ISSN: 2710-0588

Study on the Mineralization Modification of Recycled Coarse Aggregate by Bacillus pasteurii and the Performance of Recycled Concrete

Sheng Fu[1], Yuwen Feng[2]

[1] School of Green Mining and Resource Engineering, Liaoning Petrochemical University, Fushun 113001, China

[2] School of Green Mining and Resource Engineering, Liaoning Petrochemical University, Fushun 113001, China

Abstract

Recycled aggregate concrete is an important approach for realizing the resource utilization of construction waste and alleviating the shortage of natural aggregates [1,2,4]. However, the engineering application of recycled coarse aggregate is severely limited by adhered old mortar, high porosity, and high water absorption [3-6]. In this study, microbially induced calcium carbonate precipitation (MICP) using Bacillus pasteurii was adopted to modify recycled coarse aggregate [7,13]. The optimal mineralization process was determined through single-factor tests, and the mechanical properties of modified recycled concrete with different replacement ratios were investigated at a fixed water-cement ratio of 0.45. In addition, the deformation and crack propagation behavior during the whole compression process was analyzed by digital image correlation (DIC). The results showed that the bacterial solution cultured for 24 h exhibited the best mineralization activity [9]. The optimum modification effect was achieved at a Ca2+ concentration of 0.50 mol/L, a urea concentration of 0.50 mol/L, and a mineralization duration of 7 d [16,19,20]. Under this condition, the water absorption of recycled coarse aggregate decreased by 46.72%, while the apparent density and bulk density increased significantly. Compared with unmodified recycled concrete, both the compressive strength and splitting tensile strength of the modified concrete were obviously improved at all replacement ratios [15,17-19]. The best comprehensive performance was obtained at a recycled aggregate replacement ratio of 50%, at which the 28 d compressive strength reached 37.62 MPa. The DIC results indicated that microbial mineralization modification effectively delayed local strain concentration, inhibited the early initiation and rapid propagation of interface cracks, and transformed the failure mode of concrete from brittle failure to quasi-ductile failure [10,12-15]. The results can provide theoretical support and technical reference for the green modification and engineering application of recycled concrete.

Keywords

Recycled coarse aggregate, Bacillus pasteurii, microbially induced calcium carbonate precipitation, mechanical properties, digital image correlation.

1. Introduction

With the continuous acceleration of urbanization, a large amount of waste concrete is generated during building demolition and renewal. If it cannot be effectively recycled, it will not only occupy considerable land resources, but also cause environmental pollution and resource waste. Producing recycled coarse aggregate from waste concrete through crushing and screening, and then using it to partially or completely replace natural aggregate in concrete, is

ISSN: 2710-0588

an important way to realize the high-value utilization of construction and demolition waste [1,2,4]. However, recycled coarse aggregate usually contains a large amount of adhered old mortar and numerous pores and microcracks, resulting in high water absorption, high crushing index, and a weak interfacial transition zone [3-6]. Consequently, recycled concrete generally exhibits lower strength, poorer deformation compatibility, and inferior durability than ordinary concrete [3,5,6].

To improve the quality of recycled aggregate, researchers have proposed various physical, chemical, and combined modification methods [1,4]. Physical methods, such as mechanical grinding, thermal treatment, and microwave treatment, can remove adhered old mortar to some extent, but they often involve high energy consumption and may induce new cracks. Chemical methods, such as acid treatment, silane impregnation, and cement slurry coating, can improve aggregate surface properties, but they may also suffer from high cost, complex processes, and environmental risks. Compared with these methods, microbially induced calcium carbonate precipitation (MICP) has attracted increasing attention in recycled aggregate modification because of its mild reaction conditions, environmental friendliness, and good compatibility between the precipitated products and cement-based materials [7,13].

Bacillus pasteurii possesses strong urease activity and can hydrolyze urea to produce carbonate ions, which further react with Ca^{2+} to form calcium carbonate crystals [8,9,11,13]. The generated calcium carbonate can fill the pores and microcracks on the surface and inside recycled aggregate, improve aggregate compactness, and enhance the interfacial bonding between aggregate and fresh mortar [10,12-15]. Previous studies have shown that MICP can effectively reduce the water absorption of recycled aggregate and improve the mechanical properties of recycled mortar or recycled concrete [14-20]. For example, Grabiec et al. [14] and Wu et al. [15] confirmed the feasibility of calcium carbonate biodeposition for improving recycled concrete aggregate, while Zhao et al. [16], Feng et al. [18], Ma et al. [19], and Zhang et al. [20] further optimized treatment parameters and clarified the factors affecting the modification effect. In addition, Sahoo et al. [17] demonstrated that bacteria-based treatment could significantly enhance the properties of recycled coarse aggregate concrete.

