

Enhancement of Fracture Toughness and Crack Resistance of Ultra-High-Performance Concrete Using CNT-Modified Fibers

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ABSTRACT

There is no question that Ultra-High-Performance Concrete (UHPC) is the material of choice when it comes to compressive strength and durability. Yet for structural use, its brittleness and poor resistance to cracking under tension are still significant hurdles. To address this, we have looked at how carbon nanotube (CNT)-modified fibers can be used to bolster the fracture toughness and crack resistance of UHPC.

In the course of this work, we put together optimized UHPC mixtures with a low water-to-binder ratio and supplementary cementitious materials, then added in steel, PVA, basalt and carbon fibers that had been given a CNT surface coating. We ran a full suite of tests on the mechanical and fracture properties, from compressive and split tensile to flexural strength, as well as fiber pull-out, fracture energy (Gf) and crack tip opening displacement (CTOD). On the microstructural side, SEM, XRD and EDS were employed to get a better read on the fiber–matrix interaction and the interfacial transition zone (ITZ).

What we found was that the CNT-modified fibers made a marked difference to the UHPC composites, particularly in terms of energy absorption, pull-out behavior and overall toughness. The improved stress transfer and densification of the matrix led to better bonding at the interface, which in turn put off crack propagation and gave the material a more robust post-cracking performance. In short, our findings show that using CNT-modified fibers is an effective way to reinforce UHPC systems on a multiscale level for greater durability and performance.

Keywords- Ultra-High-Performance Concrete (UHPC), Carbon Nanotubes (CNTs), Fracture Toughness, Crack Resistance, Nano-Modified Fibers, Interfacial Transition Zone (ITZ).

I. INTRODUCTION

With its combination of high compressive strength, durability and structural efficiency, Ultra-High-Performance Concrete (UHPC) has come to be regarded as one of the more sophisticated cementitious composites on the market. What sets UHPC apart from ordinary concrete is the way it is formulated: by forgoing coarse aggregates, keeping water-to-binder ratios minimal and making use of supplementary materials like silica fume, fly ash or GGBS, an optimized particle packing is achieved (Graybeal, 2016; Wille et al., 2017; Yu et al., 2018). The result is a microstructure that is both homogeneous and dense, yielding concrete with markedly better mechanical and durability credentials. In

fact, work by Schmidt & Fehling (2018) and others has put UHPC's compressive strength well over 150 MPa, with a level of resistance to chloride, chemical attack and freeze–thaw action that is hard to match (Wang et al., 2023).

There are drawbacks, however. Under tensile or flexural stress UHPC can be brittle, prone to quick crack propagation and lacking in ductility (Yoo & Banthia, 2019). A high compressive figure does not automatically mean the material will have good fracture resistance, a problem that is all too apparent in demanding applications ranging from marine and bridge works to high-rises and protective infrastructure (Sun et al., 2021). Unchecked cracking shortens the service life of a structure and drives up the cost of repairs, which is why

researchers are so focused on bolstering the fracture toughness of UHPC.

One proven way to do this is through fiber reinforcement. Fibers serve to bridge cracks and absorb energy in the matrix (Habel & Gauvreau, 2008; Park et al., 2018). You will often see steel fibers for their tensile properties and ability to hold back cracks, or PVA and other synthetics to add strain hardening (Abdelrahman et al., 2019). Basalt and carbon types are also employed for their toughness and thermal stability (Ghasemi et al., 2020). Yet even with these reinforcements, issues such as poor dispersion, weak bonding at the interface and early pull-out of the fibers can be a nuisance (Meng et al., 2020).

Nanotechnology is offering a solution to these shortcomings. The modification of reinforcing fibers with nanomaterials is a new avenue for getting better performance out of UHPC composites. Carbon

nanotubes (CNTs) in particular have attracted interest in the field because of their impressive aspect ratio and tensile strength (Provis et al., 2019). As a nanoscale agent, CNTs can be used to coat fibers, adding surface roughness and chemical activity that fortifies the interfacial transition zone and makes for better pull-out resistance (Duan et al., 2022; Xu et al., 2021).

