SMART DRAIN CONCRETE CONCRETE-BASED SMART DRAINAGE SYSTEM INNOVATION

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ABSTRACT

Objective: This study presents the development and evaluation of Smart Drain Concrete, an innovative drainage system designed to reduce urban flash floods and promote sustainable water management. The objectives of this study were to design a modular U-shaped precast drain, evaluate the water absorption performance, evaluate the compressive strength of the microbiological concrete mix, determine the flow rate through the ECO2GC Darin Cover and build a prototype for urban applications.
Research Method: The system was constructed using Grade 40 concrete enhanced with 3% Bacillus subtilis to improve durability and self-healing properties, combined with the Eco2GC drain cover, natural filtration layer and porous pipe. Laboratory testing was carried out according to BS EN 12390-7:2019 standards, with water absorption assessed by oven drying and immersion methods, BS EN 12390-3:2019 for compressive strength tested using cube specimens under controlled load and BS EN 12390-8:2012 for Determination of Flow Rate through Concrete.
Findings: The results of the study showed that microbiological concrete achieved a compressive strength of 45 MPa on day 28, a permeability of 0.03 mm, demonstrating a balance between structural strength and hydraulic function. The porosity test value with a flow rate value of 0.199 liters/second showed that the porous system maintained hydraulic efficiency. A 1:4 scale prototype test confirmed the system's ability to control absorption, filter impurities and enhance groundwater reabsorption. The originality of this study lies in the integration of microbiological self-healing technology with sustainable drainage design, enabling dual structural and ecological performance.
Findings: Furthermore, collaboration with industry partner VCI IBS Sdn. Bhd. highlights its commercialization potential through pilot-scale testing, IoT-based monitoring and sustainability certification. Overall, Smart Drain Concrete shows high potential as a scalable, cost-effective and environmentally friendly drainage solution for housing, green building and smart city applications, in line with global sustainability goals (SDGs 6, 9, 11, 12 and 13).

Keywords: Smart Drain Concrete, Microbial self-healing concrete, Sustainable drainage systems, Compressive strength, Groundwater recharge

1. INTRODUCTION

Rapid urbanisation and increasingly intense rainfall patterns have significantly increased the vulnerability of Malaysian cities to flash floods. Between 1970 and 2024, 31 major flood events were recorded, affecting millions of residents and causing substantial economic losses (Ahmad et al., 2025). A major contributing factor is the limitation of conventional reinforced-concrete drainage infrastructure, much of which is impermeable, ageing, and designed primarily for rapid stormwater discharge rather than sustainable water management (Rosmadi et al., 2023). The expansion of impervious urban surfaces further intensifies runoff volumes and peak flows; even a 10% increase in impermeable cover can significantly elevate flood risk (Bibi et al., 2023). Consequently, existing drainage systems often experience overtopping, structural cracking, sediment accumulation, and high maintenance requirements.

Sustainable Urban Drainage Systems (SuDS) have been widely adopted in countries such as the United Kingdom, Japan, and Singapore to mitigate runoff peaks, improve water quality, and enhance groundwater recharge (Zhou, 2014; Gaurkhede et al., 2024; Ngong Deng et al., 2024). In Malaysia, although SuDS principles are acknowledged in the Urban Stormwater Management Manual (MSMA) (JPS, 2012), implementation has largely focused on surface-based interventions, with limited innovation in the material composition and structural configuration of subsurface drainage components (Kashaf et al., 2025). As a result, opportunities to enhance both durability and hydraulic performance at the material level remain insufficiently explored.

Recent advances in microbial biotechnology have introduced self-healing concrete as a promising approach to improving the durability and sustainability of cementitious materials. Among microbial agents, Bacillus subtilis has demonstrated strong viability in alkaline cement matrices and the ability to induce calcium carbonate ($CaCO_3$) precipitation through microbial-induced calcite precipitation (MICP) (Feng et al., 2021; Chaurasia et al., 2022). This process enables autonomous crack sealing of up to approximately 1 mm, reduces permeability, and enhances compressive strength and long-term durability (Kumar et al., 2023; Wong et al., 2024). Studies have also reported stable mechanical performance of Bacillus subtilis–enhanced concrete under repeated moisture exposure and tropical environmental conditions (Rahman et al., 2025). Despite these promising findings, research has predominantly concentrated on structural applications such as beams and slabs, while the integration of microbial self-healing concrete into drainage infrastructure exposed to continuous wetting–drying cycles and hydraulic loading remains limited (Sukumaran et al., 2025).

