IFERP Explore Your Research Journey...

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 13, Issue 03, March 2026

Design and Performance Evaluation of Porous Pavement Integrated with Piezoelectric Energy Harvesting System

[1] Deepak Kumaran SR, [2] Aswin Bharath A, [3] Mohanraj V, [4] Muniasamy S, [5] Dinesh A

[1] [2] [3] [4] [5] Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India
Corresponding Author Email: [1] deepakkumaran1412@gmail.com, [2] aswinbharath.a.ce@kct.ac.in,
[3] mohanrajvelmurugan1@gmail.com, [4] muniyasamybosethamarai@gmail.com, [5] Dineshdeshna098@gmail.com

***Abstract*— Porous pavements are receiving increased attention in modern days in terms of their ability to improve stormwater management while creating sustainable pavements. In this paper, a porous pavement system is designed and evaluated for its performance in terms of a piezoelectric energy harvesting mechanism. The primary objective of this paper is to evaluate the mechanical properties of porous pavements using different percentages of fine aggregate replacement in terms of their ability to harvest energy. An experimental investigation was carried out on porous pavements in terms of cube specimens using different percentages of fine aggregate replacement, i.e., 0%, 5%, and 10% fine aggregate replacement in terms of 8mm size. The experimental results show that an increase in fine aggregate replacement percentages results in an increase in both compressive load and stress values for different curing periods. At 28 days of curing period, the porous pavements containing 10% fine aggregate replacement show better results in terms of both compressive load and stress values compared to other percentages of fine aggregate replacement. The compressive stress values for porous pavements containing 10% fine aggregate replacement are 1.728 MPa and a compressive load of 38.9 kN, while for 0% fine aggregate replacement, the values are 1.351 MPa and 30.4 kN. Similar results are obtained for 7 and 14 days of curing periods. The improved mechanical properties of porous pavements make them suitable for energy harvesting applications.**

***Index Terms*— Porous pavement, Piezoelectric energy harvesting, Compressive strength, Stormwater management, Sustainable infrastructure, Smart pavements.**

I. INTRODUCTION

The rapid growth in infrastructure and transportation networks has resulted in a surge in demand for pavement materials with high durability and performance characteristics. Traditionally, pavements have been designed to withstand loads and offer structural stability; nevertheless, environmental sustainability and energy efficiency have been given little attention in pavement design. One major disadvantage associated with the use of traditional dense pavements is that they are impermeable to water, thus failing to allow rainwater to infiltrate into the groundwater table during heavy rainfall periods. As a consequence, flooding and waterlogging are experienced in urban areas due to excessive surface runoff. These problems are major concerns in urban regions with rapid growth in impervious surfaces.

Porous pavements have been recognized as viable alternatives to traditional pavements due to their ability to allow water to infiltrate through the interconnected voids in the concrete matrix. The optimized mix design for porous concrete pavements used in heavy-load traffic has been found to improve compressive strength significantly while maintaining permeability characteristics adequately [1].

Porous pavements have been recognized to play a major role in sustainable urban drainage due to groundwater recharge during heavy rainfall periods. Porous concrete pavements have been widely recognized to be effective in improving hydraulic conductivity and reducing peak discharges in urban areas in sustainable infrastructure development strategies [2]. In addition to that, porous pavements have been found to be effective in reducing the urban heat island effect through enhanced evaporative cooling and reduced surface temperature accumulation.

Parallel to environmental concerns, modern transportation infrastructure produces significant amounts of mechanical energy, which is unused. The transportation infrastructure has been identified as one of the promising areas for decentralized renewable energy production, especially for pavement-based energy harvesting technology [3]. The compressive stress, vibrations, and deformation of pavement structures occur due to the movement of vehicles over the pavement infrastructure. The cyclic movement of vehicles over the pavement structure offers significant mechanical energy, which can be effectively converted into electrical energy using electromechanical transduction technology [4]. Mechanical energy is normally dissipated as heat and sound waves without any utilization of the mechanical energy of the vehicles. Therefore, the utilization of mechanical energy for generating renewable energy is an innovative opportunity, especially with the increasing demand for renewable energy worldwide. Piezoelectric technology has been widely used for energy harvesting, especially in civil engineering infrastructure, such as transportation infrastructure, where mechanical stress can be converted into electrical energy [5].

Piezoelectric materials have a distinct characteristic of generating electric charges when subjected to external stress. Piezoelectric ceramic materials, such as lead zirconate titanate (PZT), have high electromechanical coupling properties that can facilitate an efficient conversion of mechanical energy into electrical energy when subjected to compressive stress [5]. When applied in pavement systems, piezoelectric materials can harness energy from vehicular stress. Various experimental investigations on piezoelectric energy harvesting systems in pavement structures have confirmed that optimized structural systems can enhance the voltage output and power density of piezoelectric harvesters when subjected to simulated vehicular stress [7]. By integrating piezoelectric materials in porous pavement systems, a sustainable pavement system can be achieved for stormwater management and energy harvesting. Recent advancements in smart cement-based materials have confirmed that a sustainable pavement system can be achieved for stormwater management and energy harvesting in a single system [7].

The current paper focuses on the design and evaluation of a porous pavement system integrated with a piezoelectric energy harvesting system. The primary objective of the research is to evaluate the mechanical properties of porous concrete mix and its applicability in integrating piezoelectric energy harvesting systems without compromising its integrity. Various reviews have confirmed that successful implementation of energy harvesting systems in pavement structures is a function of integrating various disciplines in material science, structural engineering, and electrical engineering [8].

II. OBJECTIVE OF THE STUDY

The major aim of this research is to design and experimentally investigate a porous pavement system with a piezoelectric energy harvesting system appropriate for sustainable urban infrastructure applications. This study aims to design a porous concrete mix that can attain appropriate mechanical properties while retaining porosity levels sufficient for water infiltration.

