Modelling & Analysis of Porous Pavement with Automatic Drainage Control for Urban Flood Management

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Abstract— **Urban flooding poses a significant and increasing threat to cities worldwide, occurs due to rapid urbanization, expanding impermeable surfaces, and Escalating precipitation events due to climate change. Conventional urban drainage systems (CUDS) are increasingly inadequate to manage the resulting increases in surface runoff volumes and peak flow discharge. This research presents the modelling and analysis of an integrated porous pavement system with automated drainage control for urban flood management, using Hindmata, Mumbai a chronically flood-prone low-lying junction as the Focus area. Porous pavement specimens were prepared at two cement-to-aggregate ratios 1:3 and 1:4 with a water-cement ratio of 0.35(As per reference), and their compressive strength and infiltration characteristics were evaluated. The 1:3 mix achieved a higher 28-day compressive strength of 11.2 N/mm² and lower permeability, whereas the 1:4 mix achieved a lower 28-days compressive strength of 8.1 N/mm² and higher permeability due to its increased void content. A five-year monsoon precipitation dataset (2021–2025) was acquired from the NASA POWER database, and the peak event of 161.68 mm/hr on 4 July 2022 was identified as the design storm. The SCS-CN method was employed to develop unit hydrographs for runoff estimation. An automated drainage control prototype was developed using a tipping bucket rain gauge (TBRG) and Arduino-based control logic: during high-intensity rainfall, a servo-actuated drain gate diverts excess water to groundwater recharge systems, while during low-intensity events, the gate remains closed to allow natural infiltration through the porous pavement. Results demonstrate that the integrated system effectively reduces surface runoff (15 to 25%), and promotes sustainable groundwater recharge. The study also identifies clogging as a key limitation affecting long-term pavement permeability and recommends periodic maintenance strategies. This research contributes a practical, low-cost, and scalable framework combining green infrastructure with smart control technology for flood-resilient urban drainage design.**

I. INTRODUCTION

Urban drainage systems constitute a critical component of municipal infrastructure, engineered to collect, convey, and discharge stormwater runoff from impermeable surfaces such as roads, sidewalks, and rooftops, thereby preventing surface waterlogging and reduce flood risk (1)(2).These systems are designed to regulate excess rainwater, safeguarding built assets from hydraulic stress and reducing public health and safety risks related with stagnant water (2)(3).Traditionally, their primary function has been the rapid removal of stormwater from urban environments to prevent flooding and infrastructure damage and protect from stagnant water diseases(5).

However, the effectiveness of conventional urban drainage systems (CUDS) is being increasingly challenged by rapid urbanization, climate change, and infrastructural constraints. (4)(6)(7). A major problem is the incidence of urban flooding due to heavier precipitation events and the gradual decline of system capacity over time (6)(8). Multiple cities, particularly in developing countries, exhibit drainage infrastructure that is either inadequate for current hydrological demands or persistently blocked by sediment, debris, and waste, significantly reducing hydraulic capacity (4)(6). The continuous expansion of impermeable surfaces, such as concrete and asphalt, further "worsens this issue by raising runoff coefficients and peak flow rates, while also decreasing the natural infiltration that is crucial for groundwater recharge (9) (6)(10). This hydrological disconnection not only heightens flood risk but also leads to waterlogging, traffic disruption, and adverse environmental and economic consequences. (2) (6)(7). The economic and social consequences of urban floods are considerable, representing the policy and political decisions over time (11).

In response to these widespread challenges, Sustainable Urban Drainage Systems (SUDS), also referred to as Water Sensitive Urban Design (WSUD) or green infrastructure, have developed as a transformative approach to urban stormwater management (12)(13)(14). SUDS represent a paradigm shift from treating stormwater as a waste product to be disposed of, to recognizing it as a valuable resource to be managed in an eco-friendly and sustainable manner (12)(7). The important principle behind SUDS is to mimic natural hydrological processes, such as infiltration, evapotranspiration, and water storage, within the urban fabric, thereby helping to reestablish the natural water balance (12)(15). By controlling runoff as close to its source as possible, SUDS aim to reduce flood risk, enhance water quality, and provide wider environmental and social advantages (12)(16).

