

Lecture Notes in Civil Engineering

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Lukas Beladi Sihombing ·
Yee Yong Lee · Harianto Hardjasaputra ·
Simone Stürwald *Editors*

Proceedings of the 9th International Conference of EURO ASIA Civil Engineering Forum – Volume 1

EACEF 2025, September 9–11, Kuching,
Malaysia

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ISSN 2366-2557

ISSN 2366-2565 (electronic)

Lecture Notes in Civil Engineering

ISBN 978-981-95-6894-9

ISBN 978-981-95-6895-6 (eBook)

<https://doi.org/10.1007/978-981-95-6895-6>

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Preface

Civil engineering has long been at the leading edge of human civilization, offering the essential infrastructure that continually strives for advances in both theoretical aspects and practical applications. To date, it experiences ever-expanding challenges that require sustainable, resilient, and future-ready solutions. In this spirit, the 9th International Conference of Euro Asia Civil Engineering Forum (EACEF 2025) was organized with the theme “Beyond Boundaries: Empowering Innovations in Civil and Environmental Engineering.” The conference illuminates the importance of interdisciplinary collaboration and cutting-edge research to meet future needs.

The event was hosted by Universiti Malaysia Sarawak (UNIMAS) in cooperation with Universitas Pembangunan Jaya (UPJ), Indonesia, at Dewan Tunku Abdul Rahman Putra (DeTAR Putra), UNIMAS, Sarawak, Malaysia, on 9–11 September 2025.

EACEF 2025 brought together researchers, academics, and practitioners from across the globe to share insights for a wide range of topics, including structural and materials engineering, geotechnical engineering, construction management, building information modeling, green and sustainable construction, geotechnical construction material innovations, water resources engineering, transportation engineering, and other developing fields within civil and environmental engineering.

This proceedings book reflects the rigorous academic readiness that was carried out for the conference. Eighty manuscripts were received. Each paper underwent a single-blind review process by at least two reviewers. Based on their recommendations and the publication committee’s evaluation, 37 papers were accepted for this book. This procedure ensures that the papers fulfill the required standards for quality and field-relevance.

We extend our heartiest gratitude to the authors for their valuable contributions, the reviewers for their critical and constructive comments, and the organizing team for their dedication in bringing this conference to fruition. We also acknowledge the institutional support from UNIMAS and UPJ, whose collaboration has enriched the success of this event.

To promote the healthy advancement of civil and environmental engineering, we hope that the research outcomes, discussions, and innovations in this proceeding will motivate future cross-disciplinary and cross-border cooperations.

November 2025

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Vibration Energy Harvesting in High-Performance Geopolymer Mortar: A Proof-of-Concept with Piezoelectric Integration

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Abstract. The growth of global traffic demands sustainable pavement solutions, while Portland cement production contributes 7–8% of global CO₂ emissions. Traffic-induced vibrations are generally dissipated, yet piezoelectric systems have the potential to harvest them into renewable electricity. This study presents a lab-scale proof of concept using High-Performance Geopolymer Mortar (HPGM) from industrial by-products to handle heavy loads and harsh environments, offering a medium for piezoelectric integration. Three mix groups optimized HPGM by varying fiber content, reducing anhydrous sodium silicate (ASS) with slag, or replacing ASS with liquid sodium silicate. Tests showed HPGM had high strength (up to 172.1 MPa compressive, up to 16.4 MPa flexural) and excellent durability, retaining > 93% strength with < 1.2% mass loss in chemical exposure. Separately, a laboratory-scale piezoelectric system tested under footstep loading generated battery life drops as load current rises: 500 h with no load, 5.37 h with a light bulb, 50 h for phone charging (0.20 A), and 4.81 h for combined loads. The system is more efficient for low-power DC use where scaling up piezoelectric tiles could boost its renewable energy potential. These findings lay the groundwork for future integration into multifunctional pavements that combine durability, low-carbon benefits, and renewable energy harvesting from traffic-induced loads.