Another aim of this research is to design a piezoelectric ceramic component and investigate its potential to produce electrical output under compressive load. This research also aims to investigate and analyse the compressive properties, density characteristics, and structural properties of porous concrete specimens with different percentages of fine aggregate content.

Finally, this study aims to investigate and evaluate the potential of such a system for applications such as pedestrian zones, parking areas, and low-traffic zones, where such a system can effectively utilize both stormwater management and energy harvesting. This study will create a base for developing a smart and energy-efficient pavement infrastructure.

III. RESEARCH GAP

Although extensive literature is available on porous pavements for stormwater management applications, most of the literature is focused on permeability characteristics and hydraulic behavior. However, the reduction in compressive strength for porous concrete mix design is a critical issue. Limited experimental investigations have been carried out to optimize mix design for multifunctional applications. New innovative ideas in terms of structural design for piezoelectric energy harvesters, such as power generation using footsteps, have been implemented to enhance energy harvesting using optimized mechanisms for energy transfer [10].

Similarly, extensive literature is available for piezoelectric energy harvesting systems integrated into rigid pavements and asphalt pavements. However, most of the literature is focused on dense pavement structures for highway applications involving heavy loads. Limited literature is available for integrating piezoelectric energy harvesting systems into porous pavements. Recent literature indicates that the compatibility of porous concrete mechanical properties with piezoelectric systems is essential for ensuring long-term durability under repeated loading conditions [9].

Additionally, limited experimental investigations are available for ensuring the compatibility of porous concrete mechanical properties for integrating piezoelectric systems. Recent advanced literature indicates that extensive investigations are required for ensuring improved efficiency for energy harvesting systems integrated into pavements. Additionally, long-term durability for repeated loading and environmental conditions is insufficiently documented. Recent advanced literature indicates that extensive investigations are required for ensuring improved efficiency for energy harvesting systems integrated into pavements. Additionally, long-term durability for repeated loading and environmental conditions is insufficiently documented. Recent advanced literature indicates that extensive investigations are required for ensuring improved efficiency for energy harvesting systems integrated into pavements. Additionally, long-term durability for repeated loading and environmental conditions is insufficiently documented [10].

The present investigation aims to bridge the existing gap in literature related to porous pavements for integrating piezoelectric energy harvesting systems.

IV. MATERIALS USED

The materials utilized in the development of porous pavement concrete cube and prototype were chosen to guarantee similarity, durability, and suitability in line with the relevant standards. All the materials were subjected to tests before the mixing process. Pervious concrete using recycled concrete aggregate can attain satisfactory levels of both mechanical strength and hydraulic properties when well proportioned [11].

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 13, Issue 03, March 2026

❖ OPC 53 Grade Cement

Ordinary Portland Cement (OPC) 53 Grade was utilized as the binder in the concrete mixture in the current study. The OPC 53 grade cement utilized in the development of the concrete mixture conforms to IS 269:2015 – Ordinary Portland Cement Specification. OPC 53 grade cement was chosen because of the improved early development of strength as well as the improved compressive strength properties compared with lower-grade cement. The selection of binder content significantly affects the mechanical performance and durability characteristics of porous concrete mixtures used in pavement applications [12].

The cement used in the mixture was fresh, free from lumps, and stored in a dry environment to prevent moisture absorption. The physical properties such as fineness and specific gravity satisfied standard requirements. The specific gravity of cement was taken as 3.15 for mix design calculations.

The use of OPC 53 grade cement ensured proper hydration and bonding between aggregates while maintaining the structural stability necessary for embedding piezoelectric elements within the porous concrete matrix.

❖ Fine Aggregate

Natural river sand was used as fine aggregate in controlled proportions of 0%, 5%, and 10% by weight of total aggregate to evaluate its influence on compressive strength and bonding characteristics.

The fine aggregate conformed to IS 383:2016 and was classified under Zone II grading. The sand was clean, well graded, and free from clay, silt, and organic impurities.

In porous concrete, fine aggregate is generally minimized to maintain permeability. However, a small percentage was included in this study to enhance bonding between aggregate particles and improve mechanical strength without significantly affecting porosity.

The specific gravity of fine aggregate used in mix proportion calculations was 2.66.

Figure 1

❖ Coarse Aggregate

Crushed angular coarse aggregates of 10 mm nominal maximum size were used in the preparation of porous concrete. The aggregates were clean, hard, durable, and free from organic impurities and other deleterious materials. Aggregate gradation plays an important role in controlling interconnected porosity, compressive strength, and permeability characteristics of pervious concrete pavements [13].

The coarse aggregates satisfied the requirements of IS 383:2016 – Coarse and Fine Aggregate for Concrete.

Since porous concrete relies on interconnected voids, uniformly graded 10 mm aggregates were used to achieve the desired porosity. The reduced fine aggregate content combined with controlled aggregate gradation ensured the formation of continuous void channels for water infiltration.

The specific gravity of coarse aggregate used in the mix design was 2.68. Aggregates were surface-dried before mixing to maintain an accurate water–cement ratio.

Figure 2

❖ Porous Concrete Specifications

The porous concrete mix was designed according to the guidelines of

- IS 456:2000 – Plain and Reinforced Concrete
- IS 10262:2019 – Concrete Mix Proportioning

The target grade was M30 with a water–cement ratio of 0.28. Reduced fine aggregate content was adopted to maintain the pervious nature required for stormwater infiltration. High-strength pervious concrete can be achieved through optimized aggregate–binder interaction while maintaining adequate void structure for drainage [14].

❖ Piezoelectric Components

To incorporate the energy harvesting feature within the pavement system, piezoelectric ceramic discs were used, which operate on the principle of direct piezoelectricity, where stress produces electrical charges on the material's surface. Piezoelectric materials such as PZT possess high electromechanical coupling properties, which can effectively convert compressive stress into electrical energy [5]. Applicability studies on piezoelectric-based energy harvesting confirm that the system can withstand stress while maintaining stable electrical properties [15].