A wide range of SUDS components is available to achieve these objectives. Common methods include green roofs, which store water and delay runoff through soil media and plant evapotranspiration (17)(18); rain gardens, which are planted depressions designed for infiltration and remove pollutant; infiltration trenches, providing underground storage and groundwater replenishment (19). and detention and retention basins, which provide scalable attenuation of stormwater flows (20). These methods collectively help to reduce surface runoff volumes and peak flows, enhancing overall water management and supporting to urban resilience against climate change (21)(22)(23).

Among these sustainable drainage solutions, porous pavement systems (PPS) are particularly significant for their dual functionality, acting as load-bearing surfaces while facilitating stormwater infiltration (24)(5)(25). Permeable pavements, such as porous asphalt (PA) and porous concrete, are constructed with a highly permeable structure that enables water to infiltrate directly through the surface into underlying layers, which usually consist of a base and sub-base with high void content (26)(27)(28). This percolation significantly lowers surface runoff and contributes to groundwater recharge, effectively mitigating urban flooding risks and improving the natural water cycle (27)(29)(30). Studies has consistently demonstrated the capacity of porous pavements to manage stormwater quantity and quality, removing pollutants such as suspended solids and different chemical contaminants (31)(29)(10). Research, such as those examining stormwater harvesting from permeable pavements, highlight their ability to conserve potable water in buildings by collecting and reusing infiltrated rainwater (30). The long-term effectiveness of these systems, however, can be affected by clogging from sediments accumulation, which reduces infiltration capacity and requires proper evaluation and maintenance strategies (31)(19). Acknowledging these limitations, the integration of automatic drainage operating mechanisms and real-time monitoring systems can substantially enhance the performance and flexibility of permeable pavement systems, enabling for optimized infiltration, storage, and regulated release of stormwater in dynamic urban environments, thereby further improving urban flood management (32).

II. POROUS PAVEMENT:

Porous pavement is a type of paving system constructed with a permeable surface layer that enables rainwater and surface runoff to infiltrate through its structure and percolate into the underlying soil (33).Unlike conventional impervious pavements made of dense concrete or asphalt, porous pavements are built using materials with high air void content such as porous concrete, porous asphalt, or permeable interlocking pavers allowing stormwater to flow freely through the pavement structure (34). A typical porous pavement system comprises a porous surface layer, a filter fabric, a reservoir course (coarse aggregate base with high air void content for temporary water storage), and the underlying subgrade soil (34)(33).

The interconnected void network is the defining feature; for instance, porous asphalt is described as a "highly permeable asphalt surface" engineered specifically for water transmission (35). Porous pavements provide stormwater management (reducing runoff volume and peak loads), groundwater recharge, traffic noise reduction, improved wet-weather skid resistance, urban heat island mitigation, and pollutant filtration (36)(34). Porous pavements are typically deployed in low-to-moderate traffic areas such as parking lots, pedestrian walkways, residential driveways, bicycle paths, and service roads (34). They are not recommended for highways with heavy traffic, steep slopes, areas prone to erosion, or locations where hazardous chemical spills are likely (34).

III. METHODOLOGY:

In this study, existing literature review was performed according to Hindmata Mumbai The primary Objective of this research is to analyze and evaluate an integrated, sustainable, and smart solution for urban flood management The methodology involves a systematic progression beginning with material characterization to the construction of a porous pavement model, culminating in the integration of an automated drainage control system.