Keywords: High-Performance Geopolymer Mortar (HPGM) · Piezoelectric Energy Harvesting · Proof-of-Concept Pavement

1 Introduction

Rising global traffic increases the need for sustainable, durable pavements in heavily loaded wheel-path zones. Conventional OPC concrete suffers from cracking and fatigue under heavy loads, while its production contributes 5–8% of global CO₂ emissions and 80% of concrete's carbon footprint. It also demands high raw material, energy, and water use, worsening environmental impacts. [1]. These issues highlight the urgent need for low-carbon, high-performance materials, especially for high-stress wheel-path zones. (see Fig. 1).

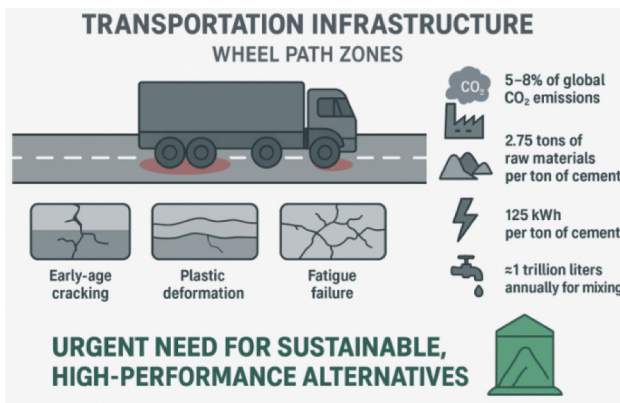


Fig. 1. OPC pavements experience cyclic loading failures and impose a high environmental impact.

Geopolymer concrete (GPC), made from silica- and alumina-rich wastes like fly ash, slag, and silica fume, offers superior strength, chemical resistance, and durability. In Sarawak, Malaysia, underused industrial residues offer potential for sustainable alkali-activated binder production [2]. See Fig. 2 shows rising industrial waste mismanagement, stressing the need for sustainable use in civil engineering materials. HPGM offers ultra-high strength with environmental benefits, while piezoelectric systems harvest traffic-induced vibrations into electricity, enabling smart, energy-efficient roads. Piezoelectric pavements have been tested [3], but not with HPGM. Embedding piezo devices in HPGM could create strong, low-carbon, energy-generating pavements, though challenges remain in structural integrity, power stability, and activator cost.

This study fills the research gap with a lab-scale proof of concept using ultra-strong HPGM blocks and a piezoelectric system generating voltage under foot-step loading. The objective is to establish the groundwork for future integration, laying the foundation for innovative, multifunctional pavements. Figure 3 shows the wheel-path zone as the key area for placing HPGM modules to protect piezo components and extend pavement life. Figure 4 shows the precast block with an integrated energy harvesting system for road use. The study presents a sustainable, energy-harvesting pavement for low-carbon infrastructure.

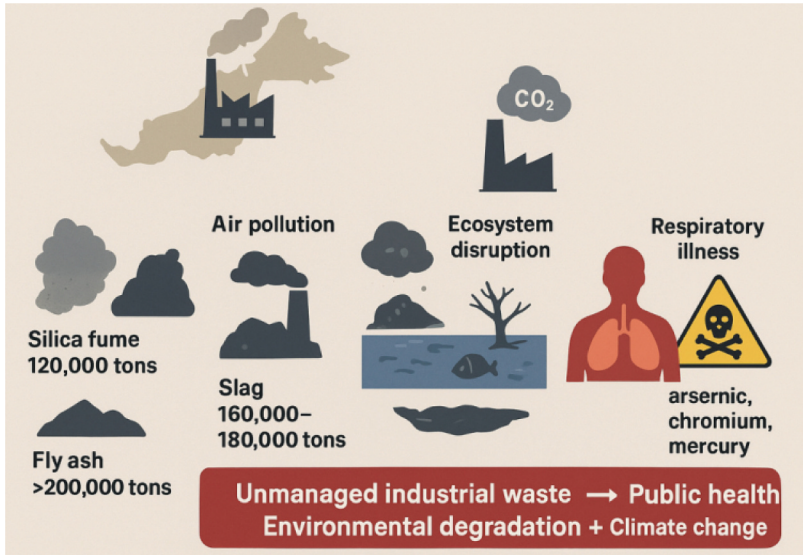


Fig. 2. Unmanaged industrial waste in Sarawak poses risks from silica fume, slag, and fly ash.



Fig. 3. Tire contact and wear on the wheel path.

This study conducts lab-scale validation of HPGM blocks and piezo modules. Results serve as a preliminary step toward high-strength, durable, energy-harvesting pavements.