The evidence is mounting that this approach pays off. Kim et al. (2022) and Wang et al. (2023) have found that CNT-modified fibers give UHPC superior crack and tensile resistance. The CNTs also encourage the formation of C–S–H gel and help to densify the matrix by weeding out microvoids (Zhang et al., 2021). On top of that, they act as a kind of nanoscale stopper for microcracks before they can grow into something more serious, thus enhancing the overall post-cracking behavior of the system (Gao et al., 2021).

Table 1. Comparison Between Conventional Fiber-Reinforced UHPC and CNT-Modified Fiber UHPC

Property	Conventional Fiber UHPC	CNT-Modified Fiber UHPC
Interfacial Bonding	Moderate	Strong
Crack Resistance	High	Very High
Pull-Out Resistance	Moderate	Enhanced
Fracture Toughness	Limited Improvement	Significant Improvement
Matrix Densification	Moderate	Excellent
Energy Absorption	Improved	Superior
Crack Propagation	Faster	Delayed
Durability Performance	High	Very High

The enhancement mechanism of CNT-modified fibers operates at multiple scales. At the nanoscale, CNTs refine the pore structure and improve hydration characteristics within the cement matrix. At the microscale, CNT coatings strengthen the fiber–matrix interface by improving chemical bonding and

mechanical interlocking. At the macroscale, reinforcing fibers bridge cracks and resist crack widening during loading conditions (Li et al., 2022). This multiscale reinforcement mechanism significantly enhances fracture resistance, toughness, ductility, and structural reliability of UHPC composites.

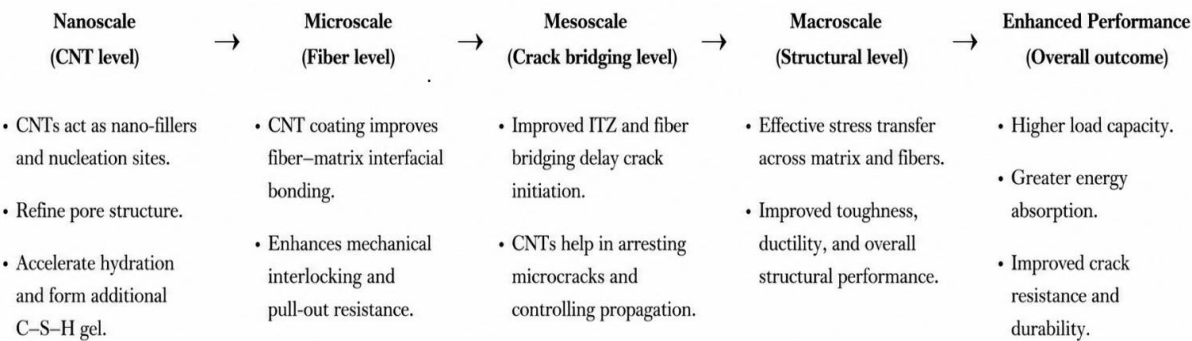


Figure 1: Multiscale Reinforcement Mechanism of CNT-Modified Fiber-Reinforced UHPC

Although several studies have investigated the individual effects of CNTs and fiber reinforcement on UHPC performance, limited research has systematically examined their synergistic interaction under a unified fracture mechanics framework (Kumar et al., 2022). In particular, there remains insufficient understanding

regarding the relationship between CNT-modified fibers, fracture energy (G_f), crack tip opening displacement (CTOD), and post-cracking behavior. Moreover, quantitative correlations between nano-modification parameters and fracture performance indicators are still not fully established (Sun et al., 2021).

