Brief Report

Ultra-High-Performance Fiber-Reinforced Concrete: Applications

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Abstracts

UHPC is a type of cement-based composite used in new construction and/or rehabilitation of existing buildings to extend service life. It is a novel composite material that can serve as an alternative to concrete construction in hostile climates. Following decades of study and production, a diverse variety of commercial UHPC compositions are now available globally to meet the rising number of applicants and demand for high-quality building materials. Although UHPC offers major benefits over normal concrete, its utilization is restricted due to restrictive design rules and exorbitant costs. As a result, a thorough examination of the durability properties of UHPC is required to give important information for material testing requirements and processes, as well as to broaden its practical uses. This report is aimed at increasing basic understanding of UHPC and supporting more UHPC research and applications.

Keywords:Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC); applications

1. Introduction

UHPC is a high-strength, high-durability cementitious material. It has the potential to be a viable solution for improving the sustainability of buildings and other infrastructure components [1-7]. UHPC has grown in popularity in many countries over the last two decades, with applications ranging from building components, bridges, architectural features, repair and rehabilitation, and vertical components such as windmill towers and utility towers, to oil and gas industry applications, offshore structures, hydraulic structures, and overlay materials [8-11]. Among all of these applications, road and bridge construction are the most common for UHPC use. UHPC is used in a variety of nations, including Australia, Austria, Canada, China, the Czech Republic, France, Germany, Italy, Japan, Malaysia, the Netherlands, New Zealand, Slovenia, South Korea, Switzerland, and the United States (US) [8, 12, 13]. The majority of projects in the aforementioned countries were inspired by government entities as pilot projects to stimulate future implementation. However, with tardy follow-up implementation, most countries' demonstration programs did not achieve the desired acceptability [14-19]. The lack of design codes, inadequate knowledge of both the material and production technology, and expensive costs appear to be limiting the implementation of this excellent material beyond the early demonstration projects [8, 20-22]. Both the business and public sectors are increasingly paying closer attention to and pushing for greater efforts to make use of this novel and promising material [23-28].

Several varieties of UHPC have been developed to date in various countries and by various manufacturers, including Ceracem+, BSI+, compact reinforced composites (CRC), multiscale cement composite (MSCC), and reactive powder concrete (RPC) [29-34]. In Malaysia, UHPC began its industrial-commercial penetration as a sustainable construction material under the brand name Dura+ in late 2010 [31, 35-38].

Throughout the world, successful successes in the application of UHPC can be seen. However, there are still obstacles that limit its application. Ongoing study and investigation efforts are filling knowledge gaps in order to commence innovative, affordable, sustainable, viable, and economical UHPC in the future, which will have

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a significant impact on its acceptability. This paper provides a general introduction to UHPC as well as the most up-to-date information on its definitions, development, applications, and problems .

Many researchers have conducted studies on UHPC, but information on the materials and structural properties of UHPC is still limited. This review includes five parts. The purpose of this report is to summarize previous research and to suggest some needs for future research [39-45].

2. Applications

With an expanding number of applications in recent years, UHPC's exceptional performance opens up new options for infrastructure work, building construction, and numerous niche markets. According to Grand View Research (GVR) market research, the global UHPC market was valued at USD$ 892 million in 2016 and is predicted to expand by 8.6 percent to USD$ 1867.3 million in 2025. With commercialization available in several countries, including Australia and New Zealand [46], Austria [47], Canada [48], US [49], Germany [50], France [51], Italy [52], Japan [53], Malaysia [54], Netherlands [55], and Slovenia [56], UHPC has gained worldwide interest. Over the last two decades, scholars and engineers around the world have conducted extensive research initiatives in an attempt to industrialize UHPC technology as the future sustainable construction material [57]. A thorough search of the literature yielded over 200 finished bridges that used UHPC in one or more of their components [8]. Other UHPC uses include building, structural strengthening, retrofitting, precast elements, and other unique applications [29, 51]. Both business and public sectors are focusing their efforts and resources on exploiting UHPC as the future sustainable construction material [58-71].

4.2. Bridges

Precast bridge elements are particularly effective for facilitating the expedited construction timetables that are frequently required for highway projects. The reliance on the performance of field-cast connectors is one issue that comes from the usage of prefabricated bridge components. These types of connections frequently cause problems with constructability, durability, and structural performance. Because of its greater durability and strength, which has been found to improve bond strength, the inclusion of UHPC in these field-cast connections may improve their performance.

