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学位論文題目	Development of Ultra-High-Performance Fiber-Reinforced Cementitious Composites Using Multi-Scale Fiber-Reinforcement System
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論 文 内 容 要 旨

1. Introduction

Nowadays a wide variety of advanced fiber-reinforced cementitious composites (FRCCs) are available. Advanced cementitious composite materials such as ultra-high-performance fiber-reinforced cementitious composites (UHP-FRCCs) are promising materials. UHP-FRCC belongs to the group of high performance fiber-reinforced cementitious composites (HPFRCCs). HPFRCC exhibits pseudo strain-hardening behavior and multiple cracking behavior after the occurrence of the first crack. As a result, it provides an exceptional energy absorption prior to fracture, and undergoes distributed cracking with extremely small crack width prior to crack localization. Thus, UHP-FRCC can be a viable solution for improving the resistance of buildings and other infrastructures on the basis of their ultra high strength, high ductility, durability and energy absorption capacity compared with normal concrete and conventional FRCC. The motivation for development of UHP-FRCC is the creation of a new versatile material with a large energy-absorption capacity suitable for seismic design applications and with a long service life by virtue of its crack tolerance. The ability to exhibit pseudo-strain hardening in tension is highly dependent on the matrix, the type and the volume fraction of fiber and the bond properties at the interface between the matrix and the fiber. Some researchers have achieved the strain-hardening behavior of UHP-FRCC through various material design techniques. Some of them developed UHP-FRCC with hybrid fiber reinforcing systems where two or more types of fiber were blended. However, they have not succeeded in showing significant improvement of its mechanical performance. Therefore, it is necessary to develop new material design methods that achieve high performance of UHP-FRCC. In addition, the performance of those of UHP-FRCC with conventional design method is highly dependent on fiber volume fraction. On the other hand, increasing fiber volume fraction decreases workability and increases cost of UHP-FRCC. Consequently, with the sufficient performance for solving workability and cost problems, it is required to develop a method that can determine the lowest fiber volume fraction of UHP-FRCC.

UHP-FRCC exhibits multiple cracks to obtain the high mechanical performance. Those cracks have a high possibility to cause deterioration of concrete structures (i.e. decreasing durability of UHP-FRCC due to acceptance of aggressive substance ingress). Therefore, a repair of those cracks generated as a result of requirement of strain hardening behavior is also a very important work to prevent the deterioration of durability of UHP-FRCC. This thesis attempted to develop a new type of UHP-FRCC using multi-scale fiber-reinforcement system. For that purpose, the influence of factors on tensile behaviors of UHP-FRCC is clarified and a material design concept based on a multi-scale fiber-reinforcement system (i.e. fibers of different scales reinforce cracks of the scale corresponding to each fiber) is proposed based on concrete fracture mechanic (i.e. cracks initiate at the micro-scale, and then those cracks propagate) as shown in Fig. 1. Then, the lowest fiber volume fraction to achieve multiple-cracking behavior of the developed UHP-FRCC was determined for reducing cost and increasing workability. Lastly, self-healing capability of UHP-FRCC was investigated to prevent the deterioration of durability even if cracks occur.

2. General literature research

In Chapter 2, previous researches were reviewed. Especially, three major subjects (i.e. UHP-FRCC studied by other researchers, analytical model to determine the lowest fiber volume fraction, and self-healing capability of cementitious composites) were introduced. At first, previous researches on some methods to improve tensile performance of UHP-FRCC such as increasing fiber volume fraction, changing geometrical properties of fiber and using hybridization of reinforcing fibers were reviewed. However, those methods did not exhibit sufficient improvement of tensile performance of UHP-FRCC. Therefore, it became obvious that development of a new material design concept to achieve high performance of UHP-FRCC with low fiber volume fraction was required. Secondly, an analytical model to determine the lowest fiber volume fraction based on a cohesive interface analysis was reviewed. A large fiber volume fraction increases the cost and decreases workability of UHP-FRCC. This model might be useful to decrease fiber volume fraction of UHP-FRCC. However, the model was optimized for normal strength FRCC reinforced with monotype fiber. In other words, the model cannot be applied directly to UHP-FRCC reinforced together with micro-, meso- and macrofiber. Therefore, an extension of the analytical model to determine the lowest fiber volume fraction of UHP-FRCC is required. Finally, previous researches of self-healing capability of FRCC were reviewed. Cracks generally cause deterioration of concrete structures. If self-healing capability can be expected for UHP-FRCC, preventing deterioration of durability of UHP-FRCC could be possible even if cracks occur. Therefore, further investigation of self-healing capability of UHP-FRCC is required.