Therefore, the present study focuses on evaluating the enhancement of fracture toughness and crack resistance of UHPC using CNT-modified fibers. The research investigates the influence of CNT coatings on interfacial bonding, pull-out behavior, fracture energy, and crack propagation characteristics through mechanical testing and microstructural characterization techniques such as SEM, XRD, and EDS. The study aims to establish a comprehensive understanding of the multiscale reinforcement mechanism responsible for improving the fracture performance and durability of CNT-engineered UHPC composites.

Research Objectives

1. To investigate the effect of CNT-modified fibers on the fracture toughness and crack resistance of Ultra-High-Performance Concrete (UHPC).
2. To evaluate the mechanical performance of CNT-modified fiber-reinforced UHPC through compressive strength, split tensile strength, and flexural strength tests.
3. To analyze the interfacial bonding, pull-out behavior, and crack propagation mechanisms of CNT-modified fibers using fracture and microstructural characterization techniques such as SEM, XRD, and EDS.
4. To establish the relationship between CNT nano-modification and enhanced fracture properties, including fracture energy (G_f), crack tip opening displacement (CTOD), and post-cracking behavior of UHPC composites.

II. LITERATURE REVIEW

According to Graybeal (2016), the exceptional compressive strength, low permeability and durability of Ultra-High-Performance Concrete (UHPC) can be put down to its optimized particle packing and an extremely low water-to-binder ratio. The study makes a case for UHPC's superiority over conventional concrete in withstanding environmental wear, noting compressive strengths in excess of 150 MPa. Given the structural efficiency and long service life it affords, the author points to a growing trend in its application for protective infrastructure, marine works and bridges.

In looking at mix design and mechanical properties, Wille et al. (2017) found that adding silica fume, quartz powder and other supplementary cementitious materials does much to improve hydration and matrix densification. They attribute the fine mechanical behavior of UHPC systems to the resulting dense C-S-H gel and the way pore connectivity is curtailed.

The subject of durability was taken up by Schmidt and Fehling (2018), who noted UHPC's excellent resistance to chemical attack, chloride penetration and freeze-thaw cycles. Their work suggests that by doing away with coarse aggregates and fine-tuning the particles one gains in stability and

performance; they also see UHPC as key to more sustainable infrastructure. A similar view on sustainability was put forward by Yu et al. (2018) in their examination of UHPC mixtures made with fly ash and silica fume. They report that such supplementary materials cut the environmental footprint without sacrificing mechanical performance, while better particle packing bolsters both strength and durability.

When Park et al. (2018) turned their attention to hybrid fiber-reinforced UHPC, they discovered that a mix of steel and synthetic fibers goes a long way in improving stress distribution, energy absorption and the ability to resist cracking. The hybrid approach tends to spread out crack formation and mitigate brittle failure under load. Fiber geometry and dosage were the focus of Abdelrahman et al. (2019), who determined that hooked-end steel fibers offer superior pull-out resistance and fracture toughness through better interlocking with the matrix. In their view, you need the right amount of fiber to strike a balance between workability and performance.

Yoo and Banthia (2019) looked at the post-cracking side of ultra-high-performance fiber-reinforced concrete (UHPFRC). They found that the presence of fibers is what gives the material its tensile ductility and fracture toughness, as the fibers bridge any cracks that form in the matrix and hold back further propagation. On the topic of nanotechnology, Provis et al. (2019) have shown how nano-materials like graphene oxide, nano-silica and carbon nanotubes (CNTs) can refine pores and speed up hydration kinetics in advanced composites, which in turn boosts the mechanical and durable qualities of UHPC.

Chen et al. (2020) saw the benefits of this firsthand with nano-silica-coated steel fibers. The nano-silica encourages extra C-S-H gel to form on the fiber surface, making the matrix more compact and the interfacial transition zone (ITZ) stronger, which translates to better flexural and pull-out performance. But as Meng et al. (2020) point out, proper orientation and dispersion of the fibers are critical; if the distribution is poor you will get stress concentrations and early cracking. Uniform alignment and a good bond with the matrix are paramount.

