International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Performance Evaluation of Local Stone Waste Powder as a Partial Cement Replacement in Concrete under Cold-Region and Freeze–Thaw Conditions

Manjesh Kumar

Assistant Professor, Department of Civil Engineering, Arni University, Researcher Information

Abstract

The rapid growth of construction and stone-processing activities has resulted in the generation of considerable quantities of stone waste powder. Improper disposal of this fine waste can create environmental and land-management problems. At the same time, cement production is associated with significant consumption of natural resources and greenhouse-gas emissions. The partial replacement of cement with suitable stone waste powder therefore offers a potential approach toward more sustainable concrete production.

This study proposes an experimental investigation into the use of locally available stone waste powder as a partial replacement for cement in concrete intended for cold-region applications. Concrete mixtures will be prepared by replacing cement with stone waste powder at selected proportions of 0%, 5%, 10%, 15%, and 20% by mass. The control and modified mixtures will be evaluated for workability, density, compressive strength, split tensile strength, water absorption, and ultrasonic pulse velocity. In addition, specimens will be subjected to controlled freeze–thaw exposure to assess changes in mechanical and durability performance. Strength retention, mass change, water absorption, and surface deterioration will be used to evaluate resistance to repeated freezing and thawing.

The study aims to determine an optimum replacement level at which local stone waste powder can provide acceptable concrete performance while reducing cement consumption and utilizing locally generated waste. The findings may contribute to the development of more sustainable concrete suitable for construction in cold and mountainous regions.

Keywords: Stone waste powder, cement replacement, sustainable concrete, cold-region concrete, freeze–thaw, compressive strength, durability.

1. Introduction

Concrete is one of the most widely used construction materials in the world because of its high compressive strength, durability, availability, and versatility. However, conventional concrete has significant environmental impacts, particularly because cement production requires considerable energy and is associated with substantial carbon dioxide emissions.

At the same time, stone-cutting, crushing, and processing industries generate large quantities of fine stone waste. This waste is frequently dumped on open land or disposed of without adequate management. Such disposal can occupy land and may create environmental problems.

The utilization of stone waste powder in cement-based materials has therefore attracted considerable research interest. Depending on its mineralogical composition, particle size, fineness, and replacement percentage, stone powder can influence the workability, packing density, strength, and durability of concrete.

Cold-region construction introduces an additional challenge. Concrete exposed to repeated freezing and thawing may experience internal cracking, surface scaling, loss of stiffness, increased permeability, and reduction in mechanical strength. The severity of freeze–thaw deterioration depends on factors such as pore structure, water saturation, air entrainment, temperature range, number of cycles, and concrete composition.

Therefore, simply demonstrating that stone waste powder can replace cement under normal laboratory conditions is insufficient for cold-region applications. Its behavior under low-temperature and repeated freeze–thaw exposure must also be evaluated. This research proposes an experimental study combining local stone waste utilization and cold-region durability assessment.

2. Problem Statement

Stone-processing activities generate significant quantities of stone powder. Although this material may have potential for use in concrete, uncontrolled disposal remains a waste-management concern. On the other hand, cold and mountainous regions experience low temperatures and, in some locations, repeated freezing and thawing. Concrete structures in such environments require adequate durability. The major research problem can therefore be stated as:

"Can locally available stone waste powder be used as a partial replacement for cement without causing unacceptable reductions in concrete strength and freeze–thaw durability?"

3. Research Gap

Previous studies have investigated different forms of stone dust, rock powder, marble powder, granite waste, and other mineral wastes as partial replacements for cement or fine aggregate.

However, the performance of a specific locally available stone waste powder under controlled cold-region/freeze–thaw exposure requires site- and material-specific investigation.

The proposed research therefore focuses on locally sourced stone waste, controlled cement replacement levels, mechanical properties, water absorption and permeability-related indicators, freeze–thaw exposure, strength retention, and identification of an optimum replacement level.

The novelty should be stated carefully as a specific combination of material, replacement level, and exposure condition, rather than claiming that stone waste has never previously been used in concrete.

4. Aim

To experimentally evaluate the suitability of locally available stone waste powder as a partial replacement for cement in concrete exposed to cold-region and freeze–thaw conditions.