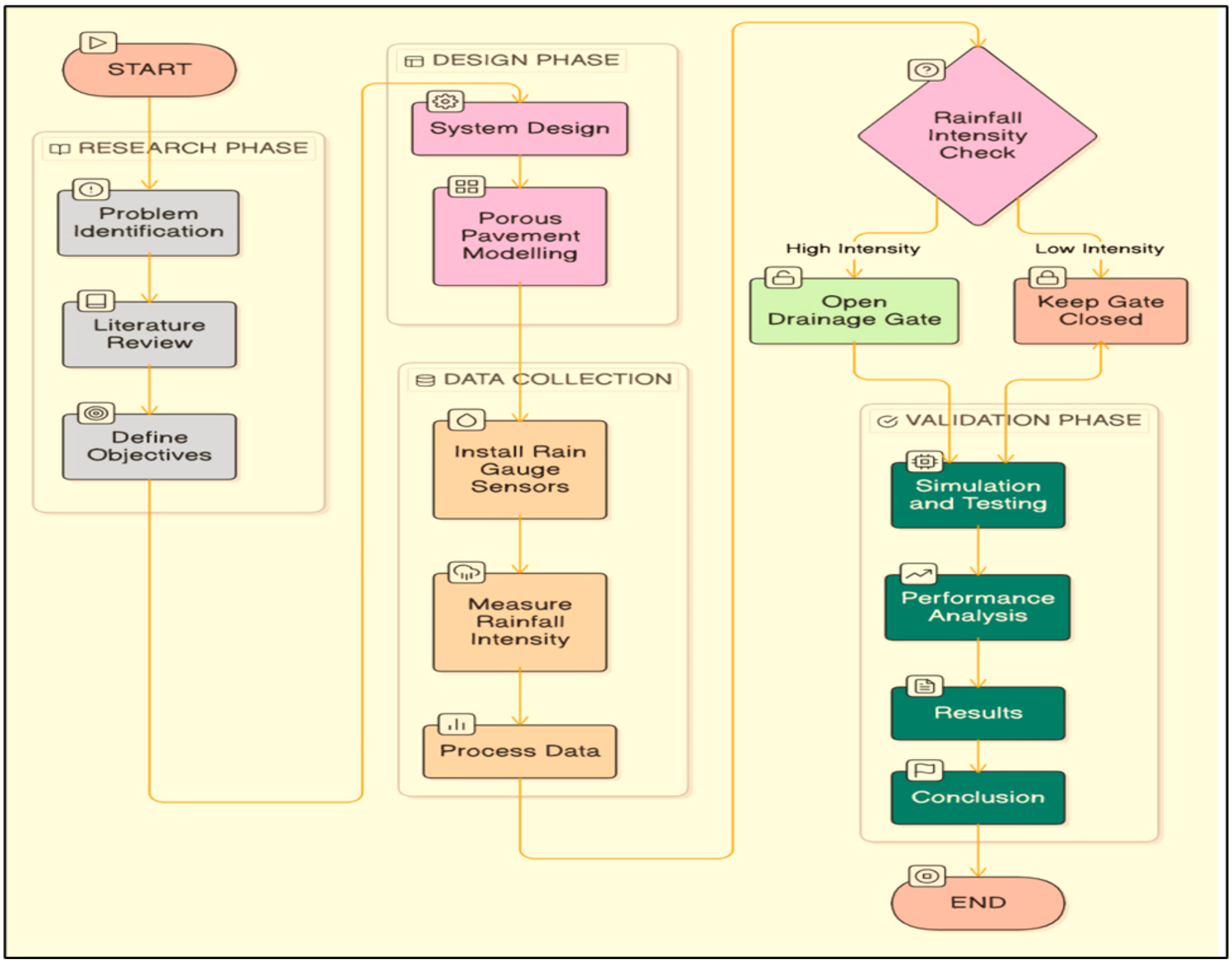


Figure 1 Methodology Flowchart

3.1 Mix Design of Porous Pavement:

The selection of suitable materials plays a vital role in achieving both high permeability and sufficient structural strength in porous pavement. The system was designed using Ordinary Portland Cement (OPC) as the binding agent and single-sized coarse aggregate retained on a 12.5 mm sieve. Both mix proportions (1:3 and 1:4) were investigated to analyze the comparison between compressive strength and permeability. The 1:3 mix achieved higher compressive strength because of increased in cement content but showed relatively lower permeability. In on the other hand, the 1:4 mix showed enhanced permeability due to its higher void content, albeit at the expense of reduced compressive strength. The coarse aggregate size of 12.5 mm was selected based on porous pavement studies indicating that aggregate gradation and size are primary determinants of void content, permeability, and compressive strength in permeable concrete.