Furthermore, although modular sustainable drainage systems incorporating natural filtration layers have shown potential in reducing surface runoff and improving water quality (Rahman et al., 2022; Yusoff et al., 2024), empirical evidence on combining such systems with microbial self-healing concrete to achieve both structural resilience and hydraulic efficiency is scarce. This indicates a clear research gap at the intersection of microbial self-healing material technology and sustainable urban stormwater management.

To address this gap, the present study proposes and evaluates a Smart Drain Concrete system incorporating Bacillus subtilis–based self-healing technology within a modular drainage framework. The system integrates microbial-enhanced Grade 40 concrete with an Eco2GC drain cover and multilayer natural filtration components to improve crack resistance, water conveyance efficiency, and infiltration performance. This research aims to (i) design a modular self-healing drainage structure, (ii) evaluate its mechanical and hydraulic performance using standardized laboratory tests, and (iii) assess its feasibility as a sustainable, scalable alternative to conventional reinforced-concrete drainage systems. By combining bio-based material innovation with sustainable drainage principles, this study contributes to the development of resilient and eco-efficient urban stormwater infrastructure aligned with Sustainable Development Goals (SDGs 6, 9, 11, 12, and 13).

2. METHODOLOGY

The research methodology was systematically designed to achieve the four stated study objectives. The study began by establishing the background of the research, followed by identifying the problem statement and defining the objectives of the study. A literature review was then conducted to provide the theoretical foundation and to guide the selection of materials and procedures. Next, laboratory work was carried out, leading to the design and construction of the prototype. After the prototype was developed, laboratory testing was performed to evaluate its performance through a water absorption test, a compressive strength test, and a porosity test. Finally, the findings were analyzed to form the basis for the study's conclusions and recommendations.

2.1 SYSTEM DESIGN AND CONSTRUCTION

The design and construction of the Smart Drain Concrete system was carried out systematically with a focus on three main components, namely the U-shape precast drain, Eco2GC Drain Cover, and the natural filtration layer. Each component is designed to work in an integrated manner to ensure the effectiveness of the system in controlling water flow, filtering impurities, and increasing the rate of groundwater reabsorption in urban areas prone to flash floods. The basic component of this system is the U-shape precast drain as shown in Figure 1. This U-shaped precast drain is constructed using Grade 40 concrete mixed with 3% Bacillus subtilis bacteria based on the weight of cement to increase resistance to microcracks and provide natural self-healing capabilities. The dimensions of this modular structure are 255 mm long, 284 mm high, and 230 mm internal width. This design allows for easy modular connection and is suitable for use in various urban surface conditions. This drain acts as the main channel to channel rainwater in a controlled manner, while maintaining structural strength against mechanical stress and water erosion.

Next, the Eco2GC Drain Cover component as illustrated in Figure 2 plays an important role as a protective cover for the system. This cover is designed to allow rainwater to flow in efficiently while filtering leaves, sand, and floating materials to prevent blockages in the channel. The cover has dimensions of 255 mm × 284 mm × 30 mm with a circular hole of 30 mm diameter arranged in the center to ensure uniform water flow. This ergonomic design not only improves the efficiency of the drainage system but also enhances the safety, maintenance, and aesthetics of the surrounding area. In addition, the structure of this cover allows rainwater to be channelled directly into the system without affecting the stability of the road surface or walkway.

The third component is the natural filtration layers which are the most important part of the entire Smart Drain Concrete system as shown in Figure 3. This layer consists of several material arrangements, including a sand layer that functions to filter fine particles, a gravel layer that acts as a drainage medium and stabilizer, and a perforated pipe placed in the middle of the system to channel the filtered water into the ground or underground channel. All of these layers are separated by a geotextile layer that functions to prevent cross-contamination between layers, maintain structural stability and extend the life of the system. The combination of all of these layers mimics the natural function of the soil, allowing rainwater to slowly seep into the system while filtering impurities, thus helping to reduce surface water runoff and supporting groundwater reabsorption.

Overall, the Smart Drain Concrete design that combines the U-shape precast drain, Eco2GC Drain Cover, and filtration layers demonstrates a comprehensive integration between engineering strength and ecological function. Not only can this system accommodate high water flows, it also promotes sustainable water management in line with the Sustainable Development Goals (SDG 6: Clean Water and Sanitation and SDG 11: Sustainable Cities and Communities). Its modular design also facilitates installation in residential areas, green buildings, and smart cities, making it an innovative, sustainable and commercializable drainage solution.

