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Improving sustainability of precast concrete sandwich wall panels through stone waste aggregates and supplementary cementitious material

Pushpender Kumar [a,b,1], Rajesh Kumar [a,b,2,*], Nikhil Sanjay Nighot [a,c,3], Surabhi [d,4], Mohd. Reyazur Rahman [a,5], R. Siva Chidambaram [a,c,6], Shahnawaz Khan [a,7]

[a] CSIR- Central Building Research Institute, Roorkee, 247667, Uttarakhand, India
[b] IIT Mandi 175075, Mandi, India
[c] Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, 201 002, India
[d] Jawaharlal Nehru Government Engineering College, 175018, Sundernagar, India
[1] pushpender8698@gmail.com; [2] rajeshkumar@cbri.res.in; [3] nikhilnighot1@gmail.com; [4] sharma.surabhi07@gmail.com; [5] reyaz@cbri.res.in; [6] schidambaram@cbri.res.in; [7] Shan.K.cbri.786@gmail.com
* corresponding author

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ABSTRACT

This study aims to enhance the sustainability of precast concrete sandwich wall panels by replacing 100% of natural aggregates with stone waste and 30% of cement with supplementary cementitious materials. The panels, consisting of two 60 mm thick concrete wythes reinforced with 1% steel fibers, were connected using basalt fiber-reinforced polymer (BFRP) connectors and separated by high-density expanded polystyrene (EPS) insulation (30 kg/m³). Full-scale panels were tested for flexural strength, showing that the inclusion of sustainable materials increased the failure load by 96% compared to conventional panels, with steel fiber-reinforced panels achieving a failure load of 110.5 kN. Panels incorporating stone waste aggregates demonstrated a 71% increase in strength compared to control samples. These results highlight that using stone waste and supplementary materials not only improves environmental sustainability but also enhances structural performance, making these panels a viable option for eco-friendly construction.

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1. Introduction

Precast Concrete Sandwich Panels (PCSP) are sustainable and efficient building systems composed of two concrete layers separated by an insulating material, offering several advantages such as design flexibility, ease of installation, costeffectiveness, and energy efficiency owing to the integrated insulation layer [1]–[4]. These panels serve as both load bearing and thermally resistant systems, making them highly suitable for sustainable construction [5]. In this study, the flexural strength of PCSPs was examined to further enhance their sustainability and performance.

Basalt fiber-reinforced polymer (BFRP) connectors were selected for this research because of their lower thermal conductivity compared to traditional steel connectors, which reduces thermal bridging and enhances energy efficiency while also offering high tensile strength at a relatively low cost [6], [7]. To ensure a uniform stress distribution along the interface and minimize premature failure, continuous shear plates were chosen over discrete plates [4]. Expanded Polystyrene (EPS) has been used as an

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insulation material because it provides improved ductility and deformability compared with alternatives such as Extruded Polystyrene (XPS) [8]–[11].

Previous studies have primarily focused on the structural and thermal performance of PCSPs, with limited exploration of the integration of sustainable materials, such as stone waste aggregates and supplementary cementitious materials, to improve both structural and environmental outcomes. The sustainability of the panels is further enhanced by replacing 100% of the natural aggregates with stone waste and substituting 30% of the cement with supplementary cementitious materials. This material substitution, combined with the use of steel fibers and BFRP connectors, is intended to improve the structural performance, particularly in terms of flexural strength and failure load, compared with conventional panels [12]–[14]. By using waste materials, such as marble stone waste, this study emphasizes the potential of creating eco-friendly and high-performance concrete products for modern construction.

2. Method

2.1. Ordinary Portland Cement

Ordinary Portland cement (OPC)-43 grade, per IS: 8112 [15], was obtained from M/s JK Cement Ltd., India, and was used as the main binder for the concrete mix. The chemical composition of the cement was examined using IS 4032, as listed in Table 1, which confirms IS:8112-1989 [16]. The results in Table 1 show that calcium oxide (CaO) was the major oxide present in the OPC binder. The average compressive strength of the JK cement after 28 d was approximately 45 MPa.

Table 1. Chemical composition of JK Cement

Chemical composition	CaO	SiO2	Al2O3	MgO	Fe2O3	K2O	Na2O	LOI	SO3
Percentage (%)	60.59	21.32	5.72	2.27	3.60	0.90	0.45	3.5	2.64

2.2. Stone Waste

Marble waste refers to leftover pieces, dust, and slurry generated as byproducts during the manufacturing, processing, and installation of marble products [17]. Marble waste is increasingly utilized in various construction applications to enhance sustainability and reduce environmental impacts [18], [19]. In this work, marble stone waste sourced from Udaipur, Rajasthan, was utilized. Various tests were conducted on marble aggregate under the specifications outlined in the Indian Standard code IS 2386 [20], as shown in Table 2.