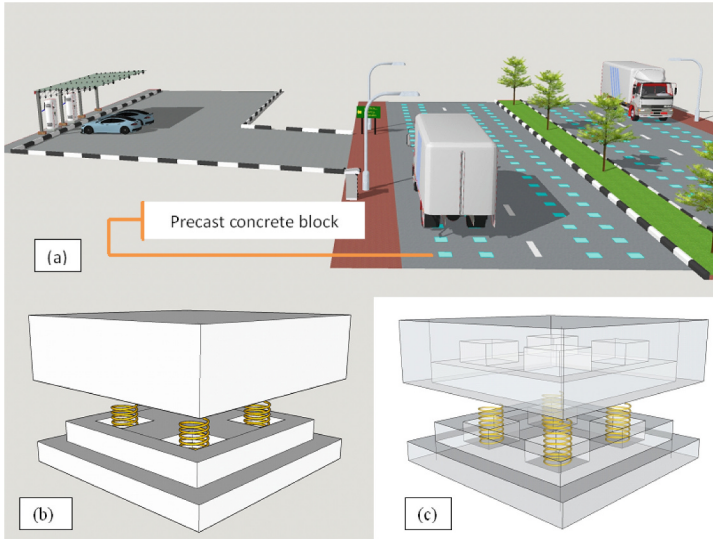


Fig. 4. Precast block incorporating energy harvest system (a) on road system, (b) precast module, (c) Transparent view of module.

2 Materials and Methods

2.1 High-Performance Geopolymer Mortar (HPGM) Mix Design

The binder in this study is geopolymer paste made from fly ash, silica fume, and slag industrial by-products rich in aluminosilicates (see Fig. 5). Activation was achieved with anhydrous and liquid sodium silicate ($\text{pH} > 11$). Steel fibers ($13 \text{ mm} \times 0.2 \text{ mm}$) enhanced tensile and flexural performance, with natural sand ($\leq 200 \mu\text{m}$) as fine aggregate. Water-to-binder ratios ($0.0950\text{--}0.1336$) were optimized for strength and workability. Three groups with four mix variations each produced three specimens, following Lao et al. [4], who achieved 222 MPa compressive strength.

The mix design was divided into three groups to optimize HPGM. Group 1 adjusted steel fiber for strength and crack resistance [5], Group 2 added slag to reduce ASS and cost while enhancing C–A–S–H formation [6], and Group 3 used liquid sodium silicate (LSS) to improve workability and geopolymerization [7]. Table 1 lists the mix proportion.

Physical Properties	Standard Test	Fly Ash	Slag	Silica fume	Fine sand
Colour	Visual	Dark Grey	White	Whitish-gray	Yellow
Specific Gravity	Pycnometer Method (ASTM C188)	2.9	2.6	2.1	2.6
Specific Surface Area (m ² /g)	BET Surface Area Analysis	0.21	0.509	5.71	0.0446
Particle Size (μm)	PSA (Particle Size Analyzer)	19.22	<30	<0.5	<200
Particle Retained on 45μm sieve (%)	Sieve Analysis	11.2	16	2	98

Fig. 5. Physical properties of raw materials used.

2.2 Fabrication of Precast HPGM Blocks

The procedure (see Fig. 6) began by preparing the alkali activator solution by dissolving ASS, LSS, and superplasticizer in water and letting it cool for 1 h. Precursors and aggregates were dry-mixed for 5 min, then combined with solution and mixed for another 5 min. Fibers were added and mixed manually for 5 min until uniformly distributed. The mixture was cast into molds, compacted on a vibrating table for 2 min, and pre-cured for two days at 27.3–29.6 °C and 74.0–92.0% humidity under plastic sheets. For optimal curing, samples were then heat-cured at 90 °C for 48 h, as high temperatures improve compressive strength [8].

Table 1. Details of the mix proportioning (in kg/m³).