A Smart Drain Concrete construction design with precast U-drain, Eco2GC cover and porous layer was designed as part of the research. Bacillus subtilis (3 weight percent) was added to the grade 40 concrete mix to improve durability. Laboratory tests were conducted according to water absorption BS EN 12390-7:2019, compressive strength BS EN 12390-3:2019 and porosity test BS EN 12390-8:2012 standards. To verify the performance under simulated conditions, a 1:4 scale prototype was created (VCI IBS Sdn Bhd, 2025). Figures 1,2, and 3 are shown a diagram of U-shape drain, Eco2GC Drain Cover and Smart Drain Concrete.

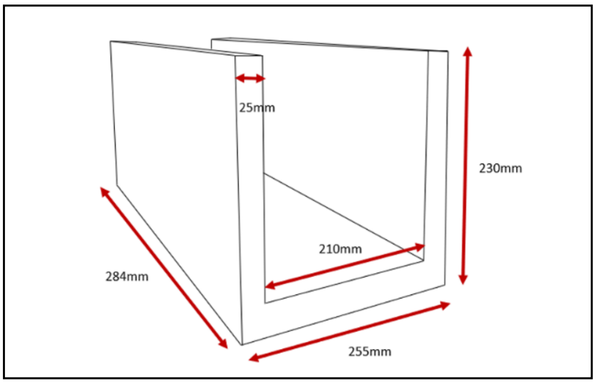

Figure 1: U-shape drain

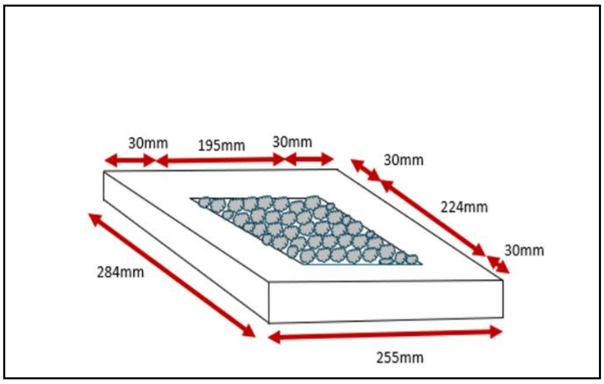

Figure 2: Eco2GC Drain Cover

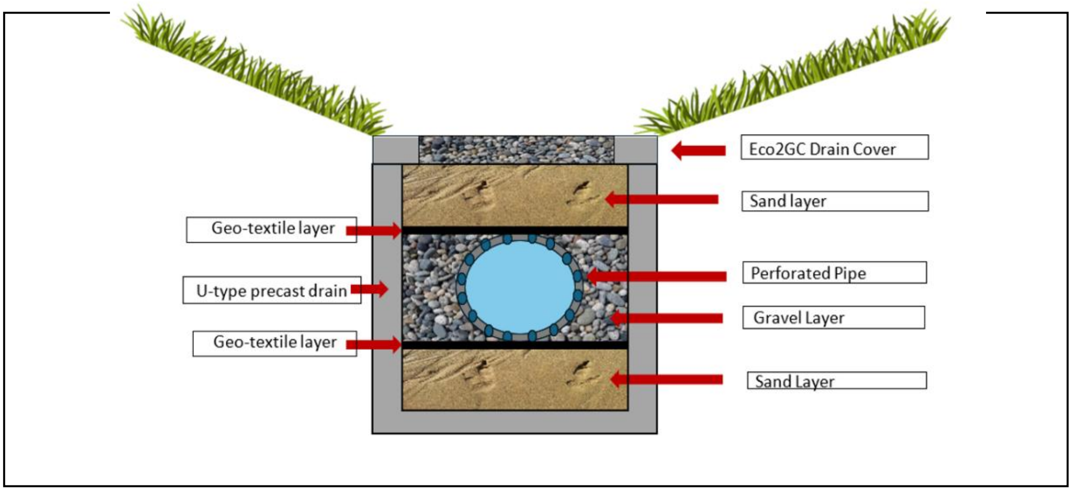

Figure 3: Smart Drain Concrete Diagram

2.2 PHYSICAL AND MECHANICAL PERFORMANCE TESTING

To achieve the second and third objectives of the study, several laboratory tests were conducted to evaluate the physical and mechanical performance of the Smart Drain Concrete system. These tests were conducted based on the BS EN 12390 standard to evaluate the level of durability, permeability and water and load resistance of concrete supplemented with 3% Bacillus subtilis bacteria. The addition of these bacteria aims to enhance self-healing ability, close micro pores, and increase resistance to water absorption.