Yuan and Graybeal [72] investigated the bond of reinforcing steel within UHPC concrete and discovered that UHPC had improved bond performance when compared to conventional high-strength concretes. However, neither compressive strength ($f'c$) nor $f'c^{1/was}$ found to be useful in forecasting bond strength in UHPC. The University of Michigan [73] also conducted a comprehensive investigation on bond length on the UHPC mix generated during their research. This UHPC blend required much less bond length than conventional concrete; nonetheless, the authors recommend further research because their specific results differ from those published by Yuan and Graybeal [74] stated above.

El-Tawil, Alkaysi, Naaman, Hansen and Liu [73] conducted field-cast joint testing between two precast bridge deck sections utilizing UHPC and determined that a 6-inch joint length could be sufficient for load transfer between the two elements. Graybeal [114] investigated field-cast connections and discovered that using UHPC in such connections can alleviate some of their potential problems. According to Graybeal [75] research, full development of reinforcing steel can be accomplished in a substantially shorter duration when compared to typical concrete and grout combinations. This enables designers to define shorter lap splices and connection details, reducing construction complexity and costs. UHPC's tensile strength and ability to attach extraordinarily well to previously cast concrete have also aided in the creation of simpler connecting details. Because of the improved characteristics of UHPC, precast bridge deck closing pours of 6 in. or less in length can be successfully constructed as thin shear keys. Full-scale structural testing has proven that field-cast UHPC deck connections can outperform monolithically cast bridge decks. This study further demonstrated

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that, even under extreme loading conditions, reinforcement in both transverse and longitudinal UHPC-filled connections does not debone from UHPC [76-83].

2.2.1. Example of bridging applications

Around 1985, the first research and development aimed toward the implementation of UHPC in construction began [1]. Since then, several technical solutions and UHPC formulations have been developed to fulfill the specific needs of distinct designs, structures, and architectural approaches. Breakthroughs in UHPC application include the first pre-stressed hybrid pedestrian bridge over the Magog River in Sherbrooke, Canada, built-in 1997 [84], the replacement of corroded steel beams in the aggressive environment of France's Cattenom and Civaux nuclear cooling towers [85], and the Bourg-les-Valence bridge built for cars and trucks in 2001 [86]. Because of UHPC's superior mechanical characteristics and endurance, standard design methods for many typical bridge components can be reconsidered. Many studies on the optimal designs incorporating UHPC elements had been undertaken, culminating in the creation, and building of UHPC bridges all over the world. The Seonyu footbridge in South Korea, with a primary span of 120 m, was built using UHPC in 2002 and completed in 2004 [87]. The Seonyu footbridge structure, the world's longest span bridge constructed utilizing UHPC, needed almost half the material amount that would have been used in standard concrete construction while providing equal strength attributes [88]. In Japan, the Sakata-Mirai footbridge with a span of 50 meters was constructed in 2003. The bridge illustrated how a perforated web in a UHPC superstructure can reduce weight while still being aesthetically beautiful [89]. Following the success of these projects, UHPC pedestrian bridges have been built-in Europe, North America (the US and Canada), Asia, and Australia [90].

According to a 2013 FHWA report, 55 bridges using UHPC have been built or are being built-in the United States and Canada. There are approximately 22 UHPC bridges in Europe and 27 UHPC bridges in Asia and Australia [91]. UHPC can be employed in various applications such as beams, girders, deck panels, protective layers, field-cast joints between different components, and so on [92-94]. In comparison to standard reinforced concrete bridges, most bridges designed using UHPC components or joints have a slim appearance, a significant reduction in volume and self-weight, simplified implementation, and improved durability [95]. Most UHPC structures require only half the section depth of typical reinforced or pre-stressed concrete components, resulting in weight savings of up to 70% [96]. UHPC structures' lighter weight construction and material efficiency result in a more sustainable structure with fewer carbon footprints [97] [98-103].

2.3. Infrastructures

The Monaco subterranean train station's acoustic panels were made from UHPC. Small holes were cast into the thin and light UHPC panels to help with their acoustic characteristics. The non-flammable panels are impact-resistant and provide passengers with a visually pleasant and bright atmosphere [104-114]. Due to their resilience to car pollution and deicing salts, acoustic panels have also been utilized along a roadway in Châtellerault, France. Other UHPC application possibilities include security infrastructure employed as barrier protection systems or as fundamental components of essential infrastructure. Extensive research on the mechanical properties of UHPC subjected to high strain loading rate [115, 116], blast resistance [117, 118] and penetration resistance [37, 119-122].