Groups	Specimens	Fly Ash	Slag	Silica fume	Fine sand	Anhydrous Sodium Silicate	Liquid Sodium Silicate	Water	Steel Fiber	Super Plasticizer
Group 1 (steel fiber variation)	G1-ST0	200	800	85	700	103	153	105	-	51
	G1-ST1	200	800	85	700	103	153	105	79.1	51
	G1-ST2	200	800	85	700	103	153	105	158.2	51
	G1-ST3	200	800	85	700	103	153	105	237.3	51
Group 2 (Adding Slag reduces ASS)	G2-SG10Na	200	810	85	700	98	153	105	79.1	51
	G2-SG20Na	200	820	85	700	93	153	105	79.1	51
	G2-SG30Na	200	830	85	700	88	153	105	79.1	51
	G2-SG40Na	200	840	85	700	83	153	105	79.1	51
Group 3 (Eliminating ASS and increasing LSS)	G3-LSS20	200	800	85	700	-	173	105	79.1	51
	G3-LSS40	200	800	85	700	-	193	105	79.1	51
	G3-LSS60	200	800	85	700	-	213	105	79.1	51
	G3-LSS80	200	800	85	700	-	233	105	79.1	51

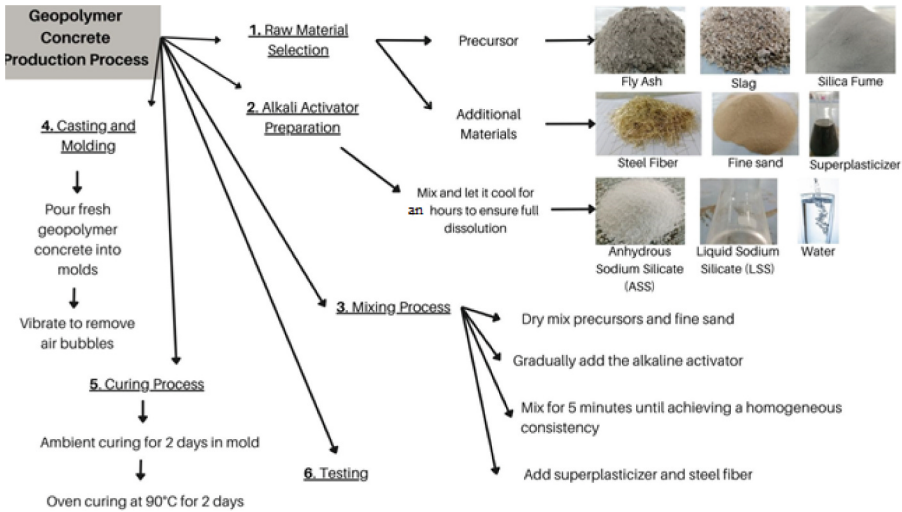


Fig. 6. Mix Procedure of HPGM.

Specimens were prepared in two geometries for strength and durability testing. Compressive strength was measured on $50 \times 50 \times 50$ mm cubes at 7 and 28 days following ASTM C39. Flexural strength was evaluated using $50 \times 50 \times 200$ mm beams (ASTM C293). Durability was assessed by immersing cube specimens in 5% H_2SO_4 and 5% NaCl solutions for 7, 28, and 90 days, in accordance with ASTM C267. Specimens were ambient cured at 23 ± 2 °C and 40–60% RH before testing. Small-scale specimens enabled a cost-effective preliminary evaluation of HPGM pavements, providing insights for larger-scale studies.

2.3 Piezoelectric Energy Harvesting System (Laboratory-Scale)

The system uses piezoelectric sensors to convert footstep pressure into AC voltage, rectified by a 2W02G bridge to DC. A relay and capacitor stabilize output for battery charging, regulated by an Arduino UNO. The stored 12 V DC powers devices through 7805 (5 V) and 7812 (12 V) regulators, while an inverter converts 12 V DC to 220 V AC for light bulbs. Figure 7 shows the footstep power generation block diagram using piezoelectric technology.