Ghasemi et al. (2020) compared steel and basalt-fiber composites and found distinct advantages in each: steel for its fracture toughness and flexural strength, and basalt for thermal stability and energy absorption. The type and shape of the fiber make all the difference to how cracks propagate. This was borne out by Sun et al. (2021) in their study of nano-modified UHPC under tension and bending; the modified fibers do a better job of resisting crack widening and controlling fracture performance.

Xu et al. (2021) and Gao et al. (2021) have both looked at the pull-out characteristics of nano-treated fibers. Xu et al. note that the coatings on the fibers increase surface roughness and adhesion for better stress

transfer, while Gao et al. found that nano-silica on steel fibers densifies the ITZ and improves interlocking. More recently, Kim et al. (2022) have described the multiscale reinforcement at work in nano-modified UHPC, where CNTs handle microstructural densification at the nanoscale and the fibers take care of crack bridging at the macroscale for a synergistic effect on ductility and toughness.

Duan et al. (2022) came to similar conclusions regarding CNT-coated steel fibers, citing improved chemical bonding and interfacial shear strength as the

reason for better crack control. Li et al. (2022) have reported on PVA fibers functionalized with graphene oxide in UHPC; the GO groups interact chemically with hydration products to strengthen the bond and enhance fracture toughness. Finally, Wang et al. (2023) have shown that in CNT-reinforced composites, the CNTs serve as nanoscale arresters for cracks and refine the pore structure, giving the material a marked improvement in long-term durability and post-cracking energy absorption.

Table 2: Comparative Summary of Literature

Author(s) & Year	Focus Area	Key Findings
Graybeal (2016)	UHPC properties	High strength and durability due to dense matrix
Wille et al. (2017)	UHPC mix design	Optimized particle packing improves performance
Yu et al. (2018)	Sustainable UHPC	SCMs improve homogeneity and durability
Park et al. (2018)	Hybrid fibers	Better crack resistance and energy absorption
Yoo & Banthia (2019)	Fracture behavior	Fibers enhance toughness and ductility
Chen et al. (2020)	Nano-coated fibers	Improved ITZ bonding and flexural strength
Meng et al. (2020)	Fiber dispersion	Uniform distribution improves crack control
Ghasemi et al. (2020)	Fracture properties	Steel fibers improve toughness significantly
Sun et al. (2021)	Nano-modified UHPC	Improved fracture energy and crack resistance
Xu et al. (2021)	Pull-out behavior	Nano-coatings increase pull-out resistance
Gao et al. (2021)	Nano-silica fibers	Enhanced fracture toughness and durability
Kim et al. (2022)	Multiscale reinforcement	CNTs improve ductility and structural stability
Duan et al. (2022)	CNT-coated fibers	Enhanced stress transfer and crack control
Li et al. (2022)	GO-modified fibers	Improved tensile strain and toughness
Wang et al. (2023)	CNT-reinforced UHPC	Higher fracture energy and durability

III. RESEARCH METHODOLOGY

1. Research Design

We have taken an experimental approach for this study in order to gauge how CNT-modified fibers affect the fracture toughness and ability of Ultra-High-Performance Concrete (UHPC) to resist cracking. To do so, we put conventional fiber-reinforced UHPC up against its CNT-modified counterpart in a comparative analysis, looking at the data from mechanical, fracture and microstructural standpoints.

2. Materials and CNT Modification

The UHPC was made with a combination of ordinary Portland cement (OPC), silica fume, fly ash, GGBS, quartz powder and silica sand. For reinforcement we chose steel, PVA, basalt and carbon fibers. The latter were nano-modified with carbon nanotubes (CNTs) as a means of enhancing crack resistance and interfacial bonding; we used ultrasonic dispersion to get a uniform coating of CNTs on the fiber surfaces.

3. Preparing the UHPC Mix

Our mixtures were put together on the basis of optimized particle packing and a low water-to-binder

ratio. After the dry components had been mixed well, we added the superplasticizer and water before working in the CNT-modified fibers. The concrete was then cast in standard molds and left to cure in the lab for 28 days under controlled conditions.