Although there is no specific IS code available for piezoelectric ceramics, the materials used for the project were commercial-grade piezoelectric ceramic elements, which operate on the principle of piezoelectricity, used for mechanical-to-electrical energy conversion. Stacked piezoelectric-based energy harvesting components show better voltage production characteristics than single piezoelectric elements [16].

Components used for the prototype:

- Piezoelectric Ceramic Disc
- IN4007 Diode (Rectifier)
- 10 µF Capacitor (Energy Storage)
- 5 mm LED (Output Indicator)
- Push Switch
- MDF Board (Base Support Structure)

Diode: The diode rectifier is used for converting AC voltage, which is obtained from the piezoelectric ceramic element, into DC voltage.

Capacitor: The capacitor stores electrical energy temporarily.

LED: The 5 mm LED is used for indicating the electrical energy production, which is obtained after applying mechanical stress.

Integrated electrical and mechanical analysis of piezoelectric pavement materials, which can operate on bidirectional cyclic loads, indicate constant voltage production characteristics [17].

Figure 3

❖ **Water**

Potable water, which is free from harmful impurities, oils, acids, salts, and other organic matter, is used for mixing purposes. The water used for the project meets the requirements of IS 456:2000 – Plain and Reinforced Concrete Code of Practice.

Water affects the properties of concrete, including cement hydration, which affects the strength of concrete. Therefore, drinking water is used for the project so that adverse chemical reactions can be avoided within the concrete matrix itself. The water-cement ratio of innovative pervious concrete mixtures indicates that water can be used for improving strength properties [18].

V. METHODOLOGY

The experimental methods of this research were designed around the investigation of both the mechanical and electrical properties of a combined system. Initially, a mix design for a porous concrete was developed to produce an M30 with a water-cement ratio of 0.28. Test specimens were created using three different amounts of fine aggregate (0%, 5%, and 10%) by weight of the cement.

Concrete cubes (150 mm × 150 mm × 150 mm) were cast and then compacted sufficiently. After 24 hours of demoulding specimens they were cured for 7, 14 and 28 days in water.

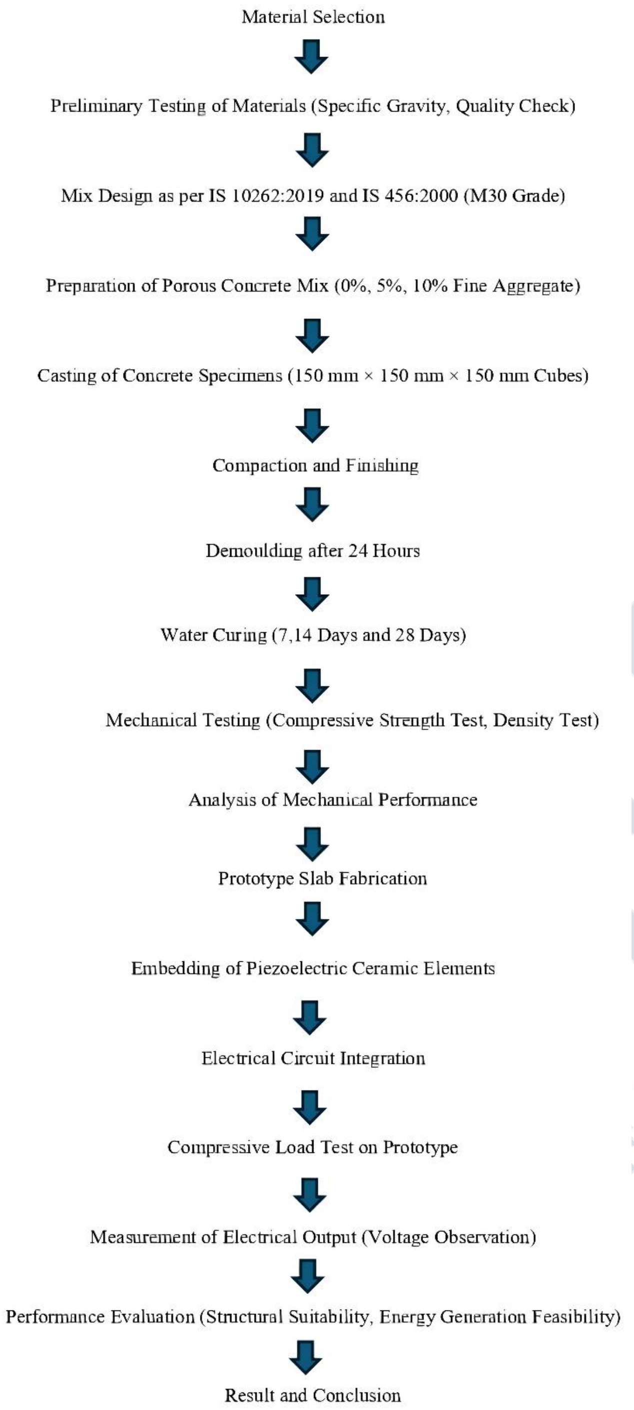
After the completion of the curing period, compression testing on the concrete cylinders was carried out using the Compression Testing Machine (CTM). The maximum load applied at failure was recorded and used to calculate compressive stress for each specimen. The results of the compression testing were used to conduct multiscale finite element simulations that showed how electromechanical responses of piezoelectric harvesters integrated into the porous concrete matrix are affected by the distribution of mechanical stress and the extent to which loads from the surrounding environment were confined to the embedded piezoelectric devices [19].

Density testing was carried out by calculating the density of the specimens based on their weight and their volume measured.