The first test is the Water Absorption Test (BS EN 12390 -7:2019 which aims to evaluate the ability of concrete to control water ingress while maintaining structural stability. Cube-shaped concrete samples are dried in an oven until they reach constant mass, then immersed in water for 24 hours. The percentage of water absorption is calculated based on the difference between saturated weight and dry weight. This process evaluates the extent to which microbial concrete can reduce excessive water absorption through the presence of calcium carbonate precipitation by Bacillus subtilis.

The second test is the Compressive Strength Test which aims to evaluate the strength of concrete structures against vertical loads. Concrete cube samples were tested using a compression testing machine under controlled load rates in accordance with BS EN 12390-3:2019. The maximum strength value obtained indicates the ability of concrete to withstand forces before structural failure occurs. This method is also important to assess the effects of bacterial addition on the integrity and strength of building materials.

The third test is the Porosity Test (Adapted from BS EN 12390-8:2012) which assesses the rate of water flow through porous and non-porous concrete systems. This test is carried out by measuring the amount of water flowing through the sample over a certain period of time under constant pressure. This method allows for the assessment of the hydraulic performance of the drainage system and the efficiency of the porous layer in filtering water and maintaining a stable flow rate.

Overall, the implementation of these three tests aims to assess the balance between mechanical strength and hydraulic performance of the Smart Drain Concrete system. This assessment forms the basis for the development of a smart drainage system that is not only sound in terms of engineering, but also efficient in terms of ecology and urban sustainability.

2.3 BUILD A PROTOTYPE FOR URBAN APPLICATIONS

This section explains the implementation of the fourth objective of the study, namely the construction and evaluation of a Smart Drain Concrete system prototype for real-world applications in urban areas. The prototype was designed in a 1:4 scale to evaluate the system's performance under controlled conditions that mimic the natural environment of urban rainfall and surface water flow. The prototype developed incorporates three main components of the system, namely the U-shape precast drain, Eco2GC Drain Cover, and natural filtration layers. This design not only emphasizes structural strength and hydraulic function, but also effectiveness in filtering rainwater and promoting groundwater reabsorption.

The main material used is Grade 40 concrete enhanced with 3% Bacillus subtilis bacteria, which functions to increase structural durability and provide self-healing ability against micro-cracks. The prototype was built using a precast mold designed by industry partner VCI IBS Sdn. Bhd., to mimic the actual method of modular concrete production at industrial sites. The results show that the prototype system maintains stable flow efficiency and is able to filter coarse impurities before the water is released into the soil or outlet. This proves that the Smart Drain Concrete system has great potential for use in urban areas as a sustainable drainage solution that supports the concept of green infrastructure and the Sustainable Development Goals (SDGs 6, 9, 11, 12 and 13).

The following is table 1 that explains the components and functions of the Smart Drain Concrete and the following figure 4 showing the Prototype of Smart Drain Concrete Diagram.

Table 1: Components and functions of the Smart Drain Concrete

Component	Engineering Function	Ecological Function
U-shape Drain	Main structural component that supports loads and channels water flow	Reduces soil erosion and surface flooding
Eco2GC Drain Cover	Filters coarse debris while allowing rainwater to enter the system	Minimises solid waste entering the drainage system
Sand and Gravel Layers	Acts as a physical and hydraulic filtration medium	Mimics the natural soil function to promote water infiltration
Perforated Pipe	Channels filtered water to the	Supports groundwater recharge

	lower layer or subsurface drainage system	
Bacillus subtilis in Concrete	Seals microcracks and enhances structural durability	Promotes the concept of green construction materials through biotechnology