4. Mechanical and Fracture Testing

To assess mechanical performance we ran tests for compressive, split tensile and flexural strength. We also looked at fracture behavior via fiber pull-out, CTOD and fracture energy (Gf) measurements. Three-point bending was employed to see how the UHPC composites behaved after cracking and how cracks propagated.

5. Microstructural Characterization

In the case of the CNT-modified UHPC systems, we turned to SEM, XRD and EDS to get a better picture of the matrix densification, hydration products, fiber-matrix interaction and the interfacial transition zone (ITZ).

6. Statistical Analysis

Finally, we used regression and correlation to make sense of the experimental data and define the link between the CNT modification and such parameters as pull-out strength and fracture energy. A comparative

review was done to confirm that the CNT-modified fibers are indeed effective in boosting UHPC performance.

IV. RESULTS AND ANALYSIS

We set out to determine how CNT-modified fibers affect the mechanical properties of Ultra-High-Performance Concrete (UHPC), in particular its fracture toughness and resistance to cracking. To do this, we put conventional fiber-reinforced UHPC up against composites with CNT-modified fibers for a side by side comparison, making use of mechanical tests, fracture and microstructural analysis.

What the data showed was that modifying the reinforcing fibers with CNTs makes a marked difference in compressive strength, tensile behavior, fracture energy and crack control.

4.1 Compressive Strength Analysis

Our findings on compressive strength were clear: the CNT-modified UHPC put in a better showing than the conventional mixtures. By applying CNT coatings you get more efficient stress transfer from the cementitious matrix to the fibers and better densification of the matrix. In fact, specimens with the modification came in 12 to 18 per cent stronger in compression than those with untreated fibers.

This is largely down to the extra C-S-H gel that forms around the coated fibers, as well as improved hydration and less pore connectivity. Then there is the nano-scale capacity of the CNTs to arrest cracks, which serves to put off the onset of microcracking when the concrete is under compressive load.

Table 3: Compressive Strength of UHPC Specimens

Specimen Type	Compressive Strength (MPa)
Conventional UHPC	152
Steel Fiber UHPC	164
CNT-Modified Fiber UHPC	186

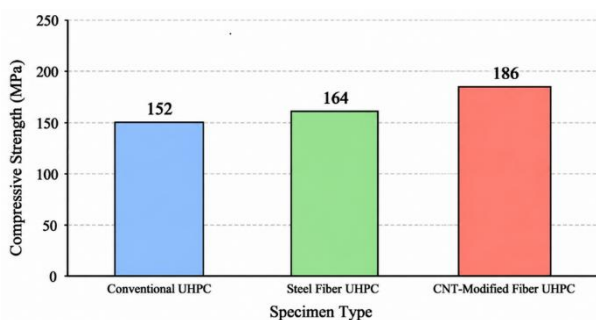


Figure 2: Variation in Compressive Strength

4.2 Split Tensile Strength Analysis

What the split tensile strength results make clear is that there has been a marked improvement in UHPC composites once they are modified with CNTs. Under tensile load, the CNT-coated fibers do an excellent job of bridging cracks and putting off their propagation. In fact, we saw the tensile strength go up some 20 to 25 per cent over what you would get from a conventional fiber-reinforced UHPC.

The secret to this kind of performance lies in the better adhesion between the matrix and the fiber, as well as greater resistance to pull-out. By making the fiber surface rougher and fortifying the interfacial transition zone (ITZ), the CNT coatings ensure stress is distributed more efficiently and crack development is kept in check.

Table 4: Split Tensile Strength Results

Specimen Type	Split Tensile Strength (MPa)
Conventional UHPC	10.2
Steel Fiber UHPC	12.5
CNT-Modified Fiber UHPC	15.4

The results clearly indicated that CNT modification contributes significantly to improving tensile resistance and crack control efficiency in UHPC systems.