A prototype slab containing piezoelectric ceramic elements was fabricated in the second phase. The piezoelectric discs were embedded into a porous concrete matrix and connected to a rectifier-capacitor circuit. Compressive loading was applied manually in order to simulate traffic-induced loading, and the output of electricity was monitored using illuminated LEDs. Experience indicates that the optimal design of an embedded piezoelectric harvester involves maximizing the stress amplification of the embedded piezoelectric device while transferring loads from the traffic to the embedded piezoelectric device as efficiently as possible to maximize the production of electrical energy [20].

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Volume 13, Issue 03, March 2026

Flow Chart of Methodology



VI. MIX DESIGN

The concrete mix design for the porous pavement was carried out in accordance with the guidelines of IS 456:2000. The mix was designed for M30 grade concrete to achieve adequate mechanical strength while maintaining interconnected voids for permeability. Fine aggregate was not used to ensure proper drainage characteristics.

Design Parameters:

The key parameters adopted for mix design are summarized in Table 1

Table 1. Design Parameters for concrete mix

Parameter	Value
Type	OPC 43 grade
Grade of Concrete	M30
Maximum size of aggregate	8 mm
Exposure condition	Severe
Water-cement ratio	0.28
Target slump	0-25mm
Method of Compaction	Manual/vibrator
Cube size	150 × 150 × 150 mm

The water-cement ratio of 0.28 was selected based on durability requirements specified in IS 456:2000. A low slump of 0–25 mm was adopted to maintain porosity in concrete.

Water Content

For porous concrete with 8 mm coarse aggregate and no fine aggregate, the water content is determined based on selected water-cement ratio.

Assuming water content = 180 kg/m³

Water-cement ratio (W/C) = 0.28

Cement Content

Based on selected W/C ratio of 0.28,

Cement Content = Water Content / Water-Cement Ratio

Cement Content = 180 / 0.28

Cement Content = 642.85 kg/m³

The calculated cement content satisfies the minimum cement requirement of 320 kg/m³ for severe exposure condition (IS 456:2000).

Aggregate Proportion

The quantities of coarse aggregates were determined following IS mix design procedures. The final quantities adopted for one cubic meter of concrete are as follows:

Mix ratio adopted = 1: 0: 2 (Cement: Fine Aggregate: Coarse Aggregate)

Since fine aggregate is not used:

Fine aggregate = 0

Coarse aggregate = 2 parts

Coarse aggregate content:

CA = 2 × Cement

CA = 2 × 642.85

CA = 1285.7 kg/m³

- Coarse aggregate = 1285.7 kg/m^3

These values are maintained constant for all batches of porous pavement concrete.

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 13, Issue 03, March 2026

Quantity of Materials Per Cube

The cube mould size used in the study
150 mm × 150 mm × 150 mm
Volume of cube = 0.15 × 0.15 × 0.15= 0.003375 m^3

The porous block mould size used in the study was 150mm x 150mm x 150mm, corresponding to a volume of 0.003375 m^3. The quantities of materials required for one porous block are presented in Table 2.

Table 2. Materials Quantities per paver block

Material	Quantity (kg)
Cement	2.17
Water	0.61
Fine aggregate	0
Coarse aggregate	4.34

Fine Aggregate Replacement Levels (Trial Mix Study)

Trial mixes were prepared by introducing fine aggregate at replacement levels of 0%, 5%, and 10% by weight of coarse aggregate to study its effect on strength and permeability of porous pavement concrete.

All other mix constituents such as cement content, water-cement ratio (0.28), and aggregate grading were kept constant in order to evaluate only the influence of fine aggregate addition on the performance of concrete cubes.

Observation:

❖ At 5% and 10% fine aggregate,

- Slight improvement in compressive strength was observed.
- However, permeability was reduced due to partial blockage of interconnected voids.

❖ At 0% fine aggregate,

- Adequate compressive strength was achieved.
- Maximum porosity and drainage performance were maintained.

Based on strength and permeability comparison, 0% fine aggregate (no fine aggregate) was selected as the optimum mix proportion for porous pavement.

MIX DESIGN RATIO

Specific gravity of cement = 3.15
Specific gravity of coarse aggregate = 2.68
Specific gravity of water = 1
Grade of concrete = M30
Type of cement = OPC 43

❖ Target strength

$F'_{ck} = F_{ck} + (1.65 \times S)$
$F'_{ck} = F_{ck} + X$
$F'_{ck} = 30 + (1.65 \times 5) = 38.25$
$F'_{ck} = 30 + 6.5 = 36.5$

$F'_{ck} = 38.25 \frac{N}{mm^2}$

❖ Water cement ratio

W/C = 0.28
For severe exposure condition, W/C ≤ 0.45 (IS 456 Table 5)
Provided = 0.28 → SAFE

❖ Mix calculations

Volume of concrete = 1 m^3
Volume of cement = $\frac{mass}{spc.gravity \times 1000}$
= $\frac{642.85}{3.15 \times 1000}$ = 0.204 m^3
Volume of water = $\frac{180}{1 \times 1000}$ = 0.18 m^3
Volume for coarse aggregate = 1 – (0.204 + 0.18) = 0.616 m^3
Mass of coarse aggregate = 0.616 × 2.68 × 1000
Mass of CA = 1650.88 kg

VII. TESTING AND VALIDATION

- **Compressive Strength Test:**

Compressive strength testing was conducted using a calibrated Compression Testing Machine. Load was applied gradually until specimen failure. Stress values were calculated using the formula:

Stress = Load / Area

Figure 4

- **Density Test:**

Density testing was performed by measuring the specimen weight and dividing by its volume