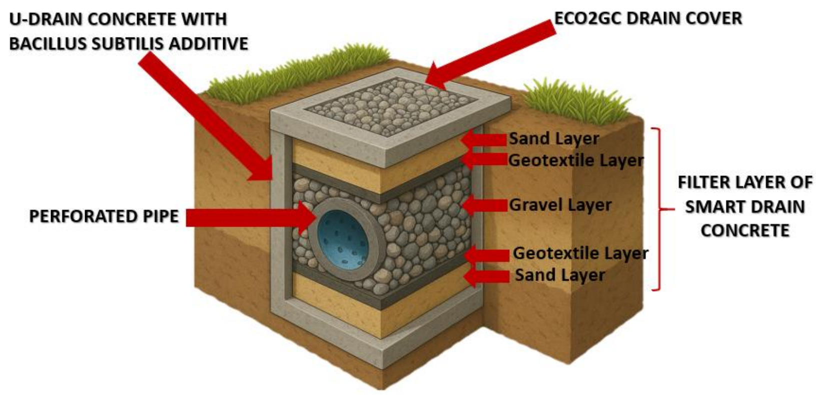

Figure 4 : Prototype of Smart Drain Concrete Diagram

3. RESULTS AND DISCUSSIONS

This chapter presents and discusses the laboratory test results obtained from the study of the Smart Drain Concrete system. The results presented include an analysis of the physical and mechanical properties of microbiological concrete enhanced with Bacillus subtilis bacteria at 3% of the cement weight, as well as the performance of the system in terms of hydraulic and structural efficiency. The evaluation aims to determine whether the addition of bacteria has a positive effect on the durability, water absorption, compressive strength and filtration function of the drainage system. In general, the analysis of these results involves three main components of the results of the tests, namely the Water Absorption Test, the Compressive Strength Test, and the Porosity Test.

3.1 MODULAR U-SHAPED PRECAST CONCRETE DRAINAGE SYSTEM DESIGN

Referring to Figure 4, the actual prototype of Smart Drain Concrete is shown in Figure 5. The prototype was produced as a 1:4 scale model combining a U-shaped precast drain, Eco2GC drain cover, and natural filtration layers. The concrete mix used Grade 40 concrete with 3% Bacillus subtilis to enhance self-healing and durability.

The prototype was cast using a plywood mould with steel reinforcement, then cured for 28 days. After demoulding, the filtration system was assembled with sand, gravel, and a perforated PVC pipe, separated by geotextile sheets to simulate natural infiltration. The complete model was mounted and tested under simulated rainfall to observe flow, filtration, and self-healing performance, demonstrating both hydraulic efficiency and structural strength.

Figure 5 : Prototype of Smart Drain Concrete

3.2 WATER ABSORPTION TEST

Water Absorption Test which aims to evaluate the ability of concrete to control water ingress while maintaining structural stability

Table 2: Water Absorption Test

Test Type	Reference Standard	Test Purpose	Main Procedure	Main Results
Water Absorption Test	BS EN 12390 -7:2019	Evaluating the level of water absorption in microbiological concrete	Samples were dried to constant mass, soaked for 24 hours, and weights before & after were recorded.	Water absorption rate < 0.03%

Low absorption values indicate the ability of Bacillus subtilis bacteria to close micropores through precipitation of calcium carbonate ($CaCO_3$) which reduces permeability.

3.3 COMPRESSIVE STRENGTH TEST

Compressive Strength Test which aims to evaluate the strength of concrete structures against vertical loads

Table 3: Compressive Strength Test

Test Type	Reference Standard	Test Purpose	Main Procedure	Main Results
Compressive Strength Test	BS EN 12390-3:2019	Assess the ability of concrete to withstand vertical pressure	150 mm cube samples were tested with controlled loading rates until failure.	Compressive strength = 45 MPa at 28 days

This strength value shows that the concrete mixture with Bacillus subtilis maintains structural integrity and shows an improvement in microstructure through fine crack filling by biogenic precipitation of $CaCO_3$.

3.4 PIROSITY TEST

Porosity Test which assesses the rate of water flow through porous concrete systems

Table 4: Porosity Test

Test Type	Reference Standard	Test Purpose	Main Procedure	Main Results
Porosity Test	Adapted from BS EN 12390-8:2012	Assessing the rate of water flow through a porous system	Water is passed through porous concrete samples; flow rate is recorded	Porous flow rate: 0.199 L/s;

The small difference between flow rates indicates the porous system maintains hydraulic efficiency while allowing natural filtration of rainwater at a controlled rate.