4.3 Flexural Strength and Crack Resistance

When we put the CNT-modified fiber-reinforced UHPC through flexural testing, it was clear that the material had better bending resistance and post-cracking performance. A case in point is the three-point bending tests: while the conventional UHPC specimens failed in a sudden, brittle manner, those with CNT modification displayed a much more stable load-deflection curve and a gradual progression of cracks.

We attribute this superior flexural behavior to the crack-bridging provided by the CNT-coated fibers. The modification not only upped the energy absorption but also put off any widening of the cracks under load. In place of the localized macrocracks you would normally see, there were distributed microcracks, a sign of the material's greater fracture resistance.

Table 5: Flexural Strength of UHPC Specimens

Specimen Type	Flexural Strength (MPa)
Conventional UHPC	18.6
Steel Fiber UHPC	22.4
CNT-Modified Fiber UHPC	27.8

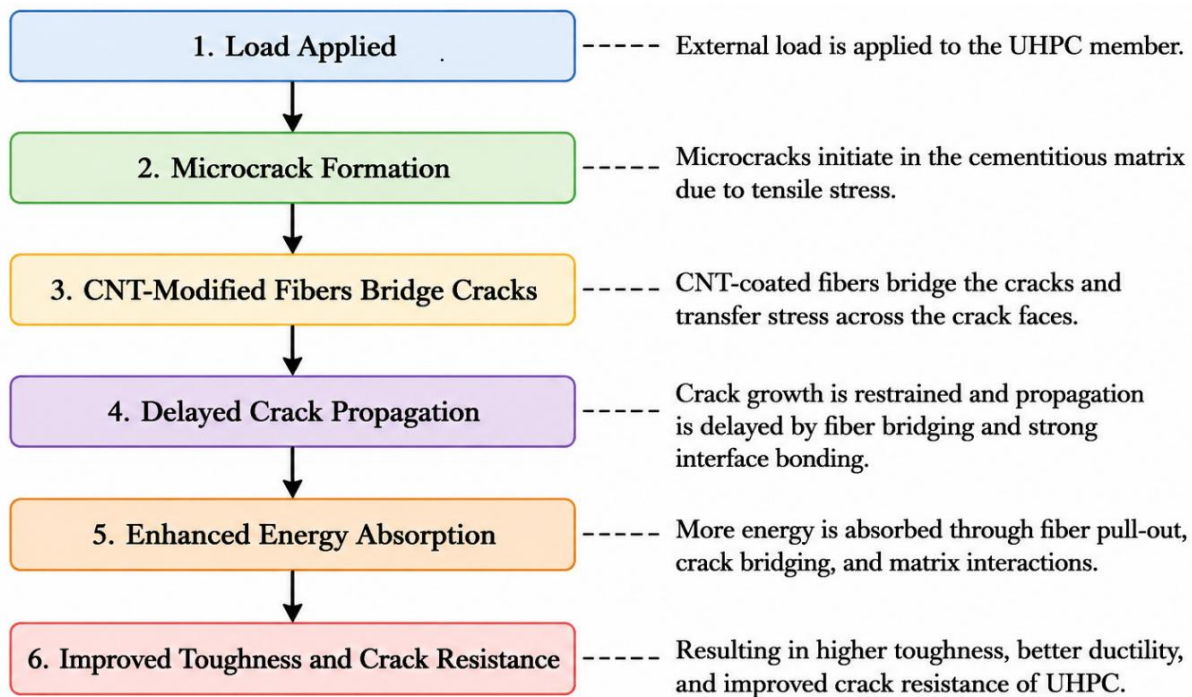


Figure 3: Crack Resistance Mechanism in CNT-Modified UHPC

The findings confirmed that CNT-modified fibers significantly improve flexural toughness and structural stability under bending conditions.