The water–cement (w/c) ratio is a critical parameter governing both the workability of the fresh mix and the final pore connectivity. For each cement-to-aggregate ratio, a w/c ratio of 0.35 was maintained, consistent with established practices in pervious concrete mix design, where typical values range from 0.30 to 0.40. A lower w/c ratio results in a stiffer cement paste that coats the aggregates while preserving void interconnectivity, whereas an excessively high w/c ratio may cause the paste to drain into the pores, thereby reducing permeability by blocking flow paths.

Table 1 shows the compressive strength of porous pavement with two different ratios.

Table 1 Compressive Strength of Porous Pavement

Mix proportion	7 days strength N/mm^2	14days strength N/mm^2	28 days strength N/mm^2
1:3	3.4	5.1	11.2
1:4	6.3	10.8	8.1

3.2 Rainfall Analysis:

3.2.1 Study Area

The study area is Hindmata, Mumbai, a chronically flood-prone low-lying junction in South-Central Mumbai, India. Hindmata is located at the confluence of several stormwater drainage channels and experiences recurrent waterlogging during the Southwest Monsoon season (June–September). Its selection as the study site is motivated by the critical need for sustainable urban drainage interventions in this locality.

3.2.2 Data Acquisition

The precipitation data for the period 2021–2025 were obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database, which provides satellite-derived meteorological parameters at a spatial resolution of 0.5° × 0.5°. The data extraction was confined to the four peak monsoon months June, July, August, and September which collectively account for over 90% of Mumbai's annual rainfall.