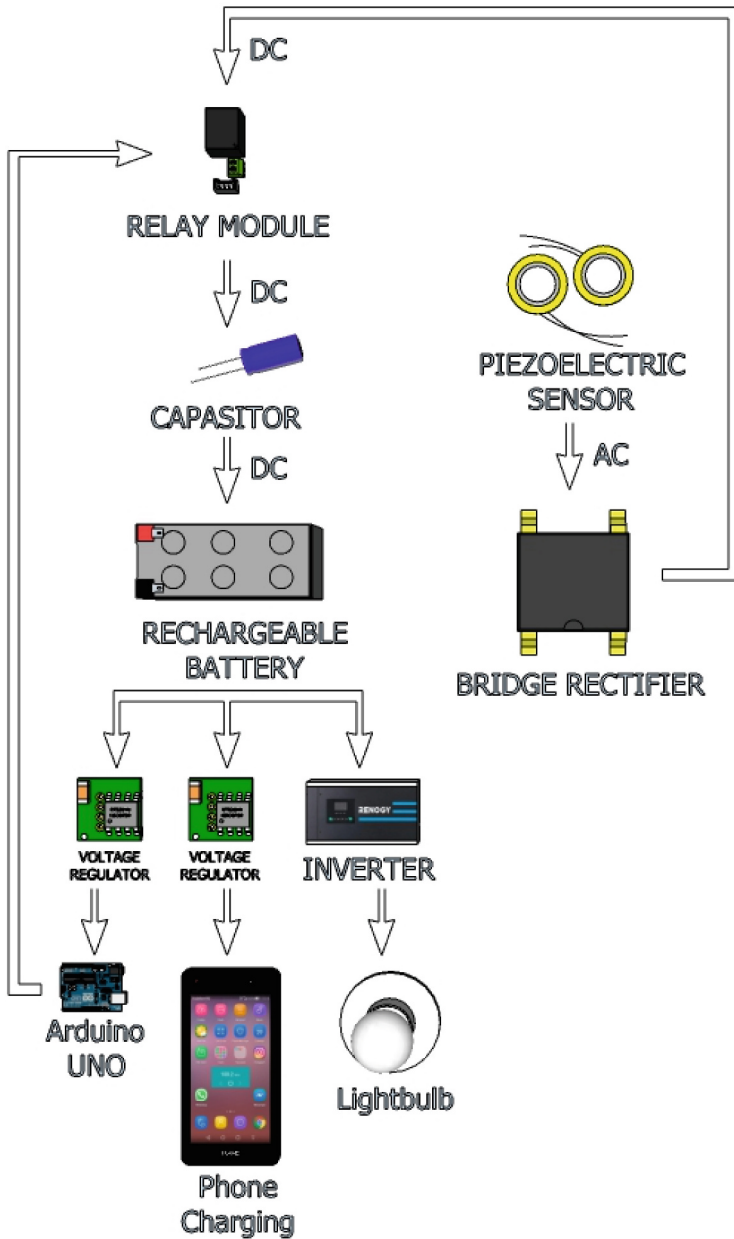


Fig. 7. Block diagram for footstep power generation system using piezoelectric sensor technology.

2.4 Testing Procedures

Mechanical Strength Tests. Compressive strength of HPGM was tested at 7 and 28 days using $50 \times 50 \times 50$ mm cubes conditioned at room temperature. Tests followed

ASTM C39 with a loading rate of 0.40 MPa/s, recording the maximum load before failure. Flexural behavior was evaluated using $50 \times 50 \times 200$ mm beams under three-point bending (ASTM C293) over a 150 mm span, where loading at mid-span induces tensile stress at the bottom fibers, ideal for smaller specimens and simpler than four-point bending.

Durability Assessment under Aggressive Conditions. The durability of the HPGM was evaluated through immersion tests in accordance with ASTM C267. Cube specimens ($50 \times 50 \times 50$ mm) were immersed in 5% sulfuric acid (H_2SO_4) and 5% sodium chloride (NaCl) solutions for exposure periods of 7, 28, and 90 days, while specimens immersed in water were used as the control group. Acidic and chloride environments simulated industrial and marine exposure. After each period, specimens were evaluated for surface damage, mass loss, and strength retention to assess long-term durability.

Piezoelectric Footstep Loading Tests. When a person stood on the piezoelectric tile, the applied pressure activated the piezoelectric effect, where the mechanical stress from footsteps was transformed into electrical energy. The sensors initially produced an AC output, which was then rectified into DC voltage using a 2W02G single-phase bridge rectifier. To stabilize the current, a 50 V, 100 μF capacitor was employed, ensuring a smooth DC supply for charging a 12 V lithium-iron phosphate rechargeable battery pack. The stored 12 V DC from the battery was connected to a DC-to-AC inverter, converting it into 220 V AC to power a 15 W light bulb. In addition, the battery pack was linked to a 7812 voltage regulator IC, which maintained a steady 12 V DC supply for the Arduino UNO, and to a 7805 voltage regulator IC, which delivered a regulated 5 V output suitable for charging mobile phones.