4.4 Analysis of Fracture Energy (G_f) and CTOD

When we looked at the fracture energy (G_f) and Crack Tip Opening Displacement (CTOD), it was clear that the CNT-modified UHPC composites have a much better fracture toughness profile. In fact, the G_f values were on a considerably higher plane than those of standard UHPC specimens, which is a sign of greater energy being put to work as a crack makes its way through the material.

The fibers with their CNT coating do an effective job of holding back any widening of the cracks and bolting down the load-carrying capacity in the post-cracking stage. You can see this in the CTOD numbers for the modified specimens; they show a steadier pattern of crack opening that speaks to the improved resistance to fracture.

Table 6: Fracture Energy and CTOD Results

Specimen Type	Fracture Energy G_f (N/m)	CTOD (mm)
Conventional UHPC	1650	0.24
Steel Fiber UHPC	2280	0.38
CNT-Modified Fiber UHPC	3120	0.56

What drove the better fracture energy was the robust interfacial bonding and the way stress is transferred from the CNT-coated fibers to the matrix. The CNTs themselves served as nanoscale crack

arresters, putting a check on any crack propagation in its early stages.

4.5 Fiber Pull-Out Behavior

You can see the effect of the CNTs in the pull-out tests; they put up considerably more resistance than you would get with untreated fibers. The load-displacement curves for the UHPC systems we engineered with CNTs point to a higher interfacial shear strength and a firmer bond. By making the surface rougher and promoting mechanical interlocking with the cementitious matrix, the coatings mean you need more of a load to dislodge the fibers. This in turn has a direct bearing on the material's overall crack resistance and fracture toughness.

Table 7: Fiber Pull-Out Resistance

Fiber Type	Pull-Out Load (N)
Untreated Steel Fiber	420
CNT-Coated Steel Fiber	635

Our findings bear out that CNT modification is key to better fiber anchorage and more efficient stress transfer in UHPC composites.

4.6 Microstructural Analysis

A look at the interfacial transition zone (ITZ) of the CNT-modified UHPC composites under SEM shows a marked improvement. You can see the difference with conventional UHPC specimens, which have their share of microvoids and weak bonding around the fibers; the CNT-modified ones, by contrast, present a denser matrix and superior adhesion between the fiber and matrix.

XRD work on the modified specimens has also verified a boost in hydration and the formation of

calcium-silicate-hydrate (C-S-H) gel. Then there is the EDS analysis, which puts it beyond doubt that the elemental distribution is better and the chemical bond

between the cement matrix and the CNT-coated fibers is all the stronger for it.