Table 2. Different test values of marble aggregate

Parameters	Marble Agg.
Aggregate Impact Value (IS: 2386(IV)-93)	23
Aggregate Abrasion Value (IS: 2386(IV)-63)	11.54
Aggregate Crushing Value (IS: 2386(IV)-63)	31.35
Water Absorption (%)	0.85
Bulk Specific Gravity (SSD)	2.70
Bulk Density (kg/m3)	1,740

2.3. Fine Aggregate

The fine aggregate used in this investigation was very fine grade local river sand collected from a nearby location in the Solani River, Roorkee. The river sand specifications conform to Indian Standard BIS383 [21]. The fineness modulus of sand was 1.13, indicating a very fine gradation.

2.4. Steel Fiber

Strength of brittle material according to Griffith's theory :

$$\sigma = \sqrt{\frac{2E\gamma}{\pi c}} \tag{1}$$

And $\sigma \uparrow = c \downarrow$

Where
c= crack width

σ = tensile strength

According to Equation 1, when the crack width decreases, the tensile strength increases. Introducing steel fibers to reduce the crack width can enhance the tensile strength of brittle materials. Hooked-end steel was used in the self-compacting concrete. The hooked-end geometry shown in Fig. 1 provided better fiber-matrix interfacial bonding and bridging compared to the deformed crimped shape, leading to greater improvements in strength and impact resistance [22].

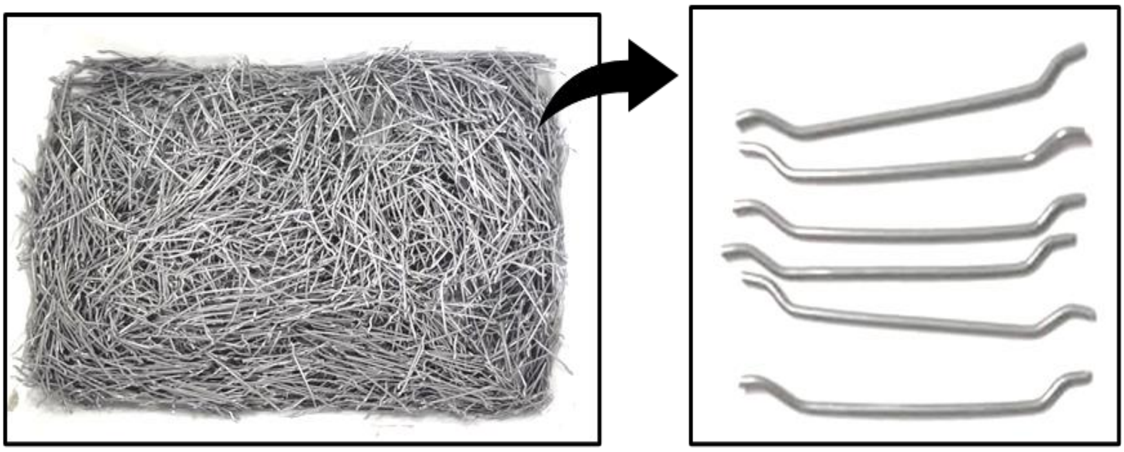

Fig. 1. Hooked-end steel fiber

The specifications of the discrete hooked-end steel fibers for concrete reinforcement are listed in Table 3.

Table 3. Different parameters for steel fiber selection [23]–[25]

Parameters	Recommendation	Adopted
Shape	Straight, End hooked, Crimped	Hooked end
Length	20 to 60mm	40mm
Diameter	0.2 – 1.0mm	1.0mm
Aspect ratio (L/D)	30-100	40
Steel fiber content	0.5% - 2.0%	1.0%
Orientation	Continuous, Discrete	Discrete

2.5. Superplasticizer

Poly(carboxylate ether)-based superplasticizers were a type of admixture used in concrete at dose of 0.8% of binder to improve its workability and rheological properties.

2.6. Fly Ash

The fly ash employed in this experiment conformed to the Indian Standard IS 3812: Part 1 [26], [27]. The fly ash applied was Class F (siliceous sort) and heavy in alumina. It was supplied by the Dadri Power Plant of NTPC, Gautam Buddh Nagar, in Uttar Pradesh. A detailed characteristic of the fly ash size distribution was obtained using a Horiba Laser particle size analyzer. The results obtained using this technique are presented in Table 4.

Table 4. Chemical composition of fly ash

Chemical composition	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	Loss on ignition	Free CaO
Percentage (%)	63.21	27.65	5.24	1.46	0.83	0.40	0.60	-

2.7. Expanded Polystyrene (EPS)

The EPS sheet purchased from the market underwent mechanical tests in the CSIR-CBRI laboratory following IS 4671:1984 [28]. The results of these tests are presented in Table 5.

Table 5. Mechanical property of EPS sheet

Characteristics	Results	Criteria	Test method
Bulk density (kg/m3)	30	≥15	IS 5688: 1984
Compressive strength @ 10%strain (MPa)	0.41	≥0.14	IS 4671: 1984

2.8. Basalt Fiber Connector

BFRP connectors are less stiff than steel connectors, but can offer comparable tensile capacities for moderate diameters of approximately 6 mm, as indicated by [7]. Additionally, basalt fibers were chosen for BFRP connectors because of their good mechanical properties, which are comparable to those of other FRP materials such as glass or carbon fibers, but at a relatively lower cost [6]. This increases the impact resistance and improves the post-cracking energy-absorption capacity [21]. A basalt fiber mesh placed 110 mm from the EPS sides was used, as shown in Fig. 2.