3 Results

3.1 Compressive and Flexural Strength of HPGM

HPGM achieved over 150 MPa compressive strength, with steel fibers enhancing ductility and flexural strength. Table 2 shows HPGM strength development for fiber variation, slag increase with reduced ASS, and full ASS replacement with LSS. For Group 1, the addition of steel fibers progressively enhanced compressive strength. At 3% fiber content, the 7-day and 28-day strengths reached 122.0 MPa and 172.1 MPa, reflecting increases of + 21.9% and + 14.6% over the control mix, respectively. In Group 2, higher slag content with reduced ASS also improved strength, though more moderately compared to fiber addition. The highest increase, obtained at 840 kg slag and 83 kg ASS, showed 118.0 MPa at 7 days and 168.2 MPa at 28 days (+7.1% and + 4.9% from the baseline). For Group 3, at 80% LSS, compressive strength reached 121.6 MPa (7 days) and 170.4 MPa (28 days), marking improvements of + 15.3% and + 9.9%. All modifications improved strength, with steel fiber giving the greatest gain, followed by LSS substitution and slag-ASS adjustment.

Table 2. Compressive Strength Results of HPGM.

Group	Mixture ID	Steel Fiber (%)	Slag (kg)	ASS (kg)	LSS (kg)	7-Day Strength (MPa)	28-Day Strength (MPa)	7-Day Change (%)	28-Day Change (%)
1 Steel Fiber Variation	G1-ST0	0	800	103	153	100.10	150.20	—	—
	G1-ST1	1	800	103	153	108.50	158.90	+8.4%	+5.8%
	G1-ST2	2	800	103	153	115.20	165.20	+15.1%	+10.0%
	G1-ST3	3	800	103	153	122.00	172.10	+21.9%	+14.6%
2 Slag ↑ / ASS ↓	G2-SG10Na	1	810	98	153	110.20	160.40	—	—
	G2-SG20Na	1	820	93	153	112.80	163.00	+2.4%	+1.6%
	G2-SG30Na	1	830	88	153	115.40	165.60	+4.7%	+3.2%
	G2-SG40Na	1	840	83	153	118.00	168.20	+7.1%	+4.9%
3 ASS Eliminated / LSS ↑	G3-LSS20	1	800	0	173	105.40	155.00	—	—
	G3-LSS40	1	800	0	193	110.80	160.10	+5.1%	+3.3%
	G3-LSS60	1	800	0	213	116.20	165.30	+10.3%	+6.6%
	G3-LSS80	1	800	0	233	121.60	170.40	+15.3%	+9.9%

HPGM achieved flexural strength above 6 MPa, with steel fibers enhancing post-peak behavior and capacity. Table 3 shows strength development across modification groups. Group 1 showed major strength gains with added fibers, rising from 8.1 to 16.4 MPa (102.5% increase), confirming strong reinforcement effects. Group 2 strength rose from 11.4 to 16.1 MPa (41.2%) with higher slag, showing slag's key role in matrix strength. Group 3 showed minimal gains ($\approx 5\%$) with LSS increase, indicating limited efficiency as a sole activator. Overall, steel fiber and slag optimization most effectively enhanced compressive strength.

Table 3. Flexural Strength Results of HPGM with three groups.

Group	Mixture ID	Steel Fiber (%)	Slag (kg)	ASS (kg)	LSS (kg)	7-Day Strength (MPa)	28-Day Strength (MPa)	7-Day Change (%)	28-Day Change (%)
1 Steel Fiber Variation	G1-ST0	0	800	103	153	6.2	8.1	—	—
	G1-ST1	1	800	103	153	8.4	11.2	+35.5%	+38.3%
	G1-ST2	2	800	103	153	10.6	13.9	+71.0%	+71.6%

(continued)

Table 3. (continued)