However, the performance evolution of modified recycled concrete with different recycled aggregate replacement ratios under a fixed water-cement ratio, especially the local deformation and crack propagation behavior during the entire compression process based on DIC, has not been sufficiently studied [16,18,19]. Therefore, in this work, recycled coarse aggregate was modified by Bacillus pasteurii through microbial mineralization. The suitable mineralization parameters were determined by single-factor tests. Modified recycled concrete with different recycled aggregate replacement ratios was then prepared at a water-cement ratio of 0.45, and its compressive strength and splitting tensile strength were systematically tested. Meanwhile, DIC technology was used to analyze the strain evolution and crack propagation during the whole compression process, so as to reveal the strengthening mechanism of microbial mineralization modification on recycled concrete.

2. Experimental Program

2.1. Materials

2.1.1. Concrete raw materials

P·O 42.5 ordinary Portland cement was used in this study. The water-cement ratio of all concrete mixtures was fixed at 0.45. Medium sand with a fineness modulus of 2.79 was used as the fine aggregate. Two types of coarse aggregate were used: natural coarse aggregate with a continuous grading of 5-20 mm, and recycled coarse aggregate modified by Bacillus pasteurii with the same particle size range. The dosage of water reducer was 0.5% of the mass of cementitious materials, and tap water was used for mixing.

ISSN: 2710-0588

The recycled coarse aggregate was obtained from waste C30-C40 concrete blocks supplied by Huizhou Xinzhitong Construction Development Co., Ltd. After crushing and screening, the recycled aggregate was tested according to GB/T 14685-2022, and its water absorption was 6.10%. To ensure the comparability of the test results, all recycled coarse aggregate was washed, sieved, and oven-dried before use.

2.1.2. Microorganism and cultivation

The microorganism used in this study was Bacillus pasteurii, an aerobic Gram-positive bacterium with strong urease activity and one of the most commonly used functional strains in MICP technology [7,9,13]. Bacterial activation and cultivation were carried out under sterile conditions to ensure cell activity and subsequent mineralization performance. The composition of the liquid culture medium is listed in Table 1. After preparation, the culture medium was sterilized in an autoclave at 121 °C for 30 min. After cooling to room temperature, inoculation was performed. The inoculated medium was then cultivated in a constant-temperature shaker at 30 °C and 140 r/min for 24 h.

Table 1. Components of LB medium

Nutrient	Content (g/L)
Tryptone	10
Yeast extract	10
Sodium chloride	5

2.2. Aggregate modification

A combined process of vacuum negative-pressure adsorption and immersion mineralization was adopted to modify the recycled coarse aggregate by MICP, considering previous studies on bio-deposition treatment and process optimization for recycled aggregates [14-16,19,20]. Specifically, 5 kg of washed and dried recycled coarse aggregate was placed in a vacuum desiccator. Then, 500 mL of active bacterial solution cultured for 24 h was uniformly sprayed onto the aggregate. After that, a vacuum pump was used to maintain the internal pressure at approximately 0.06 MPa below atmospheric pressure for 30 min, so as to remove the air in the aggregate pores and promote bacterial penetration and adsorption inside the aggregate.

Subsequently, the aggregate was immersed in the mineralization solution with a urea concentration of 0.5 mol/L and a Ca^{2+} concentration of 0.5 mol/L, which is within the commonly adopted range in MICP-related optimization studies [9,16,19,20]. To investigate the effect of mineralization duration on modification performance, four durations of 3 d, 5 d, 7 d, and 9 d were set based on previous treatment-regime studies [16,19]. The aggregate was turned over every 48 h to improve the uniformity of mineral deposition and ensure sufficient reaction.