2.4. Non-structural products

UHPC has been widely utilized as an overlay to repair existing concrete structures due to its superior characteristics, boosting mechanical and durability properties for less maintenance work [123, 124]. The first

UHPC overlay application was reported on a bridge over the La Morge River in Switzerland [125]. UHPC was used to replace the severely damaged bridge deck and curbing. After one year of use, no cracks were found on the prefabricated UHPC curb. Because these materials were successful in repair and rehabilitation applications, they paved the path for similar technology to be employed on deteriorating bridges. UHPC was used to repair and rehab hydraulic structures at the Hosokawa River Tunnel in Japan [126], as well as the Caderousse and Beaucaire Dams in France [127].
Because of its remarkable properties of high flexural strength and dense microstructure, UHPC has the potential to be used in specific settings. According to reports, UHPC was utilized for cover plates along China's high-speed railroads [128] and for the retrofit of nuclear reactor containment walls in France [129]. UHPC has also been used in marine environments due to its high resistance to hostile chemicals. Several sea windmills have been successfully created, as previously reported by researchers [130, 131], and the rejuvenation of marine signalization buildings using UHPC has also been shown to be highly effective [132]. In Japan, the Haneda Airport was expanded by building a massive UHPC slab over the sea [89]. To date, this is the largest UHPC project completed. UHPC's superior performance is responsible for its vast potential in a variety of applications; however, many have yet to be discovered to take use of its improved strength, durability, and flexural capacity. In places where CC struggles, UHPC offers cost-effective and innovative alternatives. UHPC is the future construction material; it is here to stay and will continue to grow globally.

2.5. Other applications

In addition to buildings and bridges, UHPC has the potential to be applied to tunnels, wind turbine towers, and nuclear power facilities. UHPC can develop more efficient tunnel systems with bigger usable spaces for tunnel applications by reducing tunnel element thickness [133]. UHPC components for wind turbine towers enable the construction of taller and more slender wind turbine towers, enhancing energy generation efficiency [134]. UHPC has greater radiation shielding properties and stronger blast endurance for nuclear power plants, which can improve the security of critical infrastructure [135].

2.6. Proposed applications

2.6.1. Using UHPFRC for retrofitting purposes

Another use for the proposed UHPFRC is for retrofitting existing RC constructions. Normally, time is vital for repairing and retrofitting existing structures since the elements must be overheated in order to bear the imposed loading. For that purpose, a prefabricated element can be more effective in terms of minimizing retrofitting time, improving element quality during fabrication in the laboratory and before sending for installation, and lowering labor expenses. As a result, in this study, a thin prefabricated element based on UHPFRC that is dimensioned according to the specifications can be proposed. CFRP material can be employed to increase the ductility of this system. CFRP can be employed as an attached sheet on the outer faces of prefabricated elements using Externally Bonded Fiber (EBR) techniques or as a Near Surface Mounted (NSM) technology employing a laminate inside the pre-sawn grooves on its face. The orientation of the CFRP sheets and/or laminates can be adjusted to meet the needs. This prefabricated element can be attached to the surface of RC elements using adhesive bonding, anchorage bonding, or a combination of the two.

2.6.2. Using UHPFRC as shear reinforcement in RC beams

One of the weaknesses of ordinary concrete is its low resistance to shear forces before reaching the ultimate flexural capacity of the elements. This failure is generally unexpected and unnoticed. Based on this, adding shear reinforcement as a shear stirrup is critical for hiding the weakness of concrete, increasing shear resistance, and so boosting the flexural behavior of the elements. However, after updating requirements, the amount of % shear stirrups increased to be used in a key zone where shear forces are higher than in other places. Using the number of shear stirrups increases the cost of final manufacturing in terms of labor and material costs. Even with some elements, such as thin-walled beams and hollow sections, executing the standards requirement is problematic. These shear stirrups are particularly accentuated in the area where the seismic danger is considerable, with a very condensed in some portions of the element. This shear stirrup condensate has occasionally caused complications with concrete vibration and achieving nonhomogeneous concrete.

Based on these findings, it will be effective to investigate the feasibility of utilizing UHPFRC as shear reinforcement in RC beams. The proposed material appears to be suitable for use as shear reinforcement in RC beam elements for minimizing the number of stirrups by boosting RC member shear resistance and reducing the size of longitudinal rebars by increasing flexural capacity.

3. Conclusions

Based on the review and discussions above, it can be summarized as follows:

1. Throughout the world, achievements in the application of UHPC can be seen. UHPC, on the other hand, is moving slowly, with constraints restricting its uses. High starting costs, limited codes, design challenges, and complex production techniques, combined with limited available resources, impeded its commercial development and application in modern buildings, particularly in developing countries.
2. The majority of existing UHPC applications are accomplished by factory pre-fabrication and onsite assembly. Given the prohibitive cost and complexity of the curing process, standard materials, and common technology, such as conventional casting and room temperature curing, are the UHPC trends.

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