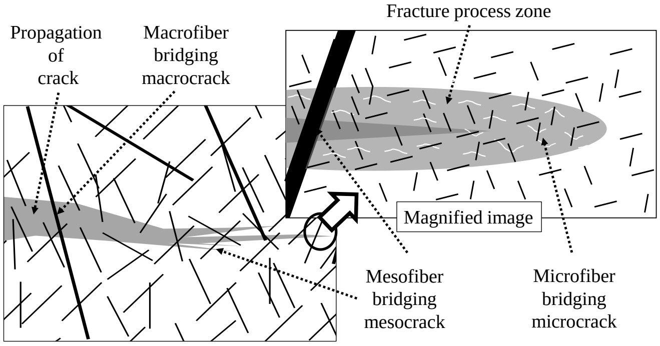

Fig. 1 Schematic illustration of multi-scale fiber-reinforcement system

3. Development of multi-scale fiber-reinforcement system

In Chapter 3, a new material design concept based on a multi-scale fiber-reinforcement system was proposed. The material design concept was based on fracture mechanics of concrete. The author focused on cracks initiated at the micro-scale level, i.e. on microcracks in the so-called fracture process zone (FPZ). The idea of multi-scale fiber-reinforcement system is given in Fig. 1. Microfibers can bridge microcracks more efficiently, because they are very thin and the number in cementitious composites is much larger than those of meso- and macrofibers. The ubiquitous distribution of microfibers controls the microcrack formation in FPZ. This phenomenon occurs in the first phases of the fracture process under tensile loading and thus the microfiber can increase the tensile performance. As the microcracks grow and combine into mesocracks, the mesofibers become more active in crack bridging. The pullout resistance of mesofibers increases due to additional bond stress caused by snubbing friction and the microfiber helps the increase of the snubbing friction mechanism. As the mesocracks grow and join into larger macrocracks, macrofiber becomes more active in crack bridging. In this way, primarily the ductility and also the tensile strength can be improved. Macrofibers can provide the UHP-FRCC with a stable post-peak response. From a mechanical point of view a material design concept based on multi-scale fiber-reinforcement system will be an effective solution to improve tensile performance including tensile strength and ductility. In this chapter, the author defined the micro-, meso- and macro-scales as being on the orders of 10^{-1} mm or less, 10^{0} mm, and 10^{1} mm or more, respectively. The first step was to confirm effectiveness of fibers on each scale and their combinations. Then the second one was to experimentally verify that multi-scale fiber-reinforcement system exhibits synergistic effects. Furthermore, the author proposed a method for optimizing the shape and size of fibers corresponding to various crack scales and for improving the tensile properties of UHP-FRCCs by reinforcing them from the micro- to the macro-scale. For that purpose, effectiveness of different types of fiber on the reinforcement and the mechanism by which multi-scale fiber-reinforcement system works were studied. Then, based on the proposed material design concept, an optimum tensile response of the UHP-FRCC with regard to tensile strength, tensile strain capacity and energy absorption capacity was determined by means of tension tests. As a result, the microfiber was very effective to improve toughness. Mesofiber showed a positive effect to prevent brittle failure and to improve tensile strength. In addition, macrofiber was very effective for improving ductility of UHP-FRCC. Finally, UHP-FRCC made by the proposed material design concept based on the multi-scale fiber-reinforcement system exhibited significant improvement of tensile properties comparing with those by monofiber reinforcement and with previously reported UHP-FRCCs as shown in Figs. 2 and 3, respectively. Therefore, the multi-scale fiber-reinforcement system was finally employed to establish a new design concept.