2.3. Concrete preparation and testing

According to previous studies, key factors affecting recycled concrete include water-binder ratio, recycled aggregate replacement ratio, and the dosage of active admixtures [1-6]. In this study, unmodified recycled aggregate concrete was used as the control group. Concrete specimens with replacement ratios of 0%, 25%, 50%, 75%, and 100% were prepared at a fixed water-cement ratio of 0.45. The specimen size was 100 mm × 100 mm × 100 mm, and all specimens were cured under standard conditions for 28 d. The compressive strength and splitting tensile strength were tested according to GB/T 50081-2019. A VIC-3D non-contact measurement system based on DIC was used to record the full-field strain and crack propagation path of the specimens during compression.

ISSN: 2710-0588

Table 2. Concrete mix proportions

Mix ID	Cement (kg/m³)	Water (kg/m³)	Sand (kg/m³)	Natural coarse aggregate (kg/m³)	Recycled coarse aggregate (kg/m³)	Water reducer (kg/m³)
N0-45	378	170	740	1112	0	1.9
R25-45 B-25-45	378	170	740	834	278	1.9
R50-45 B50-45	378	170	740	556	556	1.9
R75-45 B75-45	378	170	740	278	834	1.9
R100-45 B100-45	378	170	740	0	1112	1.9

3. Results and Discussion

3.1. Growth characteristics of Bacillus pasteurii

The growth state of Bacillus pasteurii directly affects its urease activity and subsequent mineralization performance. The experimental results showed that when the bacterial solution was cultured for 24 h, both the OD_{600} value and urease activity reached relatively high levels, indicating that the bacterial population was sufficient and the metabolic activity was strong at this stage. Therefore, the bacterial solution cultured for 24 h was selected as the active solution for recycled coarse aggregate modification in this study in order to balance mineralization performance and treatment efficiency, see Figure 1.

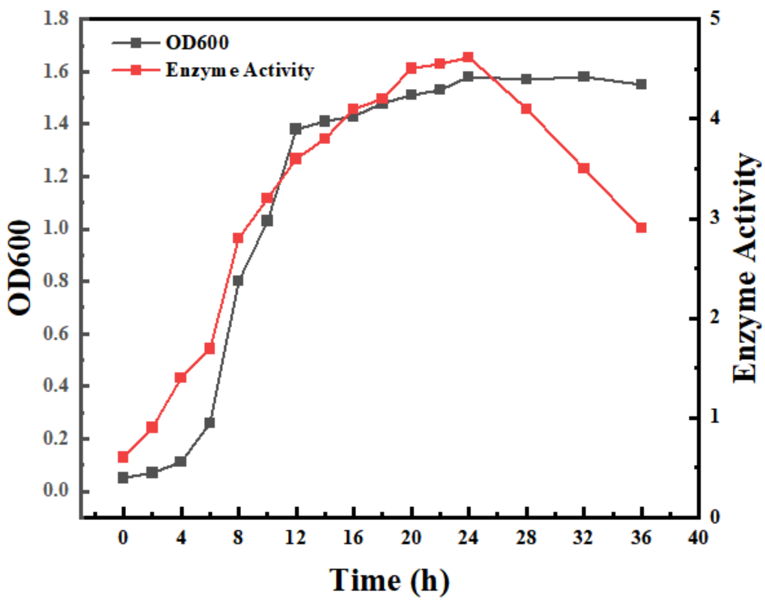

Figure 1. Growth curve of Bacillus pasteurii

3.2. Modification effect of recycled coarse aggregate

Table 3 presents the performance indicators of recycled coarse aggregate under different mineralization durations. As the mineralization duration increased, all performance indicators generally showed a trend of first improving and then becoming stable or slightly decreasing.

ISSN: 2710-0588

This indicates that the calcium carbonate precipitated by Bacillus pasteurii had a significant filling and repairing effect on the surface and internal pores of the aggregate.

Compared with the unmodified group, the mass gain ratio of the modified aggregate continuously increased and reached a maximum value of 5.25% at 7 d, indicating that the amount of calcium carbonate deposition was the highest at this stage. Meanwhile, the water absorption decreased from 6.10% to 3.25%, corresponding to a reduction of 46.72%, demonstrating that the mineralization products effectively blocked the connected pores on the surface and inside the aggregate and significantly weakened its water absorption capacity. Due to pore filling and structural densification, both the apparent density and bulk density increased with increasing mineralization duration, reaching 2640 kg/m^3 and 1372 kg/m^3 at 7 d, which were 5.18% and 7.19% higher than those of the unmodified group, respectively.

