Permeo-Concrete:
Novel Technique to Develop Higher Compressive Strength Permeable Concrete

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Presenting at
IEEE International Conference on Innovate for Humanitarian:
Tech Solutions for Global Challenge

ICIH November 2025

Making of Permeo-Concrete

IEEE Innovate for Humanitarian: Tech Solutions for Global Challenge (ICIH 2025)

Permeo-Concrete: Novel Technique to Develop High Compressive Strength Permeable Concrete

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***Abstract*— Flooding and groundwater depletion in cities is exacerbated by impervious surfaces which cover 60% of total urban surface area. This paper develops a high compressive strength permeable concrete to convert these impervious surfaces into permeable surfaces without loss in quality. Factors such as cement to water ratio, reinforcement, cement composition and aggregate sizes are optimised to develop viable high-compressive strength permeable concrete. Research reveals an unexpected negative trend between coarse aggregate size and both compressive strength and porosity. This paper develops a scalable concrete design with 65% porosity and 13.65 MPa compressive strength, outperforming commercial permeable concrete options which have porosity of 15-25% at comparable strength without using any chemical additives. Mathematical simulations derived from literature analysis predict the concrete's fully compacted strength to outperform commercially available permeable concrete and enabling construction of permeable high-volume roads according to global standards.**

Keywords- Permeability, Urban Flooding, Compressive Strength, Concrete, Pozzolans, Cement

I. Introduction

A. The Problem

Urban floods damage essential infrastructure and cause immense socio-economic damage. Globally, from 2000 to 2020 the population exposed to urban floods has risen by 135.05% to 228 million people and the economic repercussions of urban floods have increased by 181.09% to $6.48 trillion [1]. In India, urban flooding is anticipated to cost Indian cities $30 billion annually by 2070 [2]. Climate change is exacerbating urban flooding as the intensity, irregularity and frequency of rainfall increases [3].

At the same time, nearly 1 billion people living in cities face water scarcity [4]. Half of the world's megacities and hundreds of smaller cities and towns are highly dependent on groundwater [5]. However, globally more than 80% of groundwater aquifers are declining at an accelerated rate [6]. The fact that, 60% of total urban surfaces are impermeable exacerbate urban flooding and groundwater depletion [7]. Impervious surfaces reduce the percolation of floodwater, hence, increasing floodwater's runoff velocity, overwhelming urban drainage systems and preventing recharge of urban groundwater systems. However, impervious parking lots, driveways, sidewalks, roads and industrial yards amounting to 42% of impermeable urban surface area (326,760 km^2) can be converted to permeable surfaces without loss of functionality.

B. Research Gap

While research is being conducted in developing materials like metallic foams, ceramics and composites. These efforts have limited scope due to high costs and requirement of specialized technologies [8], [9]. Hence, permeable concrete which can be easily manufactured without heavy expenses or