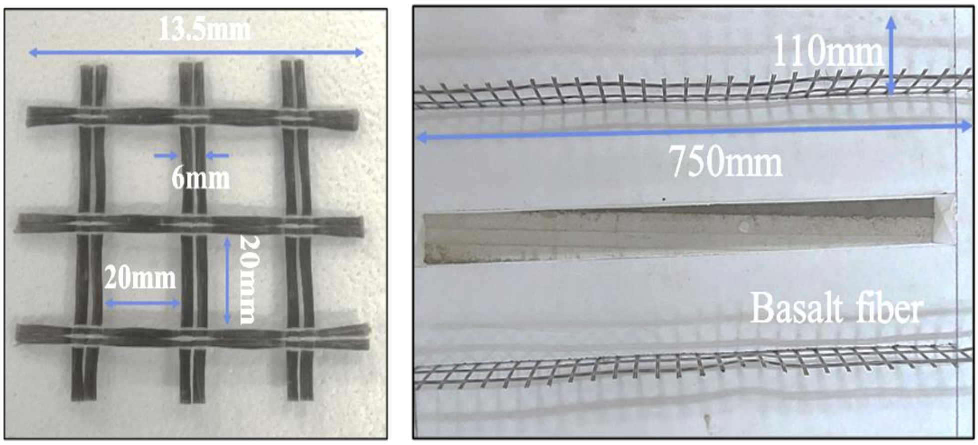

Fig. 2. Basalt fiber mesh

2.9. Mix Proportion

The mix proportions for the concrete included OPC-43 grade, fly ash, sand, stone slurry, stone aggregate, coarse aggregate, water, and superplasticizer in varying proportions. Multiple mix proportions were tested during the trial mixes and optimized before selecting the final mix, as detailed in Table 6.

Table 6. Mix proportion of the panel

Material	Cement	Fly ash	Sand	Coarse aggregate	Water/ Binder	Superplasticizer
Proportions (%)	18.12		7.75	44.73	29.38	0.38

2.10. Casting and Curing

2.10.1. Self-Compacting Concrete

A self-compacting concrete (SCC) mix was designed according to IS 10262:2019. The key parameters of the SCC mix design included a fine aggregate content of 48-60% by mass of the total aggregate and a low water/powder ratio ranging from 0.85 to 1.10 by volume. The purpose of using SCC is to avoid the need for vibration, which is particularly crucial in this case because of the incorporation of steel fibers. Steel fibers were randomly distributed within the concrete matrix, and if vibrated, they could potentially settle down, leading to a non-uniform distribution. By designing a self-compacting concrete mix with a specified fine aggregate content and low water/powder ratio, the desired flow and viscosity properties were achieved, allowing the concrete to consolidate under its own weight without external vibration.

This approach ensured that the steel fibers remained uniformly distributed throughout the concrete matrix. With a measured value of approximately 660 mm in the flowability test, as shown in Fig. 3, the concrete mix falls within the typical range of 550-850 mm for slump flow, as specified by the Indian Standard for Concrete Mix Proportioning [29], [30].

Fig. 3. Flowability test on SCC

2.10.2. Panel Casting and Curing

The total height and width of wall specimens were set at 750 mm and 500mm, respectively as shown in Fig. 4.

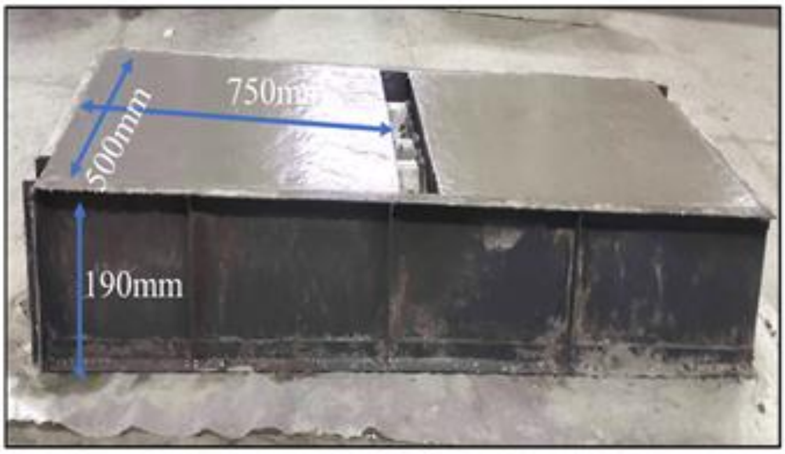

Fig. 4. Casting of panel

The thickness of each layer of concrete was 60 mm, and that of the EPS was 70 mm. To avoid cracking of the concrete sandwich walls, the thickness of the concrete layer was chosen as 60 mm, with a nominal compression strength of 46 MPa. The hooked-end steel fibers were randomly distributed in the concrete layer. In addition, basalt fiber with a thickness of 6 mm was used to firmly connect the two layers of concrete without passing through the XPS layer. During the construction process, the bottom layer of the concrete was poured with the reinforcements embedded in it. Subsequently, the XPS layer was placed on top of the bottom layer of the concrete. Finally, the upper layer of the concrete was poured. All panels were removed after 24 h from the mold and allowed to cure for 28 days by properly covering with damp gunny bags, as shown in Fig. 5.

