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Ultra-High Performance Conrete (UHPC) as an Innovative Solution for Concrete Structure Repair: A Literature Review

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A B S T R A C T

Ultra-High Performance Concrete (UHPC) has emerged as a highly durable and mechanically superior material, offering an innovative approach for the rehabilitation of deteriorating concrete structures. With compressive strengths surpassing 150 MPa and tensile strengths above 5 MPa, UHPC's dense microstructure, enhanced by fine aggregates, silica fume, and steel fibers, delivers significant improvements in ductility and post-cracking behavior. However, challenges persist in regions like Indonesia due to the scarcity and cost of nano-materials and specialized admixtures. Recent research has focused on optimizing UHPC mixes with locally available materials, such as natural sand and finely graded crushed stone, without compromising its performance. This review synthesizes the critical aspects of UHPC composition, including optimal fiber content, rheological properties, and mixing methodologies, to ensure uniform fiber dispersion and matrix densification. The application of UHPC in structural repair has demonstrated not only improved mechanical resilience but also enhanced cost efficiency and lifecycle performance of infrastructure.

Keywords: Ultra-High Performance Concrete (UHPC), concrete structure repair, steel fibers, silica fume, concrete ductility, self-consolidating concrete, local materials.

Introduction

Ultra-High Performance Concrete (UHPC) has the potential to serve as a repair material for structural columns, extending the operational lifespan of buildings, especially in the case of bridge columns, by improving durability and resistance to deterioration [1]. UHPC is a composite material consisting of fine granular materials, cement, silica fume, quartz flour, steel fiber reinforcement, superplasticizer, and water. It has a high cement ratio and a low water-binder ratio, with nano-scale particle sizes. The water-to-cement ratio in UHPC is less than 0.25. UHPC exhibits a compressive strength greater than 150 MPa and a tensile strength exceeding 5 MPa. [2]. However, nano materials are difficult to find in Indonesia and are relatively expensive. Therefore, UHPC has been developed using locally available materials, such as natural sand and crushed stone passing a 4.75 mm sieve. The water absorption of the sand is 6.24%, while that of the crushed stone is 3.99%. The water-to-binder (w/b) ratio for the UHPC mixture is set at 0.2. [3]

UHPC is classified as a type of Self-Consolidating Concrete (SCC), which allows for easy compaction without the need for excessive vibration. To achieve this property, UHPC must be produced with an optimal combination of cement, fine sand gradation, a low water-to-binder ratio (w/b = 0.25), steel fibres, and a high-range water reducer (HRWR) [4].

Steel fibres in UHPC play a crucial role in enhancing material performance by controlling micro-cracks, strengthening the bond between particles, and improving the homogeneity of the concrete. However, achieving optimal fiber composition is essential to maximize these benefits [5]. In addition to steel fibres, another critical component influencing the overall performance of UHPC is silica fume, SiO_2. With a high SiO_2 content and an ultra-fine particle size, silica fume effectively fills the voids in concrete caused by trapped air and water between sand and coarse aggregates, thereby enhancing density and durability [6]. However, an excessive dosage of silica fume can make the concrete too fluid. Therefore, an optimal silica fume dosage is recommended to achieve better concrete quality. In research studies, the proper balance of silica fume content is crucial to maintaining workability while enhancing strength and durability. [7] The silica fume content commonly used ranges from approximately 20–30% of the cementitious material mass.

Constituent of Materials of UHPC

Cement

The type of cement is the most critical factor in high-performance concrete mixtures. Cement is selected based on its water demand; high water-demand cement can lead to lower compressive strength. Therefore, it is essential to use low-hydration cement, such as Portland Slag Cement (PSC). PSC is preferred due to its low permeability, making it more resistant to water penetration. Additionally, PSC has adequate early strength and high ultimate strength, making it suitable for UHPC, which requires superior performance. More importantly, PSC interacts well with silica fume and steel fiber mixtures, enhancing the overall properties of UHPC.