Group	Mixture ID	Steel Fiber (%)	Slag (kg)	ASS (kg)	LSS (kg)	7-Day Strength (MPa)	28-Day Strength (MPa)	7-Day Change (%)	28-Day Change (%)
	G1-ST3	3	800	103	153	12.3	16.4	+98.4%	+102.5%
2 Slag ↑ / ASS ↓	G2-SG10Na	1	810	98	153	8.9	11.4	—	—
	G2-SG20Na	1	820	93	153	9.5	12.8	+6.7%	+12.3%
	G2-SG30Na	1	830	88	153	10.4	14.5	+16.9%	+27.2%
	G2-SG40Na	1	840	83	153	11.6	16.1	+30.3%	+41.2%
3 ASS Eliminated / LSS ↑	G3-LSS20	1	800	0	173	7.9	9.8	—	—
	G3-LSS40	1	800	0	193	8.1	9.9	+2.5%	+1.0%
	G3-LSS60	1	800	0	213	8.3	10.1	+5.1%	+3.1%
	G3-LSS80	1	800	0	233	8.5	10.3	+7.6%	+5.1%

3.2 Durability Performance

HPGM durability was tested in water, NaCl, and H₂SO₄. Water immersion caused minimal degradation (mass ≤ 0.36%, strength ≤ 4.7%), with Group 1 best. Under 5% NaCl, Group 1 showed ≤ 1.9% mass and ≤ 4.7% strength loss; Groups 2–3 had ~ 3.6% mass and 5.4–5.5% strength loss, with only superficial effects. In 5% H₂SO₄, deterioration increased over time: Group 1 lost 1.4–1.9% mass and 3.3–4.7% strength at 7 days, rising to 5.9–8.5% and 13.6–18.9% at 90 days; Groups 2–3 lost ~ 7.1% mass and ~ 16.5% strength. Acid caused haze, erosion, and sulfate crusts, with pH dropping to 2.7–2.9, showing more severe degradation than NaCl.

3.3 Piezoelectric Output Voltage and Power Generation

Figure 8 shows the footstep power system, including a piezo tile, relay, Arduino UNO, stripboard, battery, inverter, light bulb, and phone charger.

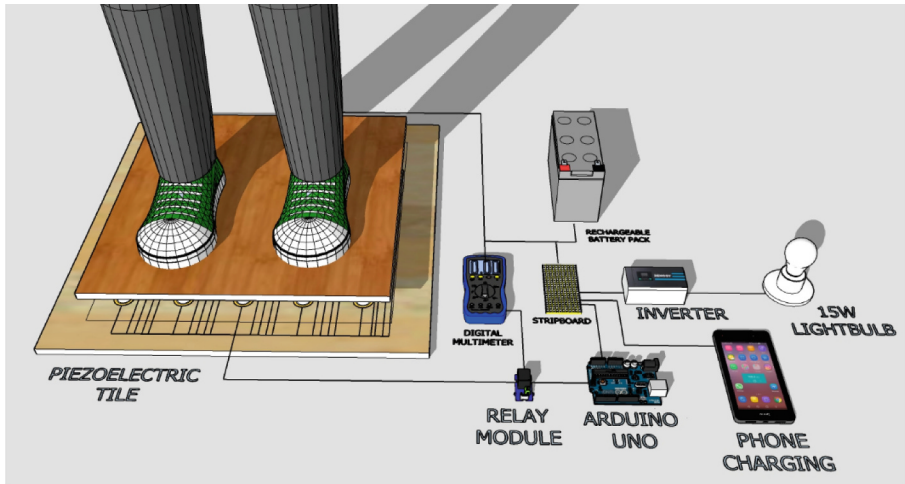


Fig. 8. Footstep power system hardware using piezoelectric sensors

Table 4. Load current (A) and Battery Life (hours) according to the situations.

Situations	Load Current (A)	Battery Life (hours)
No loads are turned on	0.02	500
Light bulb is switched on	1.86	5.37
Charging of the phone is switched on	0.20	50
Both light bulb and charging of the phone are switched on	2.08	4.81

Table 4 shows battery life decreases with load, lasting 500 h unloaded, 5.37 h for a bulb, 50 h for phone charging, and 4.81 h for combined loads. The system favors low-power DC, and more piezo tiles could boost energy for broader use.