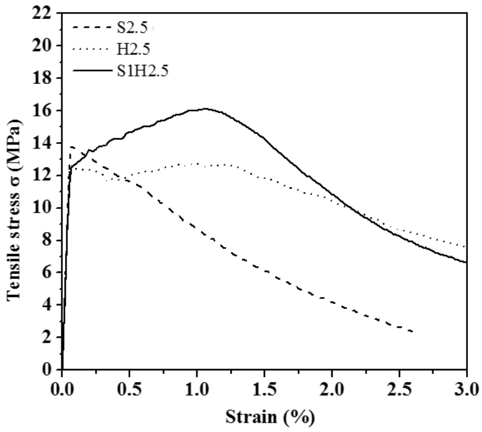

Fig. 2 Tensile stress–strain curves at the same fiber volume fraction

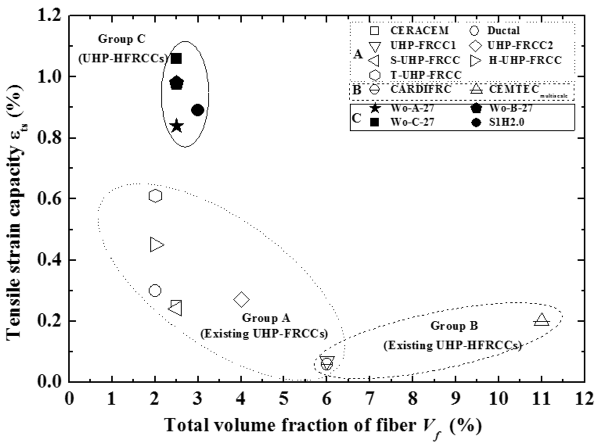

Fig. 3 Influence of the total volume fraction of fibers on tensile strain capacity on the comparison with previously reported UHP-FRCCs

4. Proposal of extended analytical model to determine the lowest fiber volume fraction of UHP-FRCC

Chapter 4 was initiated to determine the lowest fiber volume fraction with strain hardening behavior of developed UHP-FRCC. High volume fraction of fiber to obtain ductility reduces workability and increases cost. Therefore, reduction of the fiber volume fraction is one of important works to solve workability and cost problems of UHP-FRCC. As introduced in Chapter 2, analytical model was proposed to determine the lowest volume fraction of fiber. However, this proposed model was optimized for normal strength FRCC reinforced with monofiber. To apply the analytical model to UHP-FRCC, there were two obstacles. One was the fact that UHP-FRCC contains three different types of fibers. The other was that ultra-high strength mortar (UHSM) was too brittle to carry out the uniaxial tension test. For overcoming these obstacles, extended analytical model to determine the lowest fiber volume fraction of UHP-FRCC was proposed. The first obstacle was overcome as follows. Hybrid fiber composites showed a multiscale structure of cracking, in which macrofibers played the main role to prevent the sudden propagation of macro-cracks. Therefore, microfibers and mesofibers can be smeared in the cement-based matrix. Then, a method for determining the cohesive parameter (i.e. k_C) of UHSM containing micro- and mesofiber was

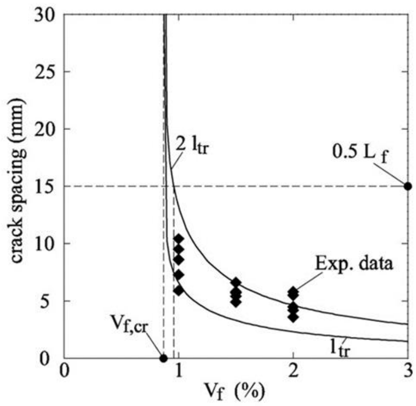

Fig. 4 Range of possible crack spacing values in the UHP-FRCC

developed to apply the analytical model to UHP-FRCC. In addition, uniaxial tension test was performed to determine the bond parameter (i.e. k_B) on the basis of crack spacing data in the UHP-FRCC. As a result, the lowest fiber volume fraction of UHP-FRCC using multi-scale fiber-reinforcement system was determined as shown in Fig. 4. Proposal of the extended analytical model to determine the lowest fiber volume fraction of UHP-FRCC can be useful to solve the problems due to cost and workability.

5. Experimental study on self-healing capability of cracked UHP-FRCC

Chapter 5 was to demonstrate the self-healing capability to prove the durability of cracked UHP-FRCC. For making UHP-FRCC ductile, crack tolerance is essential. There is a common belief that cracks cause deterioration of concrete structures. Therefore, it is necessary to repair for preventing the deterioration of durability of UHP-FRCC when cracks occur. If those cracks are self-healed, decreasing durability of UHP-FRCC might be compensated. For this purpose, an experimental series was performed to investigate the self-healing capability (i.e. filling the crack to prevent deterioration of durability) of the UHP-FRCC. As a result, self-healing of cracks in UHP-FRCC was confirmed as shown in Fig. 5. These results proved that the durability problem of UHP-FRCC can be solved by means of self-healing capability even if cracks occur to obtain ductile performance. In addition, no corrosion of steel fiber was confirmed. Because of the self-healing, UHP-FRCC could possibly protect itself against the ingress of aggressive agents, even if cracks occur.