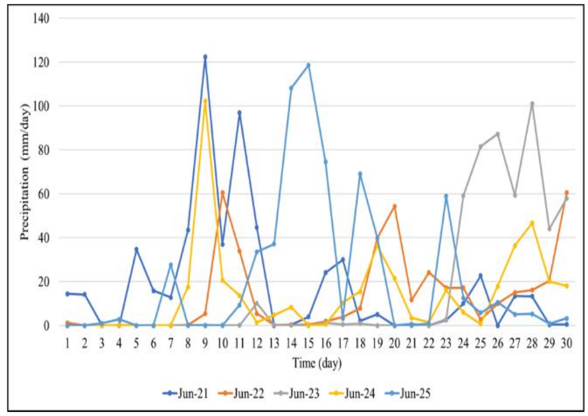


Figure 2 Five Year Daily Precipitation Records of June

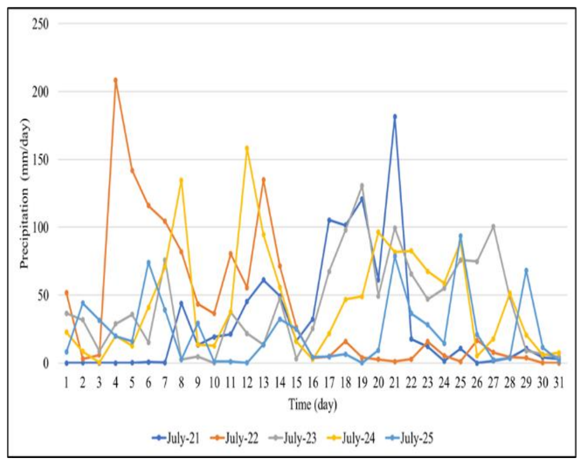


Figure 3 Five Year Daily Precipitation Records of July

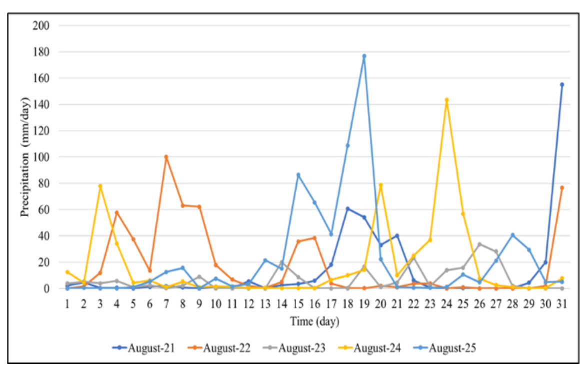


Figure 4 Five Year Daily Precipitation Records of August

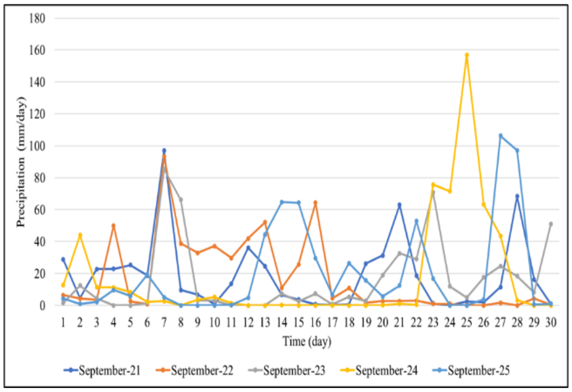
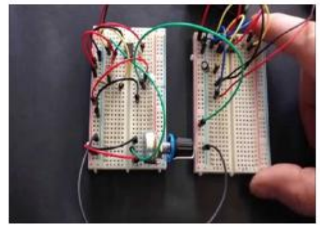


Figure 5 Five Year Daily Precipitation Records of September

3.2.3 Identification of Design Storm Event

An analysis of the five-year daily precipitation record identified 4 July 2022 as the date of maximum recorded rainfall, with a peak daily accumulation of 161.68 (mm/hr). This event was selected as the design storm for hydrological modelling of the pavement drainage system.

The selection of the extreme event ensures that the designed system is tested against a near-worst-case scenario within the observed record.

Components	Function
 TBRG	Measures rainfall by collecting water and generating pulse signals when bucket tips
 Arduino Uno	Processes input signals and executes control logic
	Converts electrical signals into controlled rotational movement
Servo Motor	
 Breadboard & Jumper Wire	Provides temporary circuit connections without soldering

3.2.4 Unit Hydrograph Development Using the SCS-CN Method

The Soil Conservation Service Curve Number (SCS-CN) method was employed to estimate the effective rainfall (runoff depth) from the gross rainfall.

3.3 Sensor:

A prototype model was developed to implement an automated drainage control system. Table 2 shows different components & their respective functions used in sensor.

Table 2 Components & Functions of Sensor Accessories

3.3.1.Working of Sensor

The rainfall sensor continuously monitors both the occurrence and intensity of rainfall, sending real-time signals to the Arduino for processing. The Arduino then analyzes this data based on predefined threshold values to determine the appropriate response. In cases of high rainfall intensity, the system activates the drain gate, allowing excess water to be efficiently diverted into designated drainage channels. This diverted water is subsequently directed towards groundwater recharge systems, promoting sustainable water management. Conversely, during low-intensity rainfall, the drain gate remains closed, enabling the water to be naturally absorbed through the porous pavement, thereby enhancing infiltration and reducing surface runoff.

3.4 Model Development:

A laboratory-scale prototype model was developed to represent the functioning of the proposed porous pavement system integrated with controlled drainage. A plastic container was used as the base structure for the model due to its ease of handling, availability, and suitability for observing water movement through different layers.