When the mineralization duration was further extended to 9 d, the mass gain ratio, water absorption, apparent density, and bulk density all showed slight fluctuations. This suggests that the mineralization reaction had gradually approached saturation, and further extension of the treatment duration had a limited effect on performance improvement. In addition, slight dissolution of the local deposition layer may have occurred due to substrate depletion or environmental changes. Therefore, under the present test conditions, the optimum modification parameters were a Ca^{2+} concentration of 0.5 mol/L, a urea concentration of 0.5 mol/L, and a mineralization duration of 7 d.

Table 3. Presents the performance indicators of recycled coarse aggregate under different mineralization durations.

Mineralization duration	Mass gain ratio (%)	Water absorption (%)	Apparent density (kg/m^3)	Bulk density (kg/m^3)
C0	—	6.10	2510	1280
C1	2.15	4.80	2557	1315
C2	3.40	4.45	2593	1338
C3	5.25	3.25	2640	1372
C4	4.90	3.45	2632	1366

3.3. Mechanical properties of modified recycled concrete

At a water-cement ratio of 0.45, the variation trends of compressive strength and splitting tensile strength of recycled concrete with different replacement ratios were basically consistent. Both strengths generally decreased with increasing recycled aggregate replacement ratio, but the modified groups exhibited significant improvement compared with the corresponding unmodified groups.

As shown in Figure 2, when the replacement ratio was 0%, the compressive strength of the modified group was the same as that of the unmodified group, and the 28 d compressive strength of natural aggregate concrete was 42.5 MPa. With increasing recycled aggregate replacement ratio, the compressive strength of the unmodified group decreased obviously, whereas the reduction in the modified group was relatively moderate, indicating that MICP treatment effectively improved the surface properties of recycled aggregate and enhanced the bonding performance between aggregate and cement paste. When the replacement ratio was 50%, the compressive strength of the modified group reached 37.62 MPa, which was 24.16% higher than that of the unmodified group (30.3 MPa), satisfying the requirement of C30 structural concrete. When the replacement ratio was 25%, the compressive strength of the modified group was even higher than that of the natural aggregate control group, suggesting that a proper amount of modified recycled aggregate can not only replace part of the natural aggregate, but also improve the overall load-bearing capacity of concrete through interface

ISSN: 2710-0588

optimization and internal densification. As the replacement ratio further increased, although microbial modification significantly improved the quality of recycled aggregate, the defects of adhered old mortar and weak interfaces introduced by a high proportion of recycled aggregate could not be completely eliminated, and thus the overall compressive strength still decreased.

As shown in Figure 3, the variation trend of splitting tensile strength was basically the same as that of compressive strength. With increasing recycled aggregate replacement ratio, the splitting tensile strength of all groups decreased, but the modified groups were always higher than the corresponding unmodified groups, indicating that microbial mineralization modification had a positive effect on improving interfacial bonding and crack resistance. When the replacement ratio was 50%, the splitting tensile strength of the modified group reached 2.72 MPa, which was 30.77% higher than that of the unmodified group (2.08 MPa). This demonstrates that calcium carbonate precipitation effectively filled the surface pores of recycled aggregate and strengthened the interfacial transition zone, thereby alleviating the weak interface problem of recycled aggregate. Based on the compressive and splitting tensile test results, the modified recycled concrete with a replacement ratio of 50% exhibited the best overall mechanical performance.

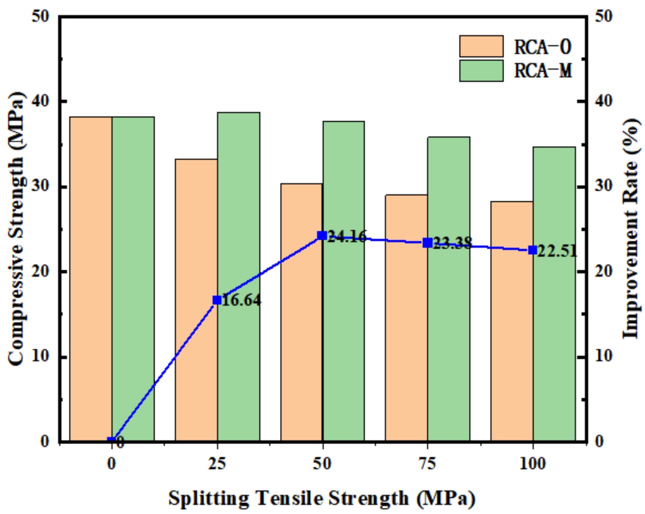

Figure 2. Compressive strength and compressive strength improvement ratio.