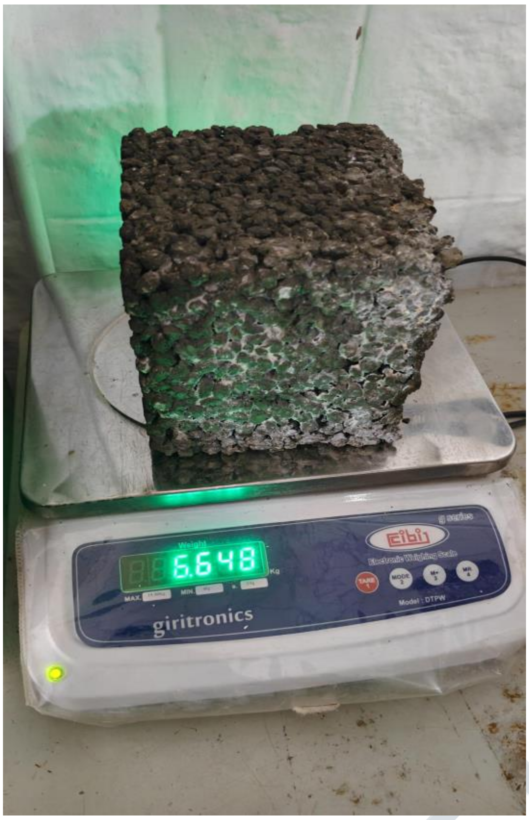


Figure 5

- **Water Absorption Test**

To evaluate porosity we have tested porous cube with water.

Figure 6

- **The Piezoelectric Validation Test**

The piezoelectric validation test involved applying compressive load to the embedded sensor. The generated alternating current was rectified using the diode and stored in the capacitor. Successful LED illumination confirmed electrical energy generation.

Figure 7

Figure 8

Figure 9

Figure 10

VIII. RESULTS AND DISCUSSION

The mechanical evaluation of porous concrete specimens and the testing of an integrated design to produce energy via piezoelectric devices are presented in this section. The analysis produced a detailed evaluation of how different amounts of fine aggregates affect compressive strength and suitability for energy harvesting application.

A. Performance of Porous Concrete Specimens under Compressive Loads

Porous concrete specimens were tested for compressive strength after 7, 14, and 28 days of curing using a mix of 0%, 5% and 10% fine aggregate. The strength increases as the curing time increases and as the fine aggregates (up to 10%) were added to the mix.

At 7 days, the control mix (0% fine aggregate) had lower compressive strength than the mixes with %, 5% and dry fine aggregate due to the greater void volume and lower bond strength between the aggregate and cement; however, the addition of 5% fine aggregate resulted in a greater load carrying capability of the porous concrete specimens as the inter-particle bond strength between the cement paste and aggregate particles was improved. The mix with 10% fine aggregate had the highest compressive strength at early ages of all specimens, indicating improved matrix continuity in the matrix without a significant reduction of the pore connectivity.

At 14 days, the strength developed with time (and in a similar manner) as the addition of fine aggregates contributed to better bonding to and greater stiffness of the structure due to the hydration products created from the fine aggregate. The addition of fine aggregates also reduced the size of micro-voids that existed between coarse aggregates resulting in the better distribution of stress to the coarse aggregates during loading.

At 28 days for the 10% fine aggregate mix maximum load is 38.9 kN and compressive stress is 1.728MPa. Whereas maximum load and compressive stress of the control mix was 30.4 kN and 1.351MPa respectively. The observed strength gain suggests that including a limited amount of fine aggregate does enhance mechanical performance while still preserving the porous properties of the final product. The increase in compressive stress due to the length of time cured supports the conclusion that there is proper hydration and structural densification occurring within the cementitious matrix.

Though the compressive strength levels obtained are less than standard M30 concrete due to intentional void space, they still provide an adequate level of strength for use in applications such as pedestrian pathways, parking lots, and low-volume traffic pavements.

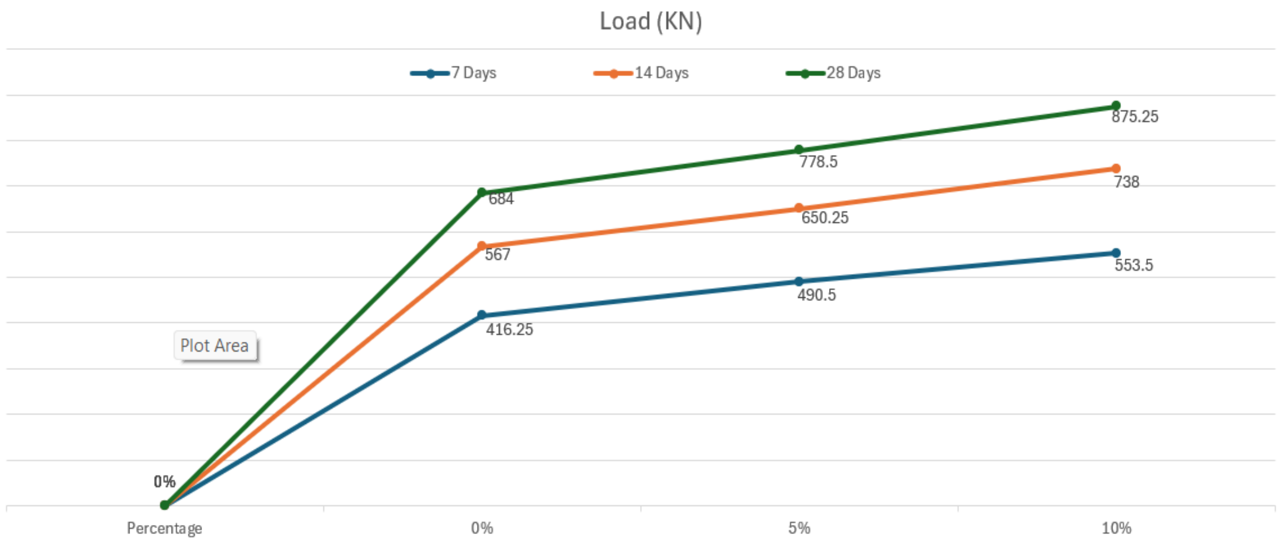
Table 1

Percentage	**7 Days**		**14 Days**		**28 Days**	
	Load (KN)	Stress (MPa)	Load (KN)	Stress (MPa)	Load (KN)	Stress (MPa)
0% of Fine Aggregate	416.25	18.5	567	25.2	684	30.4
5% of Fine Aggregate	490.5	21.8	650.25	28.9	778.5	34.6
10% of Fine Aggregate	553.5	24.6	738	32.8	875.25	38.9