5. Objectives

1. To characterize the physical and chemical properties of locally available stone waste powder.

2. To prepare concrete containing different percentages of stone waste powder as partial cement replacement.
3. To determine the effect of stone waste powder on workability and density.
4. To evaluate compressive, tensile, and flexural strength of the modified concrete.
5. To investigate water absorption and ultrasonic pulse velocity.
6. To evaluate the effect of freeze–thaw exposure on concrete containing stone waste powder.
7. To determine strength retention and mass loss after freeze–thaw cycles.
8. To identify the optimum percentage of cement replacement.
9. To assess the potential environmental benefit of utilizing local stone waste.

6. Materials

6.1 Cement

6.2 Fine Aggregate

6.3 Coarse Aggregate

7. Local Stone Waste Powder

8. Concrete Mix Proportions

9. Experimental Methodology

8. Fresh Concrete Tests (Slump, Density, Workability)
9. Casting of Specimens
10. Standard Curing
11. Mechanical & Durability Tests
12. Freeze–Thaw Exposure
13. Post Freeze–Thaw Testing
14. Comparison of Results
15. Optimum Replacement Percentage
16. Conclusions & Recommendations

Methodology Flowchart (text version):
Stone Waste Selection → Collection & Cleaning → Drying/Grinding/Sieving → Characterization → Mix Design → M0/M5/M10/M15/M20 → Fresh Tests → Specimen Casting → Standard Curing → Mechanical/Durability Tests → Freeze–Thaw Exposure → Post-Exposure Tests → Comparison → Optimum Replacement → Conclusions.

10. Specimen Preparation

Concrete specimens will be prepared for each mixture. Possible specimens include cubes/cylinders for compressive strength, cylinders for split tensile strength, beams for flexural strength, and suitable specimens for water absorption, UPV, and freeze–thaw testing. The exact number of specimens should be decided based on the adopted testing standard and statistical requirements.

Test	Suggested Specimen
Compressive strength	Cube/cylinder
Split tensile strength	Cylinder
Flexural strength	Beam
Water absorption	Cube
UPV	Cube/cylinder

Freeze–thaw	Cube/prism/cylinder depending on adopted standard

11. Curing

After casting, specimens will be demoulded after the appropriate initial curing period and placed under standard curing conditions. Tests may be conducted at 7, 28, and 56 days. The 28-day result will generally be used as the principal reference for strength comparison.

12. Freeze–Thaw Exposure

Freeze–thaw testing is the key part of the proposed research. Concrete specimens will undergo repeated cycles consisting of freezing and thawing. The exact temperature range, cycle duration, and number of cycles must be selected according to the standard adopted by the laboratory and the available environmental chamber.

Group	Exposure
A	Standard curing
B	Freeze–thaw exposure
C	Freeze–thaw exposure
D	Freeze–thaw exposure

The number of cycles can be selected based on the adopted standard/protocol, for example 50, 100, or another justified number. Do not insert a freeze–thaw cycle number merely because it appears in another paper; it should be justified by the standard or experimental design.

13. Tests on Concrete

13.1 Slump Test

The slump test will be used to evaluate the workability of fresh concrete. Increasing stone powder content may change water demand and workability depending on particle size and surface characteristics.

13.2 Compressive Strength

Compressive strength will be determined using the applicable standard testing procedure.

$f_c = P / A$

Where: f_c = compressive strength; P = maximum applied load; A = loaded cross-sectional area.

Split tensile strength will be measured to evaluate the effect of stone waste powder on tensile behavior.

13.4 Water Absorption

Water absorption can provide an indication of the pore structure and permeability-related behavior of concrete.

$\text{Water Absorption (\%)} = [(W_s - W_d) / W_d] \times 100$

Where: W_s = saturated mass; W_d = dry mass.

14. Freeze–Thaw Strength Retention

One of the most important indicators will be strength retention.

$\text{Strength Retention (\%)} = (f_{after} / f_{before}) \times 100$

Where: f_before = strength before freeze–thaw exposure; f_after = strength after freeze–thaw exposure.

15. Mass Loss

Mass loss can be calculated as:

Mass Loss (%) = [(W0 − Wn) / W0] × 100

Where: W0 = initial mass; Wn = mass after selected freeze–thaw cycles.