4 Discussion

4.1 Suitability of HPGM as Proof-Of-Concept Pavement Medium

HPGM shows high feasibility as a pavement material, with 28-day compressive strengths of 172.1 MPa (Group 1, 3% steel fiber, +14.6% vs. G1-ST0), 168.2 MPa (Group 2, high slag), and 170.4 MPa (Group 3, 80% LSS). Exceeding UHPC standards (120–150 MPa) and ACI 318 minimum (60 MPa) [4], HPGM is suitable for heavy-traffic pavements.

Flexural tests confirmed HPGM's superior performance. At 28 days, Group 1 with 3% steel fiber reached 16.4 MPa (+102.5% vs. fiber-free), Group 2 (high slag) 16.1 MPa, and Group 3 (LSS) + 5.1%. Compared with ASTM C78 (3–7 MPa) and AASHTO (4–5 MPa), HPGM exceeds 16 MPa, over three times the required strength ensuring excellent safety and durability for heavy-traffic pavements.

Immersion tests confirmed HPGM's excellent durability under aggressive conditions. In water, all groups retained $> 95\%$ strength with $\leq 0.36\%$ mass and $\leq 4.7\%$ strength loss, meeting ASTM C267. Under 5% NaCl, Group 1 showed the best performance ($\leq 0.13\%$ mass, $\leq 5.6\%$ strength loss), while Groups 2–3 had $\sim 3.6\%$ and 5.4–5.5%. No cracks appeared, only minor efflorescence, confirming chloride resistance suitable for de-icing conditions. In 5% H₂SO₄, Group 1 had 5.9–8.5% mass and 13.6–18.9% strength loss at 90 days; Groups 2–3 showed $\sim 7.1\%$ and $\sim 16.5\%$. Despite surface erosion and pH drop (3.6 \rightarrow 2.7), HPGM remained structurally intact, proving far greater acid resistance than conventional concrete.

HPGM is a promising pavement material, exceeding ACI, ASTM, and AASHTO standards and resisting water and NaCl. Acidic exposure causes some degradation, but performance remains adequate. Steel fibers offer the greatest improvement in strength and durability.

4.2 Potential Integration of Piezoelectric Systems into HPGM Blocks

Integrating piezoelectric systems into HPGM is promising because HPGM's ultra-high strength (> 170 MPa compression, > 16 MPa flexure) protects the elements from cyclic loading, and its excellent chemical resistance ensures durability in water, NaCl, and H₂SO₄, supporting both structural and environmental feasibility. Table 4 shows battery life under different loads: ~ 500 h at 0.02 A, ~ 50 h at 0.20 A, ~ 5.37 h for a 1.86 A lamp, and ~ 4.81 h for combined use. This indicates piezoelectric HPGM is suitable for low-power or intermittent applications like sensors, IoT transmissions, LEDs, or supercapacitor charging, rather than continuous high-power loads. Optimized arrays and energy management can sustain small currents (0.02–0.20 A) and extend battery life.

HPGM outperforms OPC and asphalt in strength, durability, and energy harvesting. Key practical measures include optimizing piezo placement, sealing elements, and integrating efficient circuits with supercapacitors and batteries for low-current loads (~ 0.02 A). A small-scale prototype can test energy output for sensors, LEDs, or device charging. Piezo-HPGM is feasible for low-power applications but not yet for high-power use.

5 Conclusion

This study showed that HPGM has high strength and durability under sulfate and chloride exposure. Integrated piezo elements powered low-energy devices, proving its potential as a strong, energy-harvesting pavement material. Using fly ash, slag, and silica fume in HPGM lowers embodied carbon and improves durability. Combined with piezo systems, it adds energy efficiency and smart functionality, making HPGM a key material for low-carbon, resilient, and energy-aware infrastructure.

While laboratory-scale results are promising, further studies are necessary to bridge the gap toward large-scale applications. Future research should focus on scaling up HPGM–piezoelectric pavement fabrication, optimizing costs through techno-economic assessments, and validating performance via long-term traffic and environmental tests. Advancements in circuit design and hybrid energy storage will also be essential to

maximize harvested energy use. Overall, integrating HPGM with piezoelectric systems offers a promising route to multifunctional, durable, and energy-harvesting pavements, requiring strong interdisciplinary collaboration to move from laboratory studies to real-world application.

Acknowledgment. This work was supported by Universiti Malaysia Sarawak through the VC High Impact Research Grant (UNI/F02/VC-HIRG/85527/P15-03/2022).

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