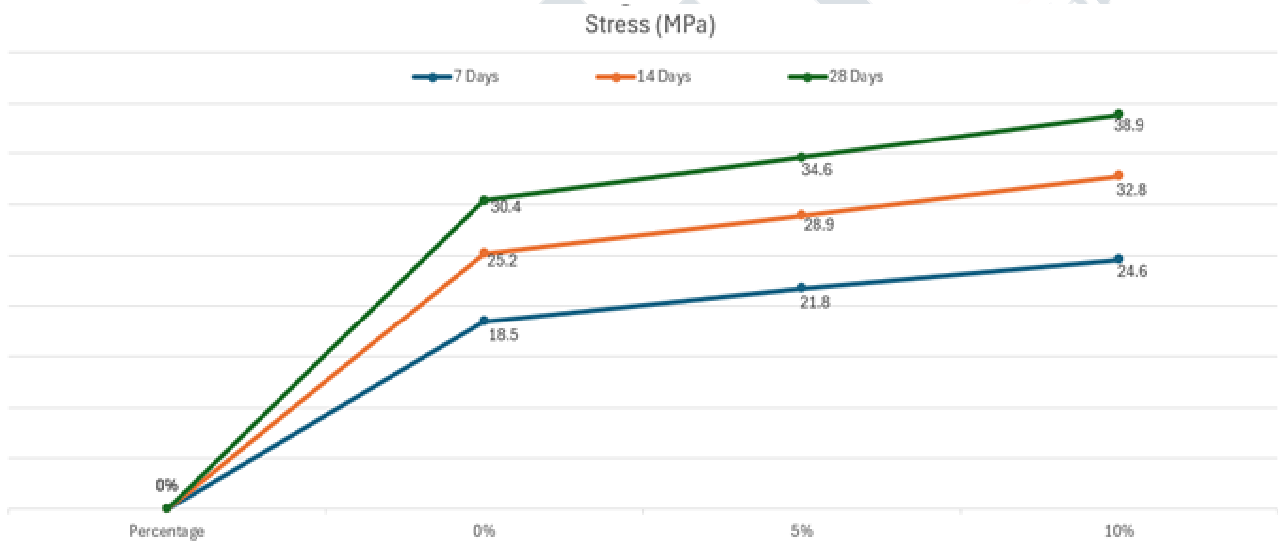
ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Volume 13, Issue 03, March 2026

Graph:

Load Results:



Stress Results:



B. Density Characteristics

The density tests show that the specimens have lower density than conventional concrete, confirming that they are porous. The lower density was caused by the presence of interconnected voids in the concrete, which were the result of very little fine aggregate in the mixture. Even though a lower density would reduce structural stiffness compared to denser concrete, it is necessary for allowing water to infiltrate into the system.

With 5% and 10% fine aggregates being added, the density of these mixtures was slightly harder than the control mixture because of the partial filling of voids and better compaction. However, the densities were still considerably lower than those found in regular concrete, maintaining the permeability characteristics of the porous concrete.

C. Structural Suitability for an Embedded Piezoelectric

The primary goal of the mechanical evaluation testing was to determine if the porous concrete structure would have sufficient strength to support the installation of the embedded piezoelectric element. The testing showed that the 10% fine aggregate mixture had the capacity to handle more loads and had better cohesion of the mixture, meaning that it was a viable option for embedding sensors into the concrete matrix.

The porous nature of concrete creates localized stress conditions because of the void distributions. Adding a limited amount of fine aggregate to the mixtures would help to reduce the localized stress conditions by increasing the bonding between adjacent particles and by providing an increased number of pathways for transferring the stress

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 13, Issue 03, March 2026

through the concrete matrix. Protecting the embedded piezoelectric ceramic disc from premature cracking or disbanding is extremely important.

The experimental results confirm that optimized porous concrete can be utilized in controlled compressive loading while maintaining sufficient stiffness to achieve an effective transfer of stress to the piezoelectric elements.

D. Piezoelectric Energy Generation Performance

After testing the prototype porous concrete block using piezoelectric ceramic discs, there was evidence of mechanical stress on the block due to traffic related stresses being applied on the block. Through dynamic-piezoelectric simulation modeling, the combined dynamics of the pavement system along with the influence of load frequency showed that both stiffness of the pavement and load frequency had a significant effect on the power output from the embedded piezoelectric devices (see reference [21]. Under the compression load, the embedded piezoelectric device produces alternating electrical power determined by the mechanical strain applied to the block.

This electrical power generated was conditioned by a rectifying diode (IN4007) and then stored in a 100uF capacitor. The illumination of an LED after multiple load cycles provided confirmation of a successful mechanical-to-electrical energy transfer process.

While the amount of electrical power produced from a single load cycle was very low; multiple load cycles created a cumulative storage of electrical charge. This shows that traffic-induced mechanical energy can be successfully harvested and used to power low energy devices such as LED lighting, wireless devices, and monitoring devices. The full-pressure piezoelectric transducers used in the roadway structures display reliable and higher energy output from the piezoelectric systems when subjected to simulated vehicular loads [22].