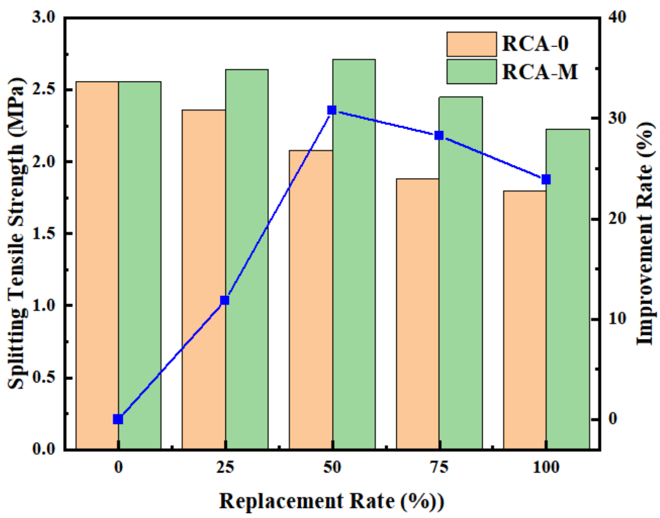

Figure 3. Splitting tensile strength and splitting tensile strength improvement ratio.

ISSN: 2710-0588

3.4. Compressive deformation and crack propagation based on DIC

To reveal the influence of microbial modification on the deformation compatibility and crack propagation behavior of recycled concrete during the whole compression process, DIC technology was employed to monitor the full-field strain of unmodified and modified recycled concrete specimens. The results showed that obvious local strain concentration occurred in unmodified recycled concrete at the early stage of loading. The strain was mainly distributed at the specimen corners and the interfacial transition zone between recycled aggregate and fresh mortar, reflecting poor internal deformation compatibility caused by adhered old mortar, abundant pores, and weak interfacial bonding of recycled aggregate. As the load increased, the strain concentration zones continuously expanded along the interfaces and gradually connected with each other. Cracks developed from local initiation to penetrating main cracks, and finally propagated rapidly along the interfaces, leading to the overall instability of the specimen and exhibiting typical brittle failure characteristics.

In contrast, the modified recycled concrete exhibited a more uniform strain distribution and a slower crack propagation process during loading. Only a small number of scattered strain concentration zones appeared in the early loading stage, and the concentration degree was significantly lower than that of the unmodified group. With increasing load, the expansion of the strain concentration bands was relatively slow, the initiation of cracks was significantly delayed, and the formation of main cracks was more gradual. The crack path was more tortuous and dispersed, and no rapid penetration along a single interface was observed. The overall behavior showed better deformation compatibility and quasi-ductile failure characteristics. The reason is that the calcium carbonate precipitated by Bacillus pasteurii effectively filled the pores and microcracks on the surface and inside the recycled aggregate, improved the structure of the interfacial transition zone between aggregate and fresh mortar, and enhanced the interfacial bonding performance, thereby suppressing local strain concentration and early crack propagation. The DIC results are consistent with the macroscopic mechanical test results, further confirming that microbial mineralization modification can significantly improve the crack resistance and deformation compatibility of recycled concrete under compression.

