and the regression equations for interfacial. The regression equation of the residual bond stiffness coefficient can be obtained after different number of freeze-thaw cycles; the post-freeze-thaw splitting tests on the bonded specimens of active powder concrete and ordinary concrete show that [5] the number of freeze-thaw cycles reflects to a certain extent the degree of freezing damage to the concrete mix, and the number of freeze-thaw cycles is one of the main factors affecting the splitting tensile strength of the bond between the active powder mix and ordinary concrete. One of. When other conditions remain unchanged, the splitting tensile strength of sex powder concrete bonded to ordinary concrete decreases with the increase in the number of freeze-thaw cycles.

Lee et al [22] investigated the interfacial bonding performance of reactive powder concrete (RPC) to existing concrete materials under rapid freeze-thaw cycling conditions. In the study, accelerated ageing conditions were simulated using a rapid freeze-thaw cycle environment, and the bond strength was determined by a 45° diagonal section shear test to evaluate the bond durability of RPC as a repair material. The existing concrete surface was sandblasted and the different repair materials were poured separately and cured for 28 days before starting the freeze-thaw cycle test. The results show that RPC has high bond strength and bond durability and good resistance to freeze-thaw compared to other concretes.

For the cold environment, Xie Jian et al [23] carried out freeze-thaw cycling tests at -60 °C on UHPC-NC bonded specimens to analyse the macroscopic morphological

changes and mass change rates of the specimens after freeze-thaw cycling. The effects of freeze-thaw cycling at -60 °C on the interfacial bonding properties of UHPC-NC specimens were analysed, as well as the effects of different treatments of interfacial wire brush brushing, high-pressure water jet brushing and splitting on the resistance to freeze-thaw cycling. The results show that the interfacial bond strength of UHPC-NC specimens is influenced by the freeze-thaw cycles, and the interfacial bond strength shows a trend of rapid decrease and then slowly decreases, and the interfacial bond strength of the split specimens decreases to 72.94%, 55.62% and 44.33% of the interfacial bond strength after 10, 15 and 20 freeze-thaw cycles respectively. After 20 freeze-thaw cycles, the residual bond strength of the split specimens was 2.03 times higher than that of the high-pressure water-jet blasted specimens.

4.2 Impermeability

The impermeability of the bonded surface of old and new concrete refers to the ability of the bonded interface to resist the invasion of external substances, such as water, gases, aggressive ions etc. The bonded interface of old and new concrete is not in close contact and is more porous than monolithic concrete. The medium enters the concrete from the pores of the bonding surface, causing dissolution corrosion of the concrete near the bonding surface, resulting in a thin and loose structure and reduced force performance. Our SL 352-2018 "Test Procedure for Hydraulic Concrete" recommends the use of a permeability meter to increase the water pressure and observe the water penetration of the specimen to study the permeability performance, as shown in Figure 2. Li Pingxian et al [24]

showed that the permeability of the new and old concrete bonded surfaces was generally greater than that of the new and old concrete bodies, with a difference of 1 order of magnitude in the permeability coefficient and 3-4 orders of magnitude individually.

Therefore, the old and new concrete bonding surface under water pressure, if not handled properly, will form a weak surface and become a permeable layer with much greater permeability than the concrete body.

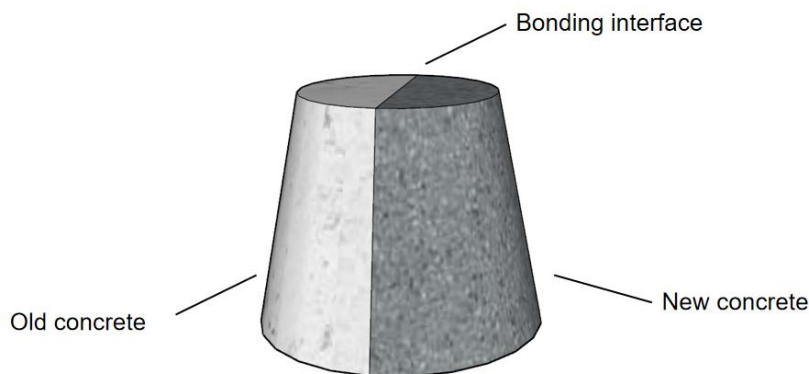


Fig. 2 Diagram of the relative permeability test specimen

B.A. TAYEH et al [19] conducted a study on the chloride ion permeability of UHPC-NC bonded specimens and the total charge values measured fell within the category of "negligible chloride ion permeability" as classified in ASTM C1202. The gas permeability and water permeability of UHPC-NC binder specimens have also been investigated and the test results show that the permeability of the binder surface is low. Therefore, UHPFC can form good interfacial bonds with NC substrates and improve the resistance of NC substrates to the penetration of chlorides and other aggressive fluids.

It is difficult to make a good or bad comparison of the permeation performance as scholars around the world use different mix designs and their testing conditions and environments are inconsistent, leading to a wide variation in test results. However, from the literature it can be concluded that factors such as age, water-cement ratio and maintenance conditions all affect the

chloride ion permeation performance of UHPC, where the greater the water-cement ratio, the greater the chloride ion diffusion coefficient of UHPC and the longer the age, the better its resistance to chloride ion permeation. The chloride ion migration coefficient of UHPC under different tests is around 10-13m²/s order of magnitude, and its resistance to chloride ion migration permeation is high and at least one order of magnitude lower compared to ordinary concrete.

5. CONCLUSIONS AND OUTLOOK

(1) UHPC-NC is a promising material in the field of concrete repair and reinforcement because of its good adhesive properties. In UHPC, many factors such as the number of fibres, the interface treatment, the maintenance method, the orientation, the strength and the age of the concrete affect the adhesion of UHPC-NC, among which the fibres and the interface treatment are the most important factors affecting the

adhesion of the interface. The effect of the type of fibre, the amount of fibre and the degree of wetness and dryness of the interface on the adhesion of UHPC-NC needs further study.

(2) There are pure shear, oblique shear, double shear, splitting and pulling tests for the mechanical properties of UHPC-NC bonding, but there is no unified standard for the test methods and evaluation criteria of UHPC-NC bonding, and the total number of tests and specimens is small.

(3) The existing tests on the mechanical properties of UHPC-NC bonding are all under static loads, but concrete structures are not only subjected to static loads such as their gravity during their service life, but also dynamic loads such as waves, earthquakes, explosions and impacts, so it is also necessary to study the bonding properties of the UHPC-NC interface under dynamic loads.

(4) the durability of the UHPC-NC interface is excellent in terms of frost resistance and impermeability, but the existing experimental studies have all been carried out at room temperature, and there are no studies on the performance of the UHPC-NC interface after high temperature, so this gap needs to be filled.

(5) Few numerical simulations of the UHPC-NC interface have been carried out using the finite element method, and the exploration of a method suitable for simulating the UHPC-NC interface is still to be carried out.

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