Fig. 5. Curing of panel

2.11. Flexural test

In a flexural test of concrete sandwich panels, the panels were subjected to bending forces to assess their structural performance and load-bearing capacity. This test involves incrementally applying a load to the center of the panel until failure or a predetermined limit is reached. Throughout the test, measurements were taken to evaluate parameters such as the deflection, ultimate load, and stress distribution. These results provide crucial insights into the panel strength and stiffness, which are vital considerations for determining the suitability of these panels for construction purposes. The free-body diagram and setup used for the 4-point bending test are shown in Fig. 6.

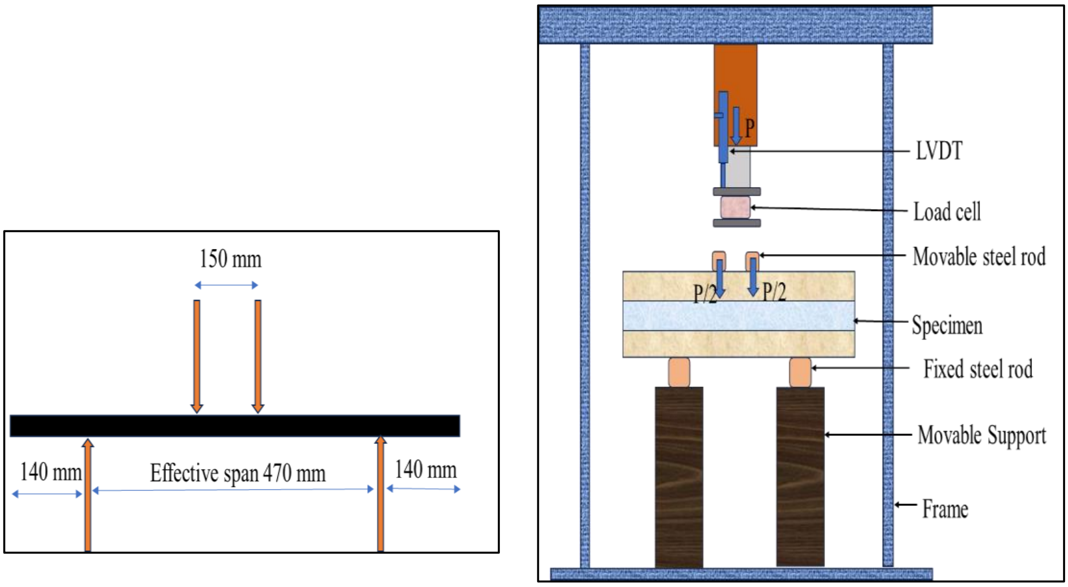

Fig. 6. Free body diagram and setup used for of 4-point bending test

3. Results and Discussion

The main aim of this study was to increase the ductility of concrete sandwich panels. To achieve this, certain design changes were introduced, compared to a previous panel work that had a failure load of approximately 9kN. The changes included increasing the thickness of the concrete wythes, using self-compacting concrete, providing grooves in the middle of the EPS sheet, as shown in Fig. 11, and introducing 1% steel fibers into the concrete. The use of self-compacting concrete (SCC) improved the quality and compaction of the concrete, potentially leading to a higher strength and better bonding between the concrete and insulation layers. Steel fibers act as reinforcement, bridging cracks and improving the tensile strength, ductility, and toughness of the concrete, as shown in Fig. 12. Stone waste inclusion is intended to make the panel environmentally friendly and cost-effective.

For the control concrete without any additions, the failure load was 51.6 kN. When steel fibers were added to the concrete, the failure load significantly increased to 110.5 kN. In the case of concrete with steel stone waste, the failure load was 96.3 kN, which was higher than the controlled concrete but lower than the concrete with steel fibers as shown in Fig. 8, Fig. 9, Fig. 10.

The maximum cracking load occurred at a displacement of 10.2 mm for the stone waste steel fiber sandwich panel, corresponding to a force of 96.3 kN. Remarkably, this maximum cracking load for the stone waste steel fiber sandwich panel was 85.7 times higher than that of the control concrete (plain concrete) sandwich panel and 8.5 times higher than that of the controlled steel fiber concrete sandwich panel. The higher cracking load and larger displacement capacity exhibited by the stone waste steel fiber sandwich panel indicated improved energy absorption and ductility. These results demonstrate the superior flexural strength and cracking resistance of the stone waste steel fiber sandwich panel compared to those of both plain concrete and conventional steel fiber-reinforced concrete panels. From a displacement of 10.2 mm at the peak load to a displacement of 15 mm when the panel finally failed in bending, the panel provided sufficient time, which in real-life situations would provide for taking remedial measures for safety. The failure of the panel is illustrated in Fig. 7.