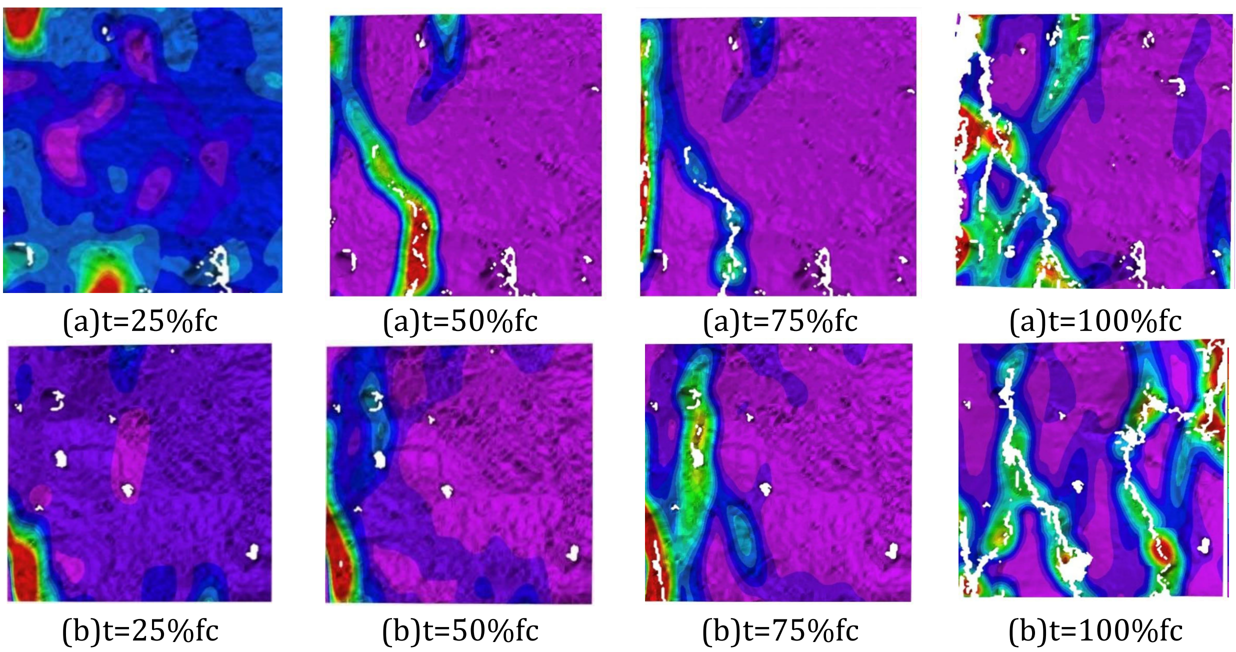

Figure 4. Principal strain contour maps of specimens at different loading stages.

ISSN: 2710-0588

4. Conclusion

(1) The MICP modification by Bacillus pasteurii can significantly improve the physical properties of recycled coarse aggregate. Under a Ca2+ concentration of 0.50 mol/L and a urea concentration of 0.50 mol/L, the optimum mineralization duration was 7 d. Under this condition, the water absorption of recycled coarse aggregate decreased to 3.25%, representing a reduction of 46.72%, while the apparent density and bulk density increased to 2640 kg/m³ and 1372 kg/m3, respectively.

(2) At a water-cement ratio of 0.45, microbial mineralization modification can obviously improve the compressive strength and splitting tensile strength of recycled concrete. Although the overall strength decreased with increasing recycled aggregate replacement ratio, the reduction in the modified groups was significantly alleviated. The best comprehensive performance was obtained at a replacement ratio of 50%, where the 28 d compressive strength reached 37.62 MPa, meeting the requirement of C30 structural concrete.

(3) The DIC results indicated that unmodified recycled concrete exhibited early local strain concentration during compression, and cracks rapidly propagated along the recycled aggregate-fresh mortar interface, showing obvious brittle failure characteristics. After microbial mineralization modification, the internal strain distribution became more uniform, strain concentration was significantly delayed, interface crack propagation was suppressed, and the failure mode changed from brittle failure to quasi-ductile failure.

(4) The mineralization modification technique using Bacillus pasteurii has the advantages of being green, low-consumption, and highly effective in enhancement, and can provide technical support for the high-value utilization of recycled aggregate and the engineering application of recycled concrete.

Acknowledgements

Natural Science Foundation.

References

[1] D. Peiris, C. Gunasekara, W.D. Law, et al.: *Impact of Treatment Methods on Recycled Concrete Aggregate Performance: A Comprehensive Review*, Environmental Science and Pollution Research, Vol. 32 (2025) No.24, p.1..

[2] N. Mao, J. Zheng, J. Jiang, et al.: *Utilization of Construction and Demolition Waste in Concrete as Cement and Aggregate Substitute: A Comprehensive Study on Microstructure, Performance, and Sustainability*, Sustainability, Vol. 17 (2025) No.22, p.10135.

[3] Y.X. Zhao and H.R. Zhang: *Integrated Interface Parameters of Recycled Aggregate Concrete*, Construction and Building Materials, Vol. 101 (2015), p.861.