16. Surface Deterioration

After freeze–thaw exposure, specimens should be visually examined for surface scaling, cracking, edge deterioration, spalling, aggregate exposure, and powdering. A photographic record should be maintained after selected cycle intervals.

17. Expected Results and Discussion

This section must be completed using actual experimental data. The study will investigate whether moderate stone waste replacement can maintain acceptable mechanical properties while reducing cement content. A possible outcome is that a moderate replacement level performs better than very low or very high replacement levels because of particle packing and filler effects. However, the actual optimum percentage must be established experimentally. Freeze–thaw exposure may reduce compressive strength and increase water absorption due to internal deterioration. The extent of deterioration is expected to depend strongly on the concrete's pore structure, saturation condition, air entrainment, and mix characteristics.

18. Result Comparison Framework

- Stone Waste Replacement (%) vs 28-Day Compressive Strength
- Stone Waste Replacement (%) vs Water Absorption
- Number of Freeze–Thaw Cycles vs Compressive Strength
- Stone Waste Replacement (%) vs Strength Retention
- Stone Waste Replacement (%) vs Mass Loss
- Replacement Percentage vs Cost/Cement Consumption

19. Environmental Benefits

- Reduction in uncontrolled stone-waste disposal.
- Reduction in demand for virgin cement.
- Better utilization of industrial by-products.
- Potential reduction in embodied environmental impacts.
- Promotion of circular-economy principles.
- Reduced transportation requirements if the waste is locally sourced.

A proper life-cycle assessment would be required before making quantitative environmental claims.

20. Economic Benefits

- Reduction in cement consumption.
- Utilization of locally available waste material.

- Reduced waste-disposal costs.
- Potential reduction in transportation costs.
- Development of locally adapted construction materials.

Grinding, sieving, transportation, and processing costs must be included in a proper economic analysis.

21. Potential Applications

- Cold-region buildings
- Rural concrete construction
- Pavement-related concrete applications
- Drainage structures
- Retaining structures
- Non-critical concrete elements
- Mountain-region infrastructure

Actual structural application should follow the relevant design codes and durability requirements.

22. Limitations of the Study

1. Only one local stone type may be investigated.
2. Laboratory freeze–thaw exposure may not exactly reproduce field conditions.
3. The chemical and mineralogical composition of stone waste may vary between sources.
4. Long-term field performance may require additional investigation.
5. Results from one region may not be directly applicable to another region.
6. The optimum replacement percentage may depend on the concrete grade and mix design.

23. Conclusion

This research proposes an experimental investigation of locally available stone waste powder as a partial replacement for cement in concrete exposed to cold-region and freeze–thaw conditions. The study will evaluate the influence of different stone waste replacement percentages on workability, compressive strength, tensile strength, water absorption, ultrasonic pulse velocity, mass loss, and freeze–thaw resistance.

The principal objective is to identify an optimum replacement level that provides an acceptable balance between mechanical performance, durability, waste utilization, and cement reduction. The proposed approach can contribute to sustainable construction by converting locally generated stone waste into a potentially useful concrete constituent. However, the suitability of the material for cold-region construction should ultimately be established through experimental results and comparison with relevant concrete and durability requirements.

24. Future Scope

- Different types of local stone waste.
- Higher and lower replacement percentages.
- Combined use of stone powder and supplementary cementitious materials.
- Air-entrained concrete.
- Longer freeze–thaw exposure.

- Microstructural analysis using SEM.
- XRD and XRF characterization.
- Chloride penetration.
- Sulphate resistance.
- Carbonation.
- Field trials in cold regions.
- Life-cycle assessment.
- Life-cycle cost analysis.
- Machine-learning prediction of concrete performance.

25. References

1. Neville, A. M., Properties of Concrete, Pearson.
2. Mehta, P. K., and Monteiro, P. J. M., Concrete: Microstructure, Properties, and Materials, McGraw-Hill.
3. Mindess, S., Young, J. F., and Darwin, D., Concrete, Prentice Hall.
4. Shetty, M. S., Concrete Technology: Theory and Practice, S. Chand.
5. Bureau of Indian Standards, IS 10262, Concrete Mix Proportioning — Guidelines.
6. Bureau of Indian Standards, IS 456, Plain and Reinforced Concrete — Code of Practice.
7. Bureau of Indian Standards, IS 4031, Methods of Physical Tests for Hydraulic Cement.
8. ASTM International, ASTM C666/C666M, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.
9. Recent peer-reviewed journal studies on stone waste/rock powder as cement replacement should be added after a systematic literature search for the specific stone type selected in the experiment.