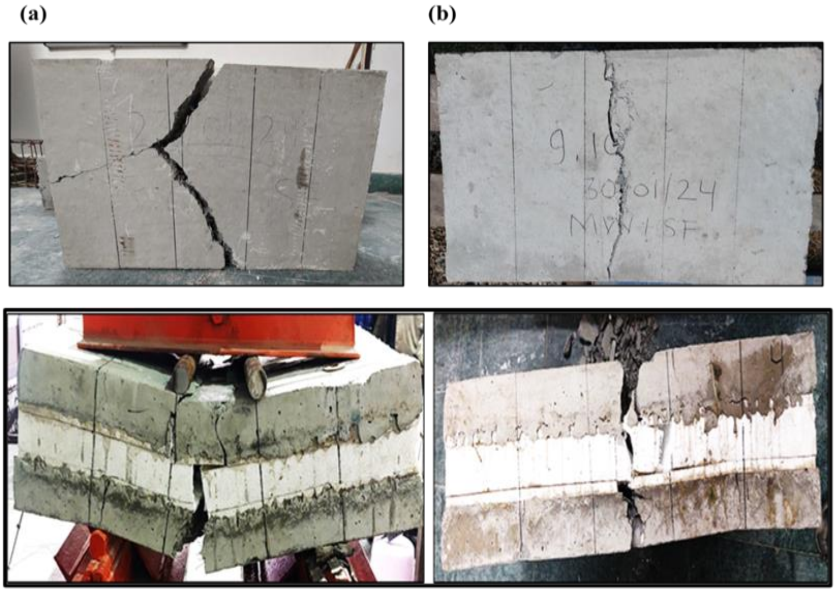

Fig. 7. Failure mode (a) Concrete with steel fiber (b) Solid waste with steel fiber