[4] N. Kisku, H. Joshi, M. Ansari, et al.: *A Critical Review and Assessment for Usage of Recycled Aggregate as Sustainable Construction Material*, Construction and Building Materials, Vol. 131 (2017), p.721.

[5] C.S. Poon, Z.H. Shui and L. Lam: *Effect of Microstructure of ITZ on Compressive Strength of Concrete Prepared with Recycled Aggregates*, Construction and Building Materials, Vol. 18 (2004) No.6, p.461.

[6] J.H. Sinduja, P. Thamilselvi, A. Siva, et al.: *A Study on Mechanical and Microstructural Characteristics of Concrete Using Recycled Aggregate*, Materials, Vol. 15 (2022) No.21, p.7535.

[7] N.U. Wilson, S.A. Abdullahi, A.M. Adisa, et al.: *Microbial Induced Calcite Precipitation on Macrostructural Properties of Concrete: A Review*, Journal of Infrastructure Preservation and Resilience, Vol. 6 (2025) No.1, p.42.

[8] S. Görgen, K. Benzerara, F. Skouri-Panet, et al.: *The Diversity of Molecular Mechanisms of Carbonate Biomineralization by Bacteria*, Discover Materials, Vol. 1 (2021) No.1, p.1.

[9] S.M.C., J.M.T., A.J.M., et al.: *Microbially Induced Calcium Carbonate Precipitation by Bacillus pasteurii: A Case Study in Optimizing Biological CaCO3 Precipitation*, Applied and Environmental Microbiology, Vol. 89 (2023) No.8, p.e0179422.

[10] V. Achal, A. Mukherjee and M.S. Reddy: *Microbial Concrete: Way to Enhance the Durability of Building Structures*, Journal of Materials in Civil Engineering, Vol. 23 (2010) No.6, p.730.

[11] A. Boquet, A. Boronat and A. Ramos-Cormenzana: *Production of Calcite (Calcium Carbonate) Crystals by Soil Bacteria Is a General Phenomenon*, Nature, Vol. 246 (12973) No.5431, p.527.

[12] S.K. Ramachandran, V. Ramakrishnan and S.S. Bang: *Remediation of Concrete Using Microorganisms*, ACI Materials Journal, Vol. 98 (2001) No.1, p.3.

[13] W. De Muynck, N. De Belie and W. Verstraete: *Microbial Carbonate Precipitation in Construction Materials: A Review*, Ecological Engineering, Vol. 36 (2009) No.2, p.118.

[14] A.M. Grabiec, J. Klama, D. Zawal, et al.: *Modification of Recycled Concrete Aggregate by Calcium Carbonate Biodeposition*, Construction and Building Materials, Vol. 34 (2012), p.145.

[15] C.R. Wu, Y.G. Zhu, X.T. Zhang, et al.: *Improving the Properties of Recycled Concrete Aggregate with Bio-Deposition Approach*, Cement and Concrete Composites, Vol. 94 (2018), p.248.

[16] Y.X. Zhao, L.G. Peng, Z.Y. Feng, et al.: *Optimization of Microbial Induced Carbonate Precipitation Treatment Process to Improve Recycled Fine Aggregate*, Cleaner Materials, Vol. 1 (2021), p.100003.

[17] A. Sahoo, et al.: *Enhancement of Properties of Recycled Coarse Aggregate Concrete Using Bacteria*, International Journal of Smart and Nano Materials, Vol. 7 (2016) No.1, p.22.

[18] Z. Feng, Y. Zhao, W. Zeng, et al.: *Using Microbial Carbonate Precipitation to Improve the Properties of Recycled Fine Aggregate and Mortar*, Construction and Building Materials, Vol. 230 (2020), p.116949.

[19] T. Ma, L. Peng, K. Yang, et al.: *Optimizing Microbial- and Enzyme-Induced Carbonate Precipitation Treatment Regimes to Improve the Performance of Recycled Aggregate Concrete*, Case Studies in Construction Materials, Vol. 19 (2023), p.e02261.

[20] J. Zhang, C. Wang and Z. Wang: *Factors Affecting the Physical Properties of Microbial Induced Calcium Carbonate Precipitation Enhanced Recycled Aggregates*, Buildings, Vol. 14 (2024) No.9, p.2851.