Kounadis, A., Sotiriadis, K., Bauerová, P., Antiohos, S., & Badogiannis, E. (2025). Freeze-thaw resistance of self-compacting concrete with marble powder & cement kiln dust filler powders and metakaolin. Low-carbon Materials and Green Construction, 3, Article 34. https://doi.org/10.1007/s44242-025-00094-6

Important Research Note

This document is a research-paper draft and framework. Experimental values must be obtained from actual laboratory testing. Do not insert fabricated results. The final paper should be updated with the selected local stone type, actual mix-design calculations, laboratory observations, statistical analysis, graphs, and verified recent journal references.

Literature-Verified Benchmark Values (For Reference Only)

Important: The numerical values in this section are taken from published studies and are NOT the experimental results of Manjesh Kumar. They are included only as reference benchmarks for designing the experimental programme and discussing your future laboratory results. They must not be presented as your own measured data.

A peer-reviewed 2023 study by Gürgöze, Çelik and Bingöl investigated waste marble powder (WMP) as a partial cement replacement at 5%, 10% and 15% in mortars made with CEM I 42.5R (OPC), white cement (WC) and calcium aluminate cement (CAC). The study used 28-day water curing and ASTM

C666 Procedure A for freeze–thaw exposure, with freezing at -18 °C and thawing at 4 °C. The authors reported that 10% WMP was the appropriate replacement level across the cement types investigated.

Table L1. Published 28-day compressive-strength change relative to control

Cement type	0% WMP	5% WMP	10% WMP	15% WMP
OPC (CEM I 42.5R)	Control	+1.62%	+3.41%	-3.06%
White Cement (WC)	Control	+2.66%	+4.19%	-2.88%
Calcium Aluminate Cement (CAC)	Control	+3.18%	+8.60%	-2.29%

These percentages are reported relative to each study's corresponding control mixture. The 10% WMP mixture showed the largest reported improvement among the three replacement levels for all three cement types; the paper reported a maximum absolute compressive strength of 104.09 MPa for CAC with 10% WMP. These data come from mortar mixtures containing silica fume and therefore should not be copied directly into a concrete results table.

Table L2. Published 28-day flexural-strength change relative to control

Cement type	0% WMP	5% WMP	10% WMP	15% WMP
OPC	Control	+10.23%	+15.67%	Decreased vs 10%
WC	Control	+4.59%	+15.14%	Decreased vs 10%
CAC	Control	+1.15%	+16.30%	Decreased vs 10%

Table L3. Published freeze–thaw findings

Finding	Replacement	Freeze–thaw exposure	Published value
WC-based mortar residual compressive strength	0% WMP	90 cycles	0.880 of pre-exposure reference
WC-based mortar residual compressive strength	5% WMP	90 cycles	0.888 of pre-exposure reference
WC-based mortar residual compressive strength	10% WMP	90 cycles	0.890 of pre-exposure reference
CAC-based mortar compressive-strength loss	0% WMP	60 cycles	16.5%

Finding	Replacement	Freeze–thaw exposure	Published value
CAC-based mortar compressive-strength loss	5% WMP	60 cycles	15.0%
CAC-based mortar compressive-strength loss	10% WMP	60 cycles	10.0%
CAC-based mortar compressive-strength loss	15% WMP	60 cycles	20.1%

The published study also reported that OPC-based mixtures showed strength losses after freeze–thaw exposure, and that the 10% WMP level performed comparatively well within the tested series. Because the study used mortar, three cement types and silica fume, these readings are reference evidence rather than target values for the present concrete research.

How to use these readings in your own experiment

- Use the published values to justify the choice of 5%, 10%, and 15% replacement levels.
- Do your own concrete mix design and laboratory testing for M0, M5, M10, M15 and M20.
- Enter your measured 7-, 28- and 56-day strengths in the experimental-results tables already provided.
- After freeze–thaw exposure, calculate your own strength retention and mass loss using the formulas in the methodology.
- Compare your results with the literature benchmarks, explicitly stating that the materials and test conditions are not identical.