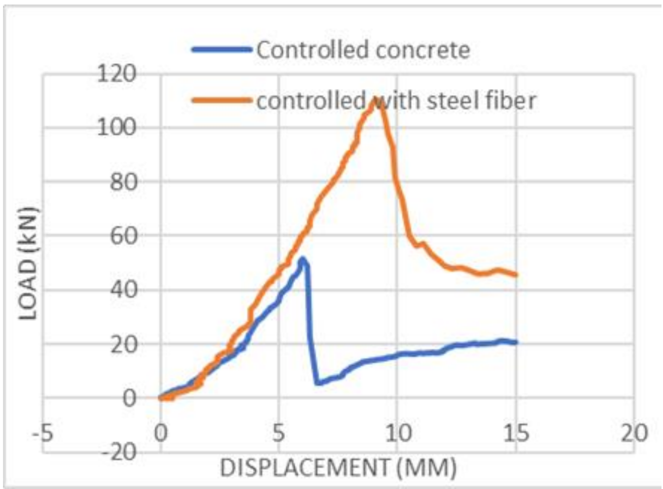

Fig. 8. Controlled concrete vs. concrete controlled with S.F waste S.F

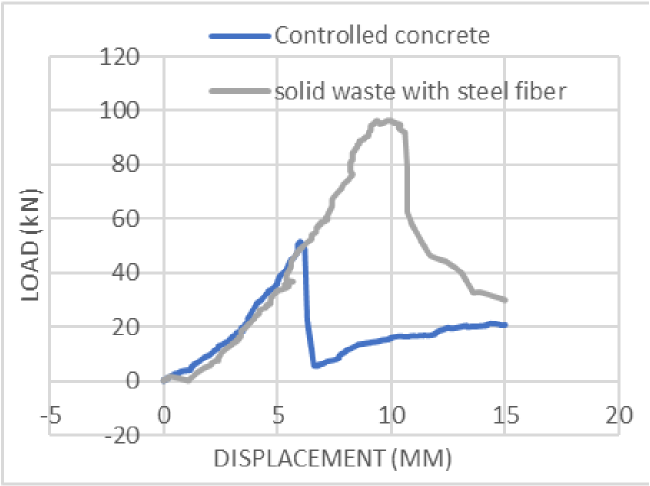

Fig. 9. Controlled concrete vs. solid

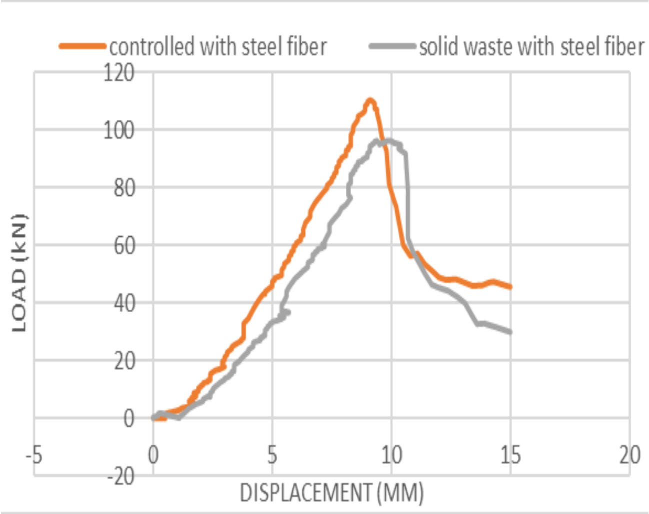

Fig. 10. Concrete steel fiber vs. solid waste steel fiber

In a flexural test, the load-displacement curve represents the relationship between the applied load and the corresponding displacement of the specimen. The area under this curve represents the energy absorbed or dissipated by the specimen during testing. The cumulative energy dissipation refers to the total amount of energy dissipated throughout the entire process. 268.04, 754.885, and 643.495 (kN·mm) were cumulative energy dissipation values for controlled concrete, controlled with steel fiber, and solid waste with steel fiber. A high cumulative energy dissipation value suggests that the material or structure is capable of absorbing and dissipating a large amount of energy during deformation.

The graph is shown in Fig. 13. compares the load-displacement behavior of insulation panels used in concrete construction, with one case involving a panel "with groove" that allows concrete to pass through the middle, and the other is a solid panel "without groove.” The "with groove" scenario exhibits a considerably higher peak load capacity, reaching 51.6 kN at 6 mm displacement, which is nearly double the maximum load of approximately 28 kN for the "without groove" case at 6.7 a displacement. The solid panel demonstrates a more gradual, monotonic increase in load with increasing displacement, whereas incorporating a groove enhances the maximum sustainable load.

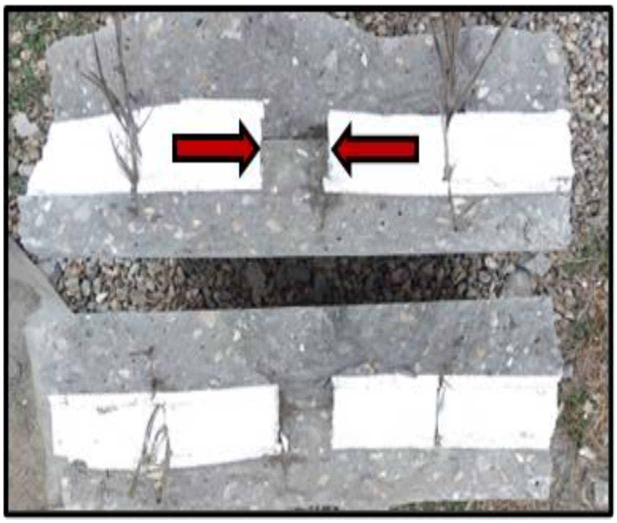

Fig. 11. Groove in EPS

Fig. 12. Steel fiber holding the upper layer

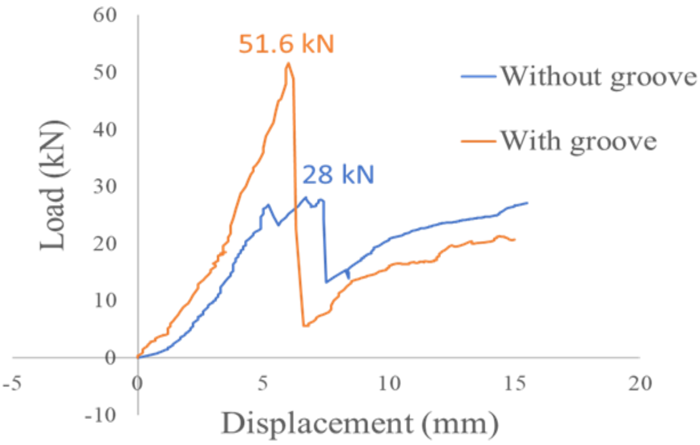

Fig. 13. Controlled concrete with and without grooves in EPS

3.1. Implications of Sustainable Precast Concrete Panels

Table 7. Summary of Construction Practice and Future Research

Aspect	Implications for Construction Practice	Implications for Future Research
Sustainability	Reduces reliance on natural materials and lowers carbon emissions.	Explore other waste materials like slag or glass.
Cost Efficiency	Lowers production costs by using waste materials.	Optimize mix design for better performance and cost-efficiency.
Performance	Increases strength, durability, and energy efficiency with steel fibers and basalt connectors.	Conduct long-term durability studies in various climates.