Coarse Aggregate

The use of coarse aggregate in UHPC differs slightly from conventional concrete. UHPC typically incorporates smaller-sized coarse aggregates with a gradation similar to fine sand. This finer aggregate distribution helps achieve a denser and more homogeneous microstructure, enhancing the mechanical properties and durability of the UHPC mixture. In the study by Shunan Wang et al.[8], coarse aggregate with a gradation of 5–10 mm was used in the UHPC mixture. Meanwhile, Oesman et al. [3] utilized locally sourced coarse aggregate passing a 4.75 mm sieve, which is categorized as very fine.

Natural Sand

In UHPC mixtures, natural sand used consists of micron-sized particles that are free from organic materials. However, since micron-sized materials are relatively expensive, they can be replaced with natural sand with a gradation above 1 mm. Natural sand is preferred because it provides higher strength compared to manufactured sand. Another advantage is that natural sand has angular particle shapes, which enhance the compressive strength of the concrete.

Silica Fume

In UHPC formulations, silica fume—comprising predominantly highly reactive amorphous SiO_2—is required to conform to ASTM C-1240 specifications, mandating a minimum SiO_2 content of 85% and a maximum carbon content of 2.5%. Empirical findings suggest that silica fume with lower carbon concentrations is more effective in promoting favorable rheological behavior and enhancing mixture workability [5]. A high amount of silica fume can negatively affect the workability and cost-effectiveness of UHPC. Excessive silica fume content may lead to increased water demand, reduced flow ability, and higher material costs, making the mixture less efficient in both performance and economic aspects. Therefore, an optimal dosage is necessary to balance strength, durability, and workability.

Silica fume contributes to the improved performance of UHPC through multiple mechanisms. Firstly, its extremely fine particle size enables effective pore filling between cement grains and coarser aggregates, thereby optimizing particle packing density. Secondly, its spherical morphology enhances internal lubrication, which facilitates better flow characteristics. Lastly, the pozzolanic activity of silica fume, involving its reaction with calcium hydroxide [$Ca(OH)_2$], results in the formation of a denser calcium silicate hydrate (C-S-H) matrix, leading to significant gains in both strength and durability.

Steel Fibers

UHPC possesses exceptionally high strength and homogeneity. The addition of steel fibers enhances toughness and ductility, allowing for greater energy absorption before structural failure occurs. The uniformly dispersed steel fibers within the UHPC mixture help distribute loads more evenly and reduce stress concentrations that can lead to localized failures. Research has shown that incorporating 3% fiber volume can result in a 4% strength increase for cubic specimens and an 8% increase for cylindrical specimens.

Other studies, such as those conducted by [9], and others, have shown similar improvements in compressive strength when steel fibers are added, with strengths reaching up to 150 MPa depending on the fiber volume used. The type of fiber used is also crucial. Steel fibers can be categorized based on their deformation (hooked or twisted), straightness (smooth), and length (short or long). These fibers not only enhance compressive and tensile strength but also improve the compression-to-tensile ratio of UHPC. Additionally, steel fibers exhibit high resistance to alkaline environments, high strength, and a high modulus of elasticity, making them an excellent reinforcement material for UHPC [10]. **Table 1** presents the various size of steel fibers used in UHPC, based on findings from previous studies.

Table 1 Summary of mechanical performance of UHPC

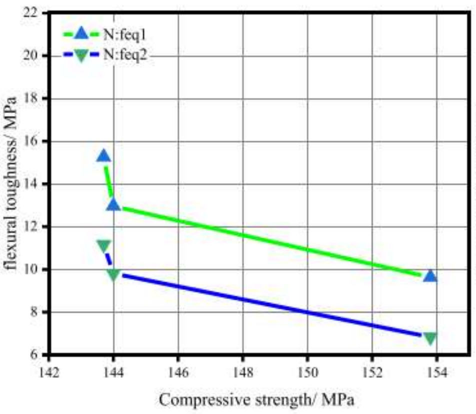
Research Studies	Type steel fiber		Compressive Strenght (MPa)	Flextural Strenght (MPa)
	l/d (mm)	Volume (%)		
[11]	13/0,15	2,5-3	165-225	-
[12]	12,7/0,2	2	112-210	28-36
[13]	13/0,2	2		
[14]	13/0,2	2%	120	13 – 17,2
[8]	13/0,2	1,5 - 3		24,1
[3]	30/0,3	2%	52,10 – 90,82	9,30 – 11,41