Verified reference added for this benchmark section

Gürgöze, R., Çelik, Z., & Bingöl, A. F. (2023). Mechanical, freeze-thaw, and sorptivity properties of mortars prepared with different cement types and waste marble powder. Journal of Sustainable Construction Materials and Technologies, 8(4), 307–318. https://doi.org/10.47481/jscmt.1361326

Recent context: Kounadis et al. reported an open-access study on freeze–thaw resistance of self-compacting concrete with marble powder, cement kiln dust and metakaolin; the article was published online in 2025. It evaluated fresh properties, compressive strength, water permeability and freeze–thaw resistance, supporting the continued relevance of freeze–thaw durability research.

Filled Literature Benchmark Tables — Verified Published Values

IMPORTANT — DATA STATUS

The numerical values in the tables below are reproduced or calculated from published research studies. They are reference/benchmark values and are NOT laboratory results obtained by Manjesh Kumar. For the present study, waste marble powder (WMP) is used as the reference example for "local stone waste powder" because the user has not yet specified the local stone type. If the actual local stone is granite, sandstone, slate, limestone, etc., its characterization and experimental values must be replaced with measurements from that material.

Table B1. Published material properties used as a reference

Material	Property	Published value	Source
Cement (CEM I 52.50 N)	Specific gravity	3.10	Alhassan et al., Materials (2022)
Cement (CEM I 52.50 N)	Average particle size	20.67 µm	Alhassan et al., Materials (2022)
Fine aggregate (natural river sand)	Specific gravity	2.45	Alhassan et al., Materials (2022)
Fine aggregate (natural river sand)	Water absorption	1.91%	Alhassan et al., Materials (2022)
Fine aggregate (natural river sand)	Fineness modulus	2.23	Alhassan et al., Materials (2022)
Coarse aggregate	Material/nominal size	8 mm crushed limestone	Alhassan et al., Materials (2022)
Local stone waste powder example	Material	Waste marble powder (WMP)	Alhassan et al., Materials (2022)
WMP	Density	2.78 g/cm³	Alhassan et al., Materials (2022)
WMP	Specific gravity	2.67	Alhassan et al., Materials (2022)
WMP	Fineness	350 m²/kg	Alhassan et al., Materials (2022)
WMP	Colour	Light gray	Alhassan et al., Materials (2022)

Table B2. Published concrete mix proportions per 1 m³

Mix	WMP replacement	Cement (kg/m³)	WMP (kg/m³)	SP (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	Water (kg/m³)
M0	0%	500	0	5.00	681	1065	179
M2.5	2.5%	487.5	12.5	4.88	681	1065	179
M5	5%	475	25	4.75	681	1065	179
M7.5	7.5%	462.5	37.5	4.63	681	1065	179
M10	10%	450	50	4.50	681	1065	179

The above mix proportions are directly reported in the 2022 high-strength-concrete study using waste marble powder as cement replacement. The study used 500 kg/m³ total cementitious cement before replacement, 681 kg/m³ natural river sand, 1065 kg/m³ coarse aggregate, and 179 kg/m³ water. These proportions should be treated as literature benchmarks, not as the final mix design for your laboratory work.

Table B3. Published 28-day compressive and split tensile strength

WMP replacement	Cube compressive strength fcu (MPa)	Cylinder compressive strength fc′ (MPa)	Split tensile strength ft (MPa)
0%	70.81	56.70	5.91
2.5%	78.65	62.93	6.68
5%	81.48	65.20	6.90
7.5%	83.11	66.45	7.03
10%	81.25	65.00	6.87

The published study reported the maximum value within its tested series at 7.5% WMP for cube compressive strength (83.11 MPa) and split tensile strength (7.03 MPa). The authors identified 7.5% as the optimum ratio for the tested high-strength concrete system.

Table B4. Published water absorption values

WMP replacement	Water absorption (%)	Source
0%	0.75	Alhassan et al., Materials (2022)
2.5%	1.12	Alhassan et al., Materials (2022)
5%	1.35	Alhassan et al., Materials (2022)
7.5%	1.56	Alhassan et al., Materials (2022)
10%	1.67	Alhassan et al., Materials (2022)

These water-absorption values are specific to the published high-strength concrete test programme and should not be treated as universal target values.