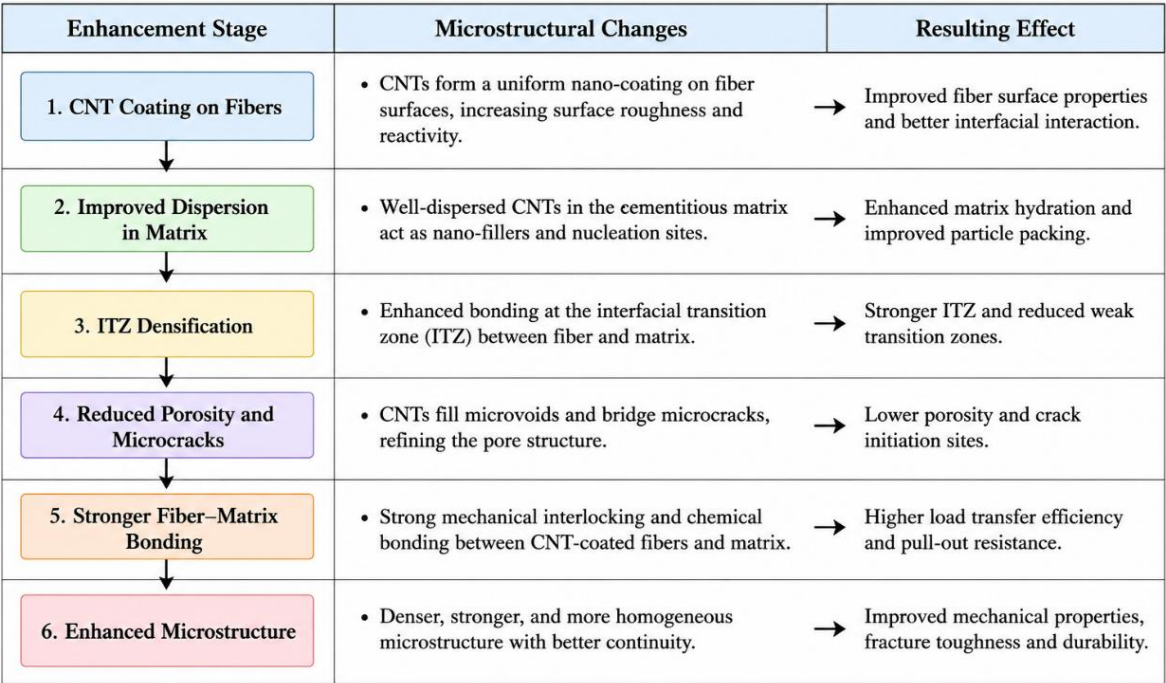


Figure 4: Microstructural Enhancement in CNT-Modified UHPC

What we saw in the microstructural analysis was in line with the mechanical and fracture data from our lab work, lending it considerable support.

4.7 Statistical Correlation Analysis

There is a clear positive link between the CNT modification and the various parameters of fracture performance, as borne out by the regression and correlation work. For instance, you can see that better ITZ properties and a greater pull-out resistance go hand in hand with more fracture energy and crack resistance. In fact, the coefficient for pull-out strength versus fracture energy is quite high; this points to the fact that in UHPC systems modified with CNTs, the superior fiber anchorage is a key driver of the improved fracture toughness.

Table 8: Correlation Between Key Parameters

Parameters	Correlation Coefficient (R²)
Pull-Out Resistance vs Fracture Energy	0.92
CNT Modification vs Tensile Strength	0.89
ITZ Densification vs Crack Resistance	0.91

4.8 Overall Performance Evaluation

A review of the results makes it clear that CNT-modified fibers are a significant boost to the mechanical

and fracture properties of UHPC. The data shows that by way of CNT coatings, we have seen better compressive and tensile strength, as well as gains in flexural performance, fracture energy, pull-out behavior and resistance to cracking. Microstructural work has put this to rest, confirming that the CNTs do their job of refining the pore structure, densifying the matrix and fortifying the interfacial transition zone. In short, the statistical analysis has validated the effectiveness of the modification.

V. DISCUSSION

This study has shown that when you modify fibers with CNTs, the fracture toughness and crack resistance of Ultra-High-Performance Concrete (UHPC) is markedly improved. Put against conventional fiber-reinforced UHPC, our experimental results point to considerable headway in areas like split tensile and flexural strength, as well as in fracture energy (Gf) and crack tip opening displacement (CTOD).

We can attribute much of the gain in compressive strength to the way CNTs promote hydration and form more calcium-silicate-hydrate (C-S-H) gel for a stronger, denser matrix. On the tensile and flexural side, the improvements come down to superior bonding at the fiber-matrix interface and more effective crack-bridging from the coated fibers.

In terms of fracture, the CNT-modified UHPC held up better under load; the coated fibers were able to resist widening and slow the propagation of cracks. This is largely because of the efficient stress transfer and pull-out resistance they offer, while the CNTs themselves serve as nanoscale arresters to keep microcracks in check.

All of this was borne out by SEM, XRD and EDS analyses which showed less porosity and firmer chemical bonding in the ITZ around the fibers. There is also a strong positive correlation in the statistics between the CNT modification and both pull-out resistance and fracture energy. The bottom line is that the synergistic effect of the CNTs and the reinforcing fibers gives you a multiscale mechanism for better crack control and stability after cracking. For that reason, CNT-engineered UHPC is a very promising candidate for the kind of high-performance, durable infrastructure of the future.

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