UHPC Mix Materials

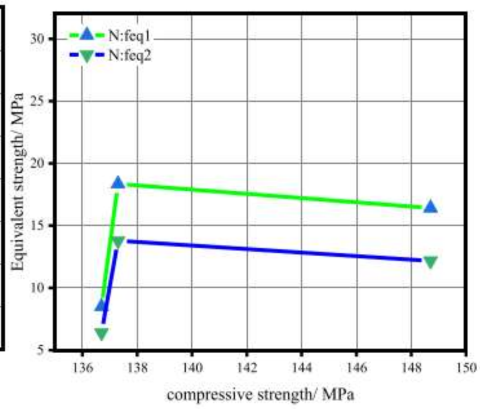
The selection of UHPC mixture components must prioritize economic feasibility and sustainability to develop a denser matrix, minimize porosity, and improve the internal microstructure, thereby attaining enhanced mechanical performance and durability. Critical parameters in the preliminary design phase include optimizing the granular composition, substituting conventional coarse aggregates with fine-graded alternatives, and determining the optimal fiber content in conjunction with other mix constituents to achieve a homogeneous, dense, and ductile microstructure.

In the study by Shangwei Wang et al. [15] the effects of steel fibers on the compressive strength and flexural toughness of UHPC with coarse aggregates were investigated. The steel fibers used had a length of 13 mm and a diameter of 0.2 mm. The fiber volume fractions were varied at 1.5%, 2%, and 3%, all of which had a straight shape. Additionally, the water-binder ratio was varied at 0.15, 0.17, and 0.19. The coarse aggregate size used ranged from 5 to 10 mm, while river sand was used as fine aggregate. The study concluded that UHPC with 2% steel fiber performed better than other percentages, improving compressive strength and toughness. However, for flexural strength, the trend was the opposite, where a higher steel fiber content resulted in increased flexural strength.

Shangwei Wang et al. [15] conducted an analysis of compressive strength improvement in relation to fiber content, as illustrated in **Fig 1**. In general, it can be concluded that the addition of 1.5% and 2.5% steel fiber volume fraction enhances compressive strength. However, when the steel fiber content reaches 2% and 3%, the curve initially increases before declining. This suggests the existence of an optimal fiber content threshold for maximizing compressive strength. A preliminary assumption is that excessive fiber concentration leads to fiber agglomeration, hindering uniform dispersion within the concrete matrix. As a result, steel fibers may not function optimally in resisting stress and could even create weak points that trigger premature cracking, ultimately causing a reduction in compressive strength beyond a certain percentage. **Table 2** presents the various mixtures used in UHPC, based on findings from previous studies.



(a)



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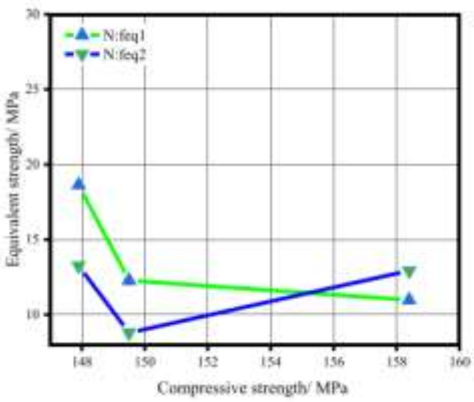

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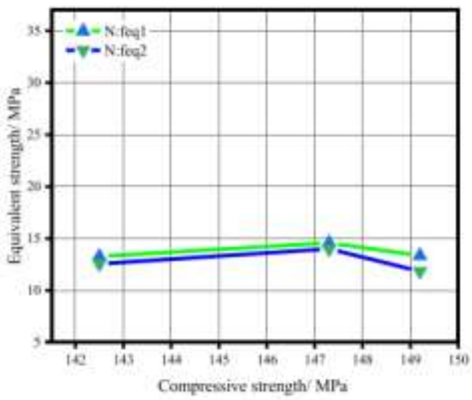

(d)

Figure 1 (a) Steel fibers 1,5%, (b) Steel fibers 2%, (c) Steel fibers 2,5% dan (d) Steel fibers 3%

Table 2 Summary of Mixture of UHPC

Reference	Materials	Mixture (Kg/m^3)