Piezoelectric elements do not severely impact the structure of the porous slab in the prototype. Less power can be produced by piezoelectric power harvesters than could be generated from the mechanical loads placed on them by using piezoelectric harvesters more effectively by placing them in locations to maximize their mechanical loads with their designs will create a much larger amount of output power [23]. Thus, confirming that porous concrete systems are compatible for energy harvesting with piezoelectric systems. By strategically optimizing the layout of multilayer piezoelectric structures, the efficiency of stress/energy conversions in energy harvesting systems built in roadways will be enhanced significantly [24].

E. Overall Evaluation of Performance:

The research performed in this project determined an optimal porous pavement mix that then can successfully support both the structural integrity as well as functionally provide an energy harvest. A 10% fine aggregate will provide the optimal balance of adding to the compressive strength while maintaining the porosity of the pavement. The piezoelectric porous structures produced by 3D printing of this project produced higher energy output as well as better stress/electric response than conventional road energy harvesting systems produced using piezoelectric aggregates [25].

The system developed through this project has great benefits associated with its dual function:

- Stormwater infiltration and groundwater recharge
- Renewable micro-energy
- Reduction of the urban heat island effect
- Integration with smart infrastructure.

This research supports the use of multifunctional pavements that can be used in addressing energy challenges and environmental issues at the same time.

IX. CONCLUSION

A study was conducted to examine how well a porous pavement system combines with a piezoelectric device to harvest energy and how to evaluate both its design and performance. The primary emphasis of this study was to evaluate the mechanical properties of the porous concrete with different percentages of fine aggregate and its application to embed energy-harvesting devices. An extensive review of the literature identified the rapid evolution of roadway energy harvesting techniques due to advances in material types, device designs and methods of integrating them into existing roadway structures [26].

Based upon the compressive strength tests, adding small amounts of fine aggregate dramatically improved the load-bearing capacity, while still providing a porous concrete structure. Compressive strength of the 10% fine aggregate concrete mix was greater than all other mixes, at all three (3) curing periods tested. Additionally, the gradual increase in strength over time indicates the development of a strong hydrating matrix. The most recent evaluations demonstrate that improving the conversion efficiency of electrical output and improving the structural integrity of the system are critical challenges to overcome prior to large-scale implementation [27].

Density analysis clearly confirmed the expected porous nature of the concrete and therefore determined its suitability for stormwater management systems. Adding renewable energy harvesting systems to the design of pavement engineering will enhance sustainable development goals as well as provide support for smart infrastructure initiatives [28]. The compressive strengths measured in (the) research have lower compressive strength than typical (M30 Dense) Concrete of comparable density; however, are suitable for use as a surface for pedestrian & Roadways that have light moderate traffic. Innovative energy harvesting Cementitious materials also use piezo (electric) materials, thermoelectric and photovoltaic to create multifunctional building materials that can be utilized/ implemented in future infrastructure systems [29].

Validation of the prototype and development of attached energy harvesting equipment to provide demonstration that Mechanical stress on the pavement caused by (vehicles moving) creates energy into the (attached) Energy harvesting systems through embedded piezoelectric ceramic materials by generating/storage of electrical energy will be able to provide power to Low Power Devices

This paper supports that Porous Pavement with Integrated Technologies used to Capture/harvest Piezoelectric will help create technologically smart/ sustainable urban infrastructure systems. In recent research- the utilization of AI- based presenting models for Traffic Conditions and loading conditions will produce more efficient analysis and optimize the Energy harvesting systems [30]. The development of multi-functional transport infrastructure is aided by the integration of both renewable energy generation and stormwater management within one pavement system as outlined above. The implementation of advanced materials and integrated smart technologies are anticipated to accelerate the practical implementation of roadway energy harvesters in the future [10].

Practical application of this energy-harvesting technology will require future studies focused on large-scale field deployment, assessment of long-term durability under cyclic loading, evaluation of permeability, investigation of fatigue behavior, and estimation of cost/benefit analysis. In terms of material characteristics, energy-harvesting cementitious materials that integrate piezoelectric, thermoelectric and photovoltaic mechanisms will provide multifunctional infrastructure capabilities for future systems [29].

REFERENCES

[1] H. D. X. Z. Z. H. R. H. T. Y. Ailing Yao, "Optimum Design and Performance of Porous Concrete for Heavy-Load Traffic Pavement in Cold and Heavy Rainfall Region of NE China," *Advances in Materials Science and Engineering*, no. 1, 2018.

[2] V.-C. A.-V. D. J.-E. J. R.-H. Eduardo-Javier Elizondo-Martínez, "Review of porous concrete as multifunctional and sustainable pavement," *Journal of Building Engineering*, vol. 27, p. 100967, 2020.

[3] A. J. X. C. Hao Wang, "Energy harvesting technologies in roadway and bridge for different applications – A comprehensive review," *Applied Energy*, vol. 212, pp. 1083-1094, 2018.

[4] F. G. J. Z. B. Z. Y. B. R. L. Jianzhong Pei, "Review and analysis of energy harvesting technologies in roadway transportation," *Journal of Cleaner Production*, vol. 288, p. 125338, 2021.

[5] J. H. Y. Y. S. Ledia Shehu, "Piezoelectric Energy Harvesting for Civil Engineering Applications," *Energies*, vol. 17, no. 19, p. 4935, 2024.

[6] A. C. C. D. Eugenio Brusa, "A Review of Piezoelectric Energy Harvesting: Materials, Design, and Readout Circuits," *Actuators*, vol. 12, no. 12, p. 457, 2023.

[7] J. Z. L. L. Chaohui Wang, "Optimization design and experimental investigation of piezoelectric energy harvesting devices for pavement," *Applied Energy*, vol. 229, pp. 18-30, 2018.