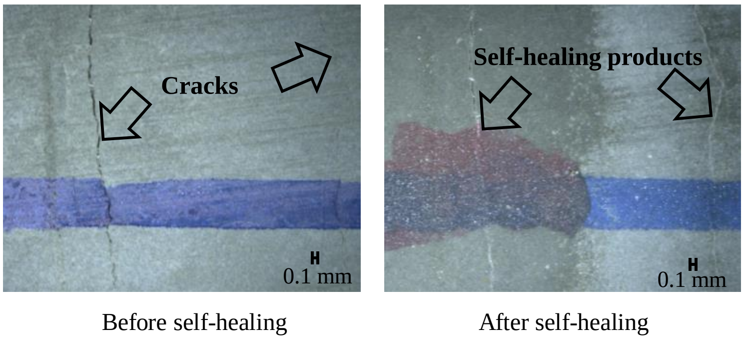

Fig. 5 Time dependence of self-healing

6. Conclusions

In this thesis, a new material design concept for the development of UHP-FRCC using multi-scale fiber-reinforcement system has been made. It has been demonstrated that applying a multi-scale fiber-reinforcement system to UHPC materials is a promising approach in the development of a very strong and ductile UHP-FRCCs. In addition, proposal of the extended analytical model to determine the lowest fiber volume fraction of UHP-FRCC can be useful to decrease cost and to increase workability. Moreover, durability problem of UHP-FRCC can be solved by means of self-healing capability even if cracks occur. Developed UHP-FRCC with an ultra-high compressive strength, tensile strength, tensile strain capacity and energy-absorption capacity are expected to lead to versatile structural applications. This is especially true from a seismic design perspective because of the large energy-absorption capacity. In addition, this thesis will provide engineers with a useful asset in material design method for UHP-FRCC, which is a promising material, for realizing the safety and security in buildings and infrastructures of next generation.

論文審査結果の要旨

本論文は、超高強度繊維補強セメント複合材料（Ultra-High-Performance Fiber-Reinforced Cementitious Composites、以下 UHP-FRCC）について、コンクリートの破壊力学を発想の起点として異なるサイズの補強繊維を組み合わせる「Multi-Scale Fiber-Reinforcement System」による新しい材料設計手法を提案し、その有効性を主に実験的な手法により示したものである。以下の全6章より構成されている。

第1章では、本研究の背景と目的について述べている。

第2章は、本研究に特に関連の深い既往の研究事例のレビューであり、3つの項目に大別される。第一には UHP-FRCC に関する既往の研究を調査し、従来のアプローチでは超高強度と高靭性の両立に限界があることを示している。また、第二点としてひずみ硬化特性を獲得するための有効繊維混入率の下限値を決定する手法、および、第三点としてひずみ硬化特性獲得に伴って発生するひび割れを塞ぐことのできる自己修復効果に関する既往の研究を紹介している。これらの調査により、本論文における研究課題を明確化している。

第3章では、Multi-Scale Fiber-Reinforcement System の材料設計コンセプトについて詳述した上で、本提案により UHP-FRCC の超高強度と高靭性が両立可能であることを実験的な検討により確認している。ミクロ・メゾ・マクロレベルからなる異なる形状・サイズの補強繊維の使用により、破壊進行領域に見られるような極めて微細なひび割れから、これらの集積によってひび割れがメゾ・マクロレベルに進展する過程において、それぞれの補強繊維が対応するレベルのひび割れをシームレスに補強可能となり、それぞれの繊維を単独で用いた際には得られない複合効果が得られることを確認している。

第4章では、UHP-FRCC に用いる繊維混入量のできる限りの削減を目的として、既往の解析モデルを超高強度領域および複合繊維補強の場合へと拡張する方法を提案し、実験により有効繊維量の下限値の決定が可能であることを確認している。

第5章では、新たに提案した UHP-FRCC の自己修復効果に着目し、微細ひび割れが迅速に自己修復されることで、透気性を例に物質移動抵抗性が回復することを実験により確認している。

第6章は、本論文による成果をまとめ、更に今後の展望について述べている。

以上、本論文はより安全な建築物の実現に寄与する新たな複合材料の開発を目的として、Multi-Scale Fiber-Reinforcement System に基づいた材料設計手法を提案し、その有効性を主に実験的な手法により確認したものであり、コンクリート工学の進展に寄与するものである。

よって、本論文は博士（工学）の学位論文として合格と認める。