[8]	*Silica fume*	4,61-8,94
	Fly ash	7,44
	Superplasticizer	4,7
	Water/binder	0,15 – 0,19
	Portland slag	0,67
	Steel fibers	1,5-3%
	Coarse aggregate	10,6
[16]	Semen	788
	Silica fume	197
	Quartz sand	315
	W/b	0,22
	Steel fibers	2-2,5%
[17]	Semen	360-900
	Silica Fume	90
	Fly ash	270-450
	Natural sands	620
	W/b	0,16
[3]	Semen	750
	Natural sands	454
	Crushed stone	556
	Silica fume	321
	Superplastisizer	10,72
	Steel fibers	2%
	w/b	0,22
[12]	Portland cement	712
	Fine sand	1020
	Silica fume	231
	Quartz	211
	HRWR	30,7
	Accelerator	30
	Steel fibers	156
	Air	109
[18]	Portland cement	1050
	Sands	514
	Silica Fume	268
	HRWR	44
	Steel fibers	858

	Air	180

UHPC Mixing Method

In UHPC mixing, the selection of mixing equipment affects quality. The increase in compressive strength occurs when using a conventional mixer, while a greater increase in compressive strength is achieved when using a vertical planetary mixer. According to the study by Shangwei Wang et al. [15] the UHPC mixing sequence begins with blending cement, coarse aggregates, and fine aggregates for approximately 2–3 minutes. Following this, 75% of the total mixing water and the complete dosage of superplasticizer are gradually introduced while stirring continues for an additional 3–4 minutes. The remaining water is then added, and mixing proceeds for a further 2–3 minutes until a uniform consistency is attained. Upon achieving the desired mix homogeneity, steel fibers are incorporated to ensure even distribution. The fresh UHPC mixture is subsequently cast into molds and subjected to vibration on a vibrating table to eliminate entrapped air. After casting, the specimens are covered with plastic sheets and kept at room temperature for 24 hours prior to demolding. Final curing is conducted in a controlled environment at $20 \pm 2°C$ and a relative humidity of $\geq 95\%$ for a duration of 28 days.

In the study [3] the UHPC mixing method is as follows: Supplementary Cementitious Materials (SCM) and cement are manually combined (without a mixer) until homogeneous. Crushed stone and natural sand are also manually combined until homogeneous. Then, all dry materials are mixed using a mixer. The dry material combination process is carried out for approximately 2 minutes until all materials are well blended.

Next, 90% of the required water is mixed with the superplasticizer. This liquid mixture is gradually added to the dry mix while stirring for 4 minutes until the mixture turns into a paste. Once the mixture becomes a paste, the mixer speed is increased for 1 minute. The mixer is then turned off, and manual mixing is performed to refine the mixture (breaking up any dry lumps) until homogeneous, for approximately 2 minutes.

The remaining water and steel fibers are gradually added to the mix and stirred for 4 minutes until a homogeneous consistency is achieved. The mixer speed is increased for 1 minute. After the mixing process is complete and the mixture is homogeneous, the fresh UHPC mixture undergoes physical property testing using the slump flow method.

Workability of UHPC

UHPC, classified as a self-consolidating concrete, is widely utilized in structures featuring intricate formwork and congested reinforcement arrangements. Among the critical parameters in UHPC production, flowability plays a pivotal role. Flow characteristics are typically assessed using a mini-slump cone test, wherein the flow table is rotated 25 times. Wille et al. recommend that UHPC should achieve a minimum mini-slump flow diameter of 280 mm to facilitate the release of entrapped air. In fiber-free UHPC, segregation and bleeding are generally negligible due to the cohesive nature of the matrix and the minimal density disparity between the paste and aggregates. However, the incorporation of steel fibers introduces a risk of segregation owing to the significantly greater specific gravity of steel relative to cementitious mortar. Consequently, careful consideration of rheological properties is imperative in UHPC design to maintain adequate flowability and ensure uniform fiber dispersion throughout the matrix [19] .