Table B5. Published freeze–thaw residual compressive strength / strength-retention benchmark

Cement system	WMP	Cycles	Relative residual compressive strength	Strength retention (%)	Strength loss (%)
OPC	0%	60	0.941	94.1	5.9
OPC	5%	60	0.942	94.2	5.8
OPC	10%	60	0.940	94.0	6.0
OPC	15%	60	0.930	93.0	7.0
OPC	0%	90	0.893	89.3	10.7
OPC	5%	90	0.892	89.2	10.8
OPC	10%	90	0.891	89.1	10.9
OPC	15%	90	0.864	86.4	13.6

White cement	0%	90	0.880	88.0	12.0
White cement	5%	90	0.888	88.8	11.2
White cement	10%	90	0.890	89.0	11.0

The relative residual strength values above are directly reported in the 2023 freeze–thaw study. Strength-retention and strength-loss percentages are calculated as ratio×100 and (1−ratio)×100, respectively.

Table B6. Published freeze–thaw mass-loss benchmark from a stone-powder composite study

Mix ID	Stone-powder system	Freeze–thaw cycles	Mass loss (%)	Important comparability note
WG100	Waste granite powder + slag + PP-fibre cement-based composite	25	0.69	Granite powder replaced fine aggregate, not cement
WG100	Waste granite powder + slag + PP-fibre cement-based composite	50	1.07	Granite powder replaced fine aggregate, not cement
WG100	Waste granite powder + slag + PP-fibre cement-based composite	100	2.88	Granite powder replaced fine aggregate, not cement
S5M0	Waste marble powder + slag + sawdust prepacked composite	30	2.56	WMP substituted silica sand; not a direct cement-replacement result
S5M0	Waste marble powder + slag + sawdust prepacked composite	60	6.21	WMP substituted silica sand; not a direct cement-replacement result

Mass-loss data are shown separately because a directly matching cement-replacement dataset was not found in the same 2023 WMP freeze–thaw study. The first three values are from a 2026 granite-powder freeze–thaw study; the last two are from a 2025 waste-marble-powder composite study. These values must be cited and described as literature benchmarks rather than as results of the present research.

Table B7. Proposed final experimental-results table for Manjesh Kumar's laboratory work

Mix	WMP %	28-d compressive (MPa)	Split tensile (MPa)	Water absorption (%)	F–T cycles	Strength after F–T (MPa)	Strength retention (%)	Mass loss (%)
M0	0%	To be measured	To be measured	To be measured	To be measured	To be measured	To be measured	To be measured
M5	5%	To be measured	To be measured	To be measured	To be measured	To be measured	To be measured	To be measured
M10	10%	To be measured	To be measured	To be measured	To be measured	To be measured	To be measured	To be measured
M15	15%	To be measured	To be measured	To be measured	To be measured	To be measured	To be measured	To be measured
M20	20%	To be	To be	To be	To be	To be	To be	To be

		measured	measured	measured	measured	measured	measured	measured

This last table is intentionally blank for actual laboratory measurements. It is the table that should contain your own experimental results after testing.

References for Filled Benchmark Tables

1. Alhassan, M. A. et al. (2022). Assessment of Waste Marble Powder on the Mechanical Properties of High-Strength Concrete and Evaluation of Its Shear Strength. Materials, 15(20), 7125. DOI: 10.3390/ma15207125.
2. Çelik, Z., Gürgöze, R., & Bingöl, A. F. (2023). Mechanical, freeze-thaw, and sorptivity properties of mortars prepared with different cement types and waste marble powder. Journal of Sustainable Construction Materials and Technologies, 8(4), 307–318. DOI: 10.47481/jscmt.1361326.
3. Demirtürk, D., Ahıskalı, A., Bayraktar, O. Y., Ahıskalı, M., Kara, H. O., & Kaplan, G. (2026). From geological waste to sustainable infrastructure: Multi-Criteria analysis of granite powder in fiber-reinforced cementitious composites. Physics and Chemistry of the Earth, Parts A/B/C, 142, 104224. DOI: 10.1016/j.pce.2025.104224.
4. Properties of green prepacked composites produced with slag cement: efficient recycling of micronized waste marble powder and waste wood sawdust. Archives of Civil and Mechanical Engineering, 25 (2025), Article 170. DOI: 10.1007/s43452-025-01231-5