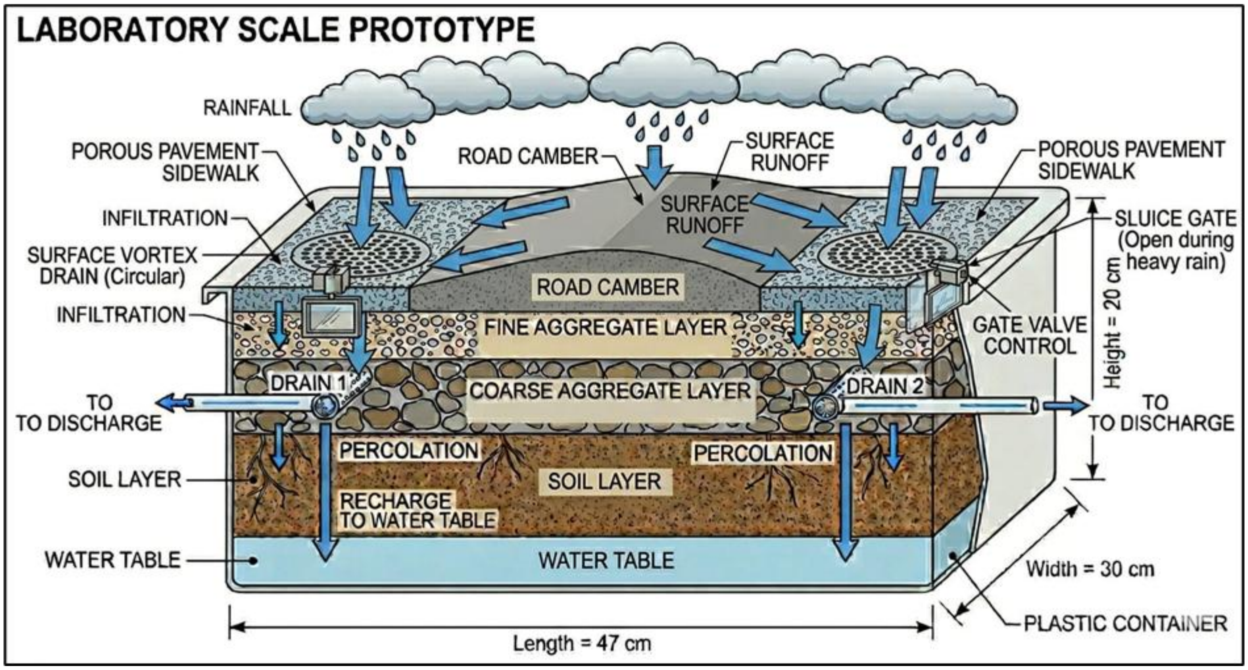


Figure 6 Laboratory Scale Prototype

At the bottom of the container, groundwater table is simulated. Above this, the pavement structure was constructed by placing different layers similar to those observed in actual road construction. These layers included coarse aggregates and supporting base materials arranged in a sequence to replicate the subgrade, sub-base, and base layers of a pavement system.

The thickness of each layer was determined proportionally based on the dimensions of the container, ensuring that the model simulates field conditions within the limited scale. Care was taken to preserve the void structure necessary for proper infiltration.

At the top surface, a porous pavement layer was provided to allow water to infiltrate through the system. Additionally, porous sidewalks were constructed on both sides of the pavement to enhance infiltration and simulate real urban road conditions.

Two drainage channels were incorporated along the sides of the model to manage excess water. These drains were connected to an outlet system, allowing controlled discharge when rainfall intensity exceeds the infiltration capacity. This setup helps in demonstrating both infiltration and drainage processes under varying rainfall conditions.

The developed model provides a simplified yet effective representation of real-world pavement behavior, enabling the study of water movement, infiltration efficiency, and drainage performance under controlled experimental conditions.

IV. RESULT AND DISCUSSION:

The developed prototype system consisting of porous pavement, tipping bucket rain gauge, and automated drainage mechanism was evaluated under simulated rainfall conditions.

4.1 Performance of Porous Pavement:

The porous pavement prepared using two different water–cement ratios (1:3 and 1:4) demonstrated effective infiltration characteristics. The 1:3 mix exhibited higher compressive strength but lower permeability, whereas the 1:4 mix showed lower compressive strength and higher permeability due to its increased void content. It was observed that low-intensity rainfall was effectively infiltrated through the pavement, resulting in a significant reduction in surface runoff and promoting percolation into the underlying layer, thereby contributing to groundwater recharge. Based on a target rainfall intensity of 41.72 mm/hr, as obtained from the unit hydrograph, the infiltration capacity of the porous pavement was estimated to range from 6.26 to 10.43 mm/hr, corresponding to an infiltration efficiency of 15% to 25%. Consequently, the remaining runoff was managed by the drainage system, which achieved an estimated drainage efficiency of 75% to 85%, indicating effective stormwater handling under the given conditions.

4.2 Rainfall Analysis Results:

The rainfall data analysis for the Hindmata region revealed that the most critical rainfall event occurred on 4 July 2022, during which the maximum rainfall intensity recorded was 161.68 mm/hr. The developed hyetograph using the SCS-CN method indicated a high runoff potential during peak rainfall hours, along with rapid accumulation of surface water in conventional pavements. These findings justified the need for a combined system of infiltration and controller drainage.