[8] V. R. N. K. L. C. E. E. Dianah Mazlan, "Piezoelectric Concrete: A Smart Material Approach for Energy-Harvesting Structural Technologies," *Journal of Sustainable Construction Materials and Technologies*, vol. 10, no. 4, 2025.

[9] E. G. S. L. S. B. E. C. Domenico Vizzari, "Pavement energy harvesting technologies: a critical review," *RILEM Technical Letters*, vol. 6, 2021.

[10] S. N. S. A.-H. G. W. H. Shasha Firzanah Binti Mohamad Zahid, "Innovative Piezoelectric Energy Harvesting Design for Footstep-Driven Power Generation: Analysis and Performance Evaluation," *2024 IEEE 12th Conference on Systems, Process & Control (ICSPC)*, 2024.

[11] M. S. Niloufar Zabihi, "Recent Developments in the Energy Harvesting Systems from Road Infrastructures," *Sustainability*, vol. 12, no. 17, p. 6738, 2020.

[12] Y. K. M. L. G. D. A. A. S. Yuan Shen Chua, "A Survey of Advanced Materials and Technologies for Energy Harvesting from Roadways," *Electronics*, vol. 13, no. 24, p. 4946, 2024.

[13] V. F. P. D. Â. G. G. W. P. N. F. R. M. M. Helena Lunkes Strieder, "Performance evaluation of pervious concrete pavements with recycled concrete aggregate," *Construction and Building Materials*, vol. 315, p. 125384, 2022.

[14] K. T. J. M. M. Aamer Rafique Bhutta, "Evaluation of high-performance porous concrete properties," *Construction and Building Materials*, vol. 31, pp. 67-73, 2012.

[15] B. T. T. F. L. Chu, "Evaluation of functional characteristics of laboratory mix design of porous pavement materials," *Construction and Building Materials*, vol. 191, pp. 281-289, 2018.

[16] J.-X. L. H. Z. S. L. C. S. P. Peiliang Shen, "Conceptual design and performance evaluation of high strength pervious concrete," *Construction and Building Materials*, vol. 269, p. 121342, 2021.

[17] S. W. G. W. Chaohui Wang, "Applicability evaluation of embedded piezoelectric energy harvester applied in pavement structures," *Applied Energy*, vol. 251, p. 113383, 2019.

[18] Z. S. G. Y. W. Chaohui Wang, "Preparation and performance research of stacked piezoelectric energy-harvesting units for pavements," *Energy and Buildings*, vol. 183, pp. 581-591, 2019.

[19] Z. L. X. Z. W. Z. G. C. L. W. Feilong Ye, "Research on integrated electrical and mechanical response of piezoelectric asphalt pavement material under bidirectional cyclic loads," *Construction and Building Materials*, vol. 375, p. 130957, 2023.

[20] Y. Z. Y. Z. X. P. Jiusu Li, "Preparation and performance evaluation of an innovative pervious concrete pavement," *Construction and Building Materials*, vol. 138, pp. 479-485, 2017.

[21] P. L. J. Y. L. J. O. Cong Du, "Evaluation of the piezoelectric and mechanical behaviors of asphalt pavements embedded with a piezoelectric energy harvester based on multiscale finite element simulations," *Construction and Building Materials*, vol. 333, p. 127438, 2022.

[22] H. Z. J. Z. Z. S. Z. Kangxu Huang, "The optimal design of a piezoelectric energy harvester for smart pavements," *International Journal of Mechanical Sciences*, vol. 232, p.

107609, 2022.

[23] J. P. J. W. L. S. J. W. Peng Wang, "Coupled dynamic and piezoelectric response of RPEHs embedded in road under traffic load via multiscale finite element models," *Smart Materials and Structures,* vol. 32, 2023.

[24] F. Z. S. Z. L. L. H. Yangsen Cao, "Energy harvesting performance of a full-pressure piezoelectric transducer applied in pavement structures," *Energy and Buildings,* vol. 266, p. 112143, 2022.

[25] J. L. A. S. L. Z. L. Yangsen Cao, "A power-intensive piezoelectric energy harvester with efficient load utilization for road energy collection: Design, testing, and application," *Journal of Cleaner Production,* vol. 369, p. 133287, 2022.

[26] M. R. M. Y. A. H. Najoua Fangachi, "Smart piezoelectric energy harvesting: how topology-optimized cavities boost performance in BaTiO3 multilayer structures," *Smart Materials and Structures,* 2025.

[27] Y. H. L. W. Shiping Song, "3D printed piezoelectric porous structure with enhanced output performance and stress-electricity response for road energy harvesting," *Additive Manufacturing,* vol. 72, p. 103625, 2023.

[28] M. A. M. M. A. F. Saifuddin Ahmad, "Energy harvesting from pavements and roadways: A comprehensive review of technologies, materials, and challenges," *International Journal of Energy Research,* vol. 43, no. 6, pp. 1974-2015, 2019.

[29] L. W. H. Q. Shijing Chen, "A Review on the Technologies and Efficiency of Harvesting Energy from Pavements," *Energies,* vol. 18, no. 15, p. 3959, 2025.

[30] D. A. F. A. Z. A. M. H. D. A. M. A. R. A. H. A. N. M. Mohammad Ali KHASAWNEH, "Renewable energy in pavement engineering and its integration with sustainable materials: A review paper," *Materials Research Forum LLC,* vol. 43, pp. 377-384, 2024.

[31] V. S. S. D. Y. M. R. A. R. O. A. A. S. Raja, "Energy-harvesting cementitious materials for sustainable infrastructure: a critical review of piezoelectric, thermoelectric, and photovoltaic mechanisms," *Innovative Infrastructure Solutions,* vol. 11, 2026.

[32] M. M. Souad Touairi, "Energy Harvesting Efficiency Analysis Using Artificial Intelligence," *International Symposium on Dielectric Materials and Applications,* p. 45–69, 2025.