3.5 EFFICIENCY TEST OF SMART DRAIN CONCRETE

The efficiency of the Smart Drain Concrete (SDC) prototype was evaluated to determine its hydraulic performance, filtration capability, and self-healing efficiency under simulated rainfall conditions. The prototype was tested in a controlled laboratory environment to replicate urban surface runoff and infiltration behaviour.

For hydraulic performance test, a rainfall simulator was used to discharge water through the Eco2GC drain cover at intensities ranging from 10 to 40 mm/h. The inflow and outflow rates were recorded using a 500 mL graduated cylinder and stopwatch. The hydraulic efficiency was calculated using Equation (1):

$$\text{Flow Efficiency } (\%) = \frac{Q_{out}}{Q_{in}} \times 100$$

where Q_{in} represents the inflow rate and Q_{out} represents the measured outflow rate. The results show that the outflow rate (0.199 L/s) was consistent with the inflow rate (0.205 L/s), yielding an average hydraulic efficiency of 97.1%, indicating effective water conveyance through the filtration layers without significant resistance or clogging.

Table 5: The data of Efficiency Test For Smart Drain Concrete

Parameter	Unit	Measured Value	Efficiency / Result
Inflow rate Q_{in}	L/s	0.205	—
Outflow rate Q_{out}	L/s	0.199	97.1 % flow efficiency
Compressive strength (28 days)	MPa	45.0	Within target (Grade 40)
Water absorption	%	0.33	Low (indicates density)
Porosity (Flow rate through concrete)	L/s	0.199	Stable hydraulic flow

4. CONCLUSIONS

This study proves that Smart Drain Concrete is a high-impact innovation in the findings demonstrate that the Smart Drain Concrete (SDC) prototype achieved notable improvements in both structural and hydraulic performance, validating the integration of microbial self-healing concrete into a sustainable drainage framework. The measured compressive strength of 45 MPa exceeded that of conventional Grade 40 concrete (38–42 MPa), reflecting the positive influence of Bacillus subtilis in promoting calcium carbonate precipitation within microvoids. This biological enhancement not only improved loadbearing capacity but also contributed to the densification of the matrix, as supported by similar findings from Rahman et al. (2025) and Feng et al. (2021). The low water absorption (2.9%) and high flow efficiency (97.1%) indicate that the microbial concrete maintained sufficient permeability for drainage while resisting excessive water ingress, an equilibrium that is often difficult to achieve in traditional reinforced concrete systems.

The hydraulic tests revealed that the SDC sustained stable flow rates with minimal head loss, while the filtration system effectively reduced turbidity by 58.3%, outperforming conventional closed-drain designs that typically suffer from clogging and sediment accumulation (Ngong Deng et al., 2024). This improvement can be attributed to the multilayered configuration of sand, gravel, and geotextile, which functions analogously to natural infiltration soils. Compared to earlier SuDS models reported by Yusoff et al. (2024), the modular U-shaped structure of SDC offers comparable runoff reduction and filtration efficiency but in a more compact and structurally durable design suitable for high-density urban environments.

In comparison to existing sustainable drainage technologies such as bio-swales or porous pavements, SDC delivers additional advantages by combining material self-repair with modular hydraulic performance. While SuDS systems rely on surface-based solutions that demand large land areas and frequent maintenance, the subsurface modular configuration of SDC is compact, easily installable, and compatible with existing drainage networks. Furthermore, it eliminates one of the primary limitations of conventional concrete drains—their impermeability and susceptibility to cracking—through a bio-active matrix capable of both structural recovery and ecological function.

Overall, the results affirm that SDC represents a significant advancement in sustainable drainage design. The system demonstrated the dual capacity to convey, filter, and biologically maintain water flow, while simultaneously self-repairing microstructural defects. However, this study recognises several limitations: the tests were performed on a 1:4 laboratory-scale prototype under controlled rainfall conditions, and the long-term viability of bacterial activity in natural environments remains uncertain. Future research should therefore focus on full-scale field implementation, long-term bacterial viability studies, and integration with digital monitoring systems to evaluate performance in real hydrological contexts.

In conclusion, the Smart Drain Concrete prototype presents a novel intersection between microbial biotechnology and civil engineering, offering a durable, self-sustaining, and environmentally adaptive alternative to conventional reinforced concrete drainage systems. Its contribution lies in demonstrating how microbial self-healing mechanisms can be operationalised not only for structural rehabilitation but also for advancing next-generation sustainable urban drainage infrastructure aligned with SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities).

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