4. Conclusion

The present study investigated the potential of utilizing sustainable materials, such as stone waste aggregates and supplementary cementitious materials, in the production of precast concrete sandwich wall panels. The aim was to enhance the sustainability and environmental friendliness of these panels, while maintaining adequate structural performance. Based on the experiments conducted, the following key observations and conclusions can be drawn: 1) The inclusion of steel fibers in concrete resulted in a substantial 96% increase in the failure load compared with the control concrete without fibers. This demonstrates the effectiveness of steel fibers in enhancing the flexural strength and toughness of concrete wythes; 2) Stone waste aggregates can be successfully used as a replacement for natural aggregates in concrete mixtures. When combined with steel fibers, the resulting panel exhibited a 71% increase in strength compared with that of the control sample without any addition. This finding highlights the viability of incorporating waste materials, such as stone waste, into precast concrete sandwich panels. 3) The cumulative energy dissipation for steel fiber-reinforced concrete was 754.885 kN·mm, which was significantly higher than the 268.04 kN·mm in conventional concrete, indicating better ductility and toughness; 4.)Panels with a groove design showed a peak load of 51.6 kN at a displacement of 6 mm, nearly doubling the load capacity of the panels without grooves. 5) Integrating stone waste and supplementary cementitious materials reduces reliance on natural resources, lowers costs, and enhances structural performance, making panels more eco-friendly and viable for sustainable construction. In summary, the incorporation of sustainable materials, such as stone waste aggregates and supplementary cementitious materials, along with the inclusion of steel fibers and basalt fiber connectors, showed promising results for enhancing the sustainability and structural performance of precast concrete sandwich wall panels. These findings pave the way for the development of eco-friendly and efficient construction systems that can contribute to sustainable building practices.

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Declarations

Author contribution. All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper

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Conflict of interest. The authors declare no conflict of interest.

Additional information. No additional information is available for this paper.

References

[1] T. Zheng, Q. Ge, F. Xiong, G. Li, Y. Xue, and X. Deng, "Study of the flexural performance and a novel calculation formula for the degree of composite action for precast concrete sandwich panels," *Struct. Des. Tall Spec. Build.*, vol. 32, no. 18, p. e2065, Dec. 2023, doi: 10.1002/tal.2065.

[2] M. Y. H. Amran, "Determination of structural behavior of precast foamed concrete sandwich panel," Universitas Putra Malaysia, p. 16, 2016. [Online]. Available at: http://psasir.upm.edu.my/id/eprint/70170/.

[3] Q. Huang, E. Hamed, and R. I. Gilbert, "Early-Age Shrinkage Effects in Precast Concrete Sandwich Panels," *PCI J.*, vol. 65, no. 1, pp. 74–88, 2020, doi: 10.15554/pcij65.1-04.

[4] A. Chen, T. G. Norris, P. M. Hopkins, and M. Yossef, "Experimental investigation and finite element analysis of flexural behavior of insulated concrete sandwich panels with FRP plate shear connectors," *Eng. Struct.*, vol. 98, pp. 95–108, Sep. 2015, doi: 10.1016/j.engstruct.2015.04.022.

[5] T. Sevil Yaman and G. Lucier, "Shear Transfer Mechanism between CFRP Grid and EPS Rigid Foam Insulation of Precast Concrete Sandwich Panels," *Buildings*, vol. 13, no. 4, p. 928, Mar. 2023, doi: 10.3390/buildings13040928.

[6] J. Huang, Q. Jiang, X. Chong, X. Ye, and C. Liu, "Structural performance of a façade precast concrete sandwich panel enabled by a bar-type basalt fiber-reinforced polymer connector," *Front. Struct. Civ. Eng.*, vol. 17, no. 1, pp. 122–137, Jan. 2023, doi: 10.1007/s11709-022-0894-1.

[7] D. Tomlinson and A. Fam, "Flexural behavior of precast concrete sandwich wall panels with basalt FRP and steel reinforcement," *PCI J.*, vol. 60, no. 6, pp. 51–71, Nov. 2015, doi: 10.15554/pcij.11012015.51.71.

[8] J. H. Kim and Y. C. You, "Composite Behavior of a Novel Insulated Concrete Sandwich Wall Panel Reinforced with GFRP Shear Grids: Effects of Insulation Types," *Mater. 2015, Vol. 8, Pages 899-913*, vol. 8, no. 3, pp. 899–913, Mar. 2015, doi: 10.3390/MA8030899.

[9] I. J. Gnip, S. A. Veyelis, V. I. Kersulis, and S. I. Vaitkus, "Deformability and strengh of expanded polystyrene (EPS) under short-term shear loading," *Mech. Compos. Mater.*, vol. 43, no. 1, pp. 85–94, Jan. 2007, doi: 10.1007/s11029-007-0009-z.

[10] G. C. Manos, L. Melidis, K. Katakalos, L. Kotoulas, A. Anastasiadis, and C. Chatziastrou, "Masonry panels with external thermal insulation subjected to in-plane diagonal compression," *Case Stud. Constr. Mater.*, vol. 14, p. e00538, Jun. 2021, doi: 10.1016/j.cscm.2021.e00538.

[11] B. Egbon and D. Tomlinson, "Experimental investigation of longitudinal shear transfer in insulated concrete wall panels with notched insulation," *J. Build. Eng.*, vol. 43, p. 103173, Nov. 2021, doi: 10.1016/j.jobe.2021.103173.

[12] H. Hou, K. Ji, W. Wang, B. Qu, M. Fang, and C. Qiu, "Flexural behavior of precast insulated sandwich wall panels: Full-scale tests and design implications," *Eng. Struct.*, vol. 180, pp. 750–761, Feb. 2019, doi: 10.1016/j.engstruct.2018.11.068.