Setting time is also critical for applications where UHPC is expected to achieve the required strength within a short duration. However, UHPC typically exhibits longer initial and final setting times compared to conventional concrete due to the high dosage of high-range water reducers (HRWR). The initial setting time of UHPC ranges from 70 minutes to 15 hours, while the final setting time varies between 5 to 20 hours, depending on the specific UHPC formulation used [12]. The use of accelerators is one solution to address the excessively slow setting time. Another method is high-temperature curing, which has been proven to significantly reduce both the initial and final setting times by increasing the curing temperature [12].

Shunan Wang et al. [8] formulated UHPC by incorporating steel fibers, GGBFS, and silica fume, while maintaining a consistent water-to-binder ratio of 0.18. The findings revealed that the flowability of UHPC increased in direct proportion to the substitution level of GGBFS. The shape of the fibers was also found to significantly affect flowability. In this investigation, samples with hooked-end fibers displayed the lowest flowability compared to those with straight and wavy fibers, even when the fiber content remained the same. Specifically, for mixtures with 1%, 2%, and 3% hooked-end steel fibers, the flowability decreased by 20.9%, 35.8%, and 51.2%, respectively. For mixtures containing 1%, 2%, and 3% wavy fibers, the flowability reduction was 17.7%, 31.2%, and 45.1%, respectively.

UHPC Repairs

UHPC is considered one of the most recent repair material in the industry. Its use has been somewhat limited in the built environment, however it is becoming more and more common as more research is being conducted on its performance and reliability. Doiron et al. [20] reports several projects conducted by Lafarge North America Inc. in Canada where they had used UHPC as a repair material in infrastructure restoration projects. These projects include the rehabilitation of CN rail in Montreal, QC where they used UHPC jacketing, this project was conducted in 2013. Mission bridge seismic retrofit at Abbotsford, BC. It was reported that the use of UHPC jacketing instead of traditional pile compaction techniques provided $1.5 Million (CAD) in savings to the project. This retrofit project receive the 2015 ACI excellence in concrete award in the repair and restoration category. The third reported project is the Hooper Rd, Town of Union in New York. The report shows how the contractor was able to leverage the characteristics of UHPC in order to save time in completing the project. The replacement project was completed in 21 days in 2014.

[21] proposed a retrofitting method of bridge piers using UHPC. A main test variable was to simulate damage caused by corrosion without corroding the specimens. The damage was represented in alteration of the sectional geometry and removal of concrete in certain locations at the base of the column. The problem with this approach is that reinforcement is not damaged nor the bond strength of reinforcement is altered. Those the results are not very reliable. Nonetheless, it was observed that UHPC significantly improves the seismic behavior of columns. It was also reported that UHPC with 2% and 4% volumetric fiber ratio resulted in similar behavior. The cover thickness however plays a role in shifting the failure location either above or below the repaired section which should be taken into account as a design consideration.

Conclusion

Ultra High-Performance Concrete (UHPC) is a highly promising material for structural repair and strengthening applications, particularly for critical elements such as bridge columns, which require high resistance to loads and environmental factors. UHPC offers a combination of compressive, tensile, and flexural strength that far surpasses conventional concrete, making it ideal for high-performance structural applications with exceptional durability.

The superior properties of UHPC, including compressive strength up to 180 MPa and tensile strength up to 15 MPa, allow this material to withstand heavy loads while maintaining structural integrity even after cracking. This makes UHPC a ductile material capable of sustaining post-crack loads, which is crucial for infrastructure subjected to dynamic loads and fatigue-induced damage. Despite its immense potential, the implementation of UHPC in Indonesia faces several challenges. One of the primary obstacles is the availability of nano materials and high-quality additives required for UHPC production. These materials are often imported at high costs, increasing the overall project expenses when using UHPC.

To address this issue, research and development efforts in Indonesia are increasingly focused on utilizing more affordable local materials, such as natural sand and finely graded crushed stone. When combined with steel fibers and silica fume in the right proportions, these materials can produce UHPC with sufficient mechanical properties. This suggests that innovation in local material utilization and mix optimization could be key to expanding UHPC applications in Indonesia.

The mixing and processing methods of UHPC play a crucial role in determining the final quality of the material. Proper mixing procedures and curing techniques are essential to ensure UHPC achieves its optimal strength and homogeneous fiber distribution, which in turn enhances its structural performance. Improvements in production methods and the adoption of modern technologies in UHPC processing will be highly beneficial in overcoming these challenges.

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