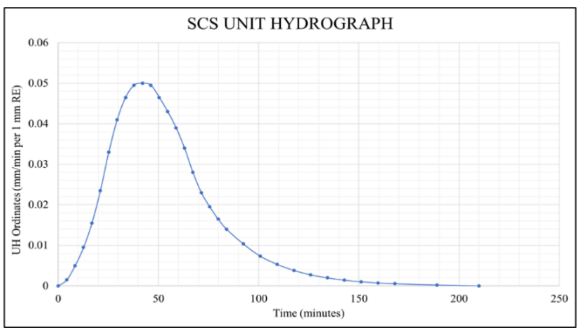


Figure 7 Unit Hydrograph for 4th July 2022

4.3 Sensor and Drainage System Performance:

The tipping bucket rain gauge successfully measured rainfall in terms of tip counts, where each tip corresponded to a fixed rainfall depth (mm per tip), and the total rainfall was accurately calculated using the cumulative tip count. The system demonstrated that at higher rainfall levels, an increased tipping frequency was observed, prompting the Arduino-based system to activate the drainage mechanism. However, it was also observed that a slight delay occurred in response due to the tipping mechanism, and while the sensor provided accurate cumulative rainfall data, it did not offer instantaneous measurements.

V. CONCLUSION

The present study successfully developed a prototype of a smart porous pavement system integrated with a tipping bucket rain gauge and automated drainage mechanism.

The results indicate that:

1. Porous pavement effectively enhances infiltration and reduces runoff.
2. The tipping bucket rain gauge provides reliable rainfall measurement.
3. The automated drainage system efficiently manages excess stormwater, achieving an estimated drainage efficiency of 75% to 85% by handling the remaining runoff not absorbed by the pavement.

Although the tipping bucket sensor introduces a slight delay in real-time response, it remains highly effective for rainfall quantification and system triggering based on accumulated rainfall.

Overall, the proposed system demonstrates a practical and sustainable solution for urban stormwater management, particularly in flood-prone areas like the Hindmata region in Mumbai

VI. LIMITATION & FUTURE SCOPES:

The present study evaluates the performance of porous pavement integrated with a rainfall measurement and automated drainage system for stormwater management. The results indicate that the system effectively enhances infiltration and reduces surface runoff; however, certain limitations are identified. A primary concern is clogging, wherein fine sediments accumulate within the pore structure, leading to a progressive reduction in permeability and drainage efficiency over time, as also reported in previous studies. Furthermore, the porous mix, particularly with a higher aggregate ratio (1:4), exhibits reduced compressive strength, thereby limiting its applicability under heavy traffic loading conditions. Long-term durability is also a challenge due to exposure to environmental factors such as repeated wetting–drying cycles and temperature variations, which may accelerate material degradation. The system requires periodic maintenance to sustain its functional performance, which may increase operational complexity. In addition, the present investigation is based on a laboratory-scale model, which may not fully capture field-scale variations such as heterogeneous soil conditions and dynamic loading. The estimated drainage efficiency (75–85%) is derived from a mass balance approach considering infiltration capacity, and lacks validation through continuous real-time flow measurements. Moreover, the accuracy of rainfall input is dependent on the calibration and sensitivity of the tipping bucket rain gauge.

Despite these limitations, the study presents significant scope for future research and development. The incorporation of geotextile layers and optimized aggregate gradation can be explored to mitigate clogging and enhance long-term permeability. Advanced material modifications, including fiber reinforcement and polymer additives, may improve both mechanical strength and durability. The integration of IoT-based monitoring systems can facilitate real-time assessment of rainfall intensity, infiltration rate, and drainage efficiency, thereby improving system reliability. Automated maintenance mechanisms, such as self-cleaning or backflushing systems, can further enhance operational efficiency. Future studies should focus on large-scale field implementation to validate laboratory findings under real environmental and traffic conditions. Additionally, the use of advanced instrumentation, such as flow sensors and soil moisture probes, can provide more accurate quantification of system performance. Such developments would contribute to the optimization and wider adoption of porous pavement systems as a sustainable solution for urban stormwater management.

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