[13] A. Christian and G. O. K. Chye, "Performance of Fiber Reinforced High-strength Concrete with Steel Sandwich Composite System as Blast Mitigation Panel," *Procedia Eng.*, vol. 95, pp. 150–157, Jan. 2014, doi: 10.1016/J.PROENG.2014.12.174.

[14] R. Prakash *et al.*, "Effect of Steel Fiber on the Strength and Flexural Characteristics of Coconut Shell Concrete Partially Blended with Fly Ash," *Materials (Basel).*, vol. 15, no. 12, p. 4272, Jun. 2022, doi: 10.3390/ma15124272.

[15] Bureau of Indian Standard(BIS), "IS: 8112 – 1989, Specification for 43 grade Ordinary Portland Cement," 2013. [Online]. Available at: https://law.resource.org/pub/in/bis/S03/is.8112.1989.pdf.

[16] "IS 8112: Specification for 43 grade ordinary Portland cement," *Bureau of Indian Standards*, 1989. Online. Available at: https://archive.org/details/gov.in.is.8112.1989.

[17] K. Khan *et al.*, "Exploring the Use of Waste Marble Powder in Concrete and Predicting Its Strength with Different Advanced Algorithms," *Materials (Basel).*, vol. 15, no. 12, p. 4108, Jun. 2022, doi: 10.3390/ma15124108.

[18] O. Benjeddou and N. Mashaan, "Experimental Study of the Usability of Recycling Marble Waste as Aggregate for Road Construction," *Sustainability*, vol. 14, no. 6, p. 3195, Mar. 2022, doi: 10.3390/su14063195.

[19] K. Moolchandani and A. Sharma, "Evaluating the Elastic Constants of Concrete, Modified with Fly Ash and Marble Waste, and Their Effects on High-Rise Buildings Using ETABS Software," *Sustainability*, vol. 15, no. 20, p. 14743, Oct. 2023, doi: 10.3390/su152014743.

[20] IS:2386 (Part I), "Method of test for aggregate for concrete (Particle size and shape)," *Indian Stand.*, p. 26, 1963, [Online]. Available at: https://law.resource.org/pub/in/bis/S03/is.2386.1.1963.pdf.

[21] R. Ralegaonkar, H. Gavali, P. Aswath, and S. Abolmaali, "Application of chopped basalt fibers in reinforced mortar: A review," *Constr. Build. Mater.*, vol. 164, pp. 589–602, Mar. 2018, doi: 10.1016/j.conbuildmat.2017.12.245.

[22] P. Mahakavi and R. Chithra, "Impact resistance, microstructures and digital image processing on self-compacting concrete with hooked end and crimped steel fiber," *Constr. Build. Mater.*, vol. 220, pp. 651–666, Sep. 2019, doi: 10.1016/j.conbuildmat.2019.06.001.

[23] R. K. Biswas *et al.*, "Effects of Steel Fiber Percentage and Aspect Ratios on Fresh and Harden Properties of Ultra-High Performance Fiber Reinforced Concrete," *Appl. Mech.*, vol. 2, no. 3, pp. 501–515, Jul. 2021, doi: 10.3390/applmech2030028.

[24] Z. Wu, C. Shi, W. He, and L. Wu, "Effects of steel fiber content and shape on mechanical properties of ultra high performance concrete," *Constr. Build. Mater.*, vol. 103, pp. 8–14, Jan. 2016, doi: 10.1016/j.conbuildmat.2015.11.028.

[25] F. Laranjeira, S. Grünewald, J. Walraven, C. Blom, C. Molins, and A. Aguado, "Characterization of the orientation profile of steel fiber reinforced concrete," *Mater. Struct.*, vol. 44, no. 6, pp. 1093–1111, Jul. 2011, doi: 10.1617/s11527-010-9686-5.

[26] IS:3812 (Part-1), "Pulverized fuel ash — specification. Part 1: For use as Pozzolana in cement, Cement Mortar and Concrete (Second Revision)," *Bur. Indian Stand. New Delhi, India*, no. October, pp. 1–14, 2003, [Online]. Available at: https://law.resource.org/pub/in/bis/S03/is.3812.1.2003.pdf.

[27] "C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," *ASTM International*, 2023. [Online] Available at: https://www.astm.org/c0618-22.html.

[28] Bureau of Indian Standards, "IS 4671: 1984 Specifications for expanded polystyrene for thermal insulation purposes," 1984. [Online]. Available at: https://archive.org/details/gov.in.is.4671.1984/page/n21/mode/2up.

[29] "IS 10262 : 2019: Concrete Mix Proportioning — Guidelines (Second Revision)," 2019. [Online]. Available at: https://archive.org/details/gov.in.is.10262.2019.

[30] "IS 456 Plain Concrete and Reinforced," 2000. [Online]. Available at: https://law.resource.org/pub/in/bis/S03/is.456.2000.pdf.