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学位論文題目	**Development of Self-Healing System in Concrete using Bacillus Subtilis Natto Immobilized in Light Weight Aggregate** **（人工軽量骨材を輸送媒体とした納豆菌によるコンクリートの自己修復システムの開発）**
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論文内容の要旨

Despite many technical improvements, concrete still faces quality degradation problems caused by cracks. Recent studies in concrete materials show that the early cracking criteria in micro-size can occur as soon as the cement matrix becomes hardened. In many ways, these cracks can become macro-size and opened cracks resulting in significant issues for the durability and appearance of concrete structures as water leakage and corrosion. Many approaches have been studied more extensively, meeting the criteria and realizing that management should be better than preventing the cracks in concrete. The technique of self-healing using bacteria has recently received attention for its potential applications. With the ability to be easily cultured and form $CaCO_3$, the potential to use *Bacillus subtilis* natto in the full-scale application is very promising. However, the effectiveness and the repeatability of this method over a long period have not been clarified. The information on both the survival and the number of bacteria after healing is limited. This study aims to improve the self-healing ability and repeatability of concrete when using

Bacillus subtilis natto and clarify the bio-mineralization with the effects of nutrient-low medium to find a suitable way to protect and maintain the self-healing ability in a long time. The high survival rate of bacteria immobilized in lightweight aggregate gave essential information for maintaining self-healing ability for a long time.

The experimental studies evaluate the effect of biomineralization with lightweight aggregate as the protecting-carrying vehicle, which can control the release of healing fluid through four cracking-healing cycles. The urease activity and the biomineralization of the bacteria with urea as the primary carbon source were assessed. We studied the effect of cracking age on the self-healing capacity, associated with the compressive strength improvement. We used the value of 90 % of 7-day compressive strength to create the crack. The self-healing effect was expected to occur over curing time (7, 14, 28, and 60 days). The recovery of the compressive strength of concrete specimens can translate into the self-healing efficiency, and then gives information about the relation between self-healing capacity and curing time. The results obtained from the optical microscope and SEM/EDS/XRD analysis indicated the existence of bacteria $CaCO_3$ forming in concrete after four healing cycles. During a long duration, bacterial concentration in concrete was determined by the microscopic counting method. Based on experimental results, the compressive strength restoration confirmed the high self-healing ability of concrete when using bacteria in lightweight aggregate.

The experimental results demonstrated that *Bacillus subtilis* natto could produce urease enzyme to break down urea in the hash condition of organic carbon source. This bacteria to form $CaCO_3$ through the biomineralization process after 7 days inside the lightweight aggregate was confirmed. Combining bacteria and nutrients in lightweight aggregate was an effective technique to control the release of healing fluid without adverse effects on setting and hardening properties. By image-analysis, crack healing capacity could reach 95 % after 90 days for the crack less than 0.5 mm. Water permeability was significantly lower in the continuous water flow test than the reference. Also, *Bacillus subtilis* natto can survive to maintain its ability to form healing products for at least 7 months after 3 cycles of cracking-healing. The use of *Bacillus subtilis* natto immobilized in lightweight aggregate is a technique with reasonable manufacturing costs without environmentally unfriendly chemicals in producing the repairing materials. Experimental results add to the understanding of the bio-mineralization of *Bacillus subtilis* natto in self-healing concrete.

論文審査の結果の要旨

本論文では、学長からの審査付託を受けて、標記 6 名の審査委員で構成する審査委員会を組織し、提出された学位論文について審査を行った。

審査委員会においては、学位申請者から、学位論文の内容や前回審査における指摘事項の対応結果について説明させ、その後、質疑応答を実施することで、博士論文として満たすべき条件や必要な修正点を確認するという形式で進めた。

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Experimental results add to the understanding of the bio-mineralization of *Bacillus subtilis* natto in self-healing concrete.

第 1 回審査では，学位申請者から学位論文の概要について説明があり，学位論文の内容について発表を行い，研究の独自性や自己修復メカニズムに関する指摘を行った。

第 2 回審査では，第 1 回審査における指摘事項の対応結果について説明があり，それらを受けた内容についての発表を行った。

第 3 回審査では，公聴会を兼ねて実施し，第二回審査での指摘事項の対応を含めて発表を行った。発表内容は指摘事項に適切に沿うものであり，内容として問題のないことを確認した。

以上により，本論文が博士（工学）の学位論文として，十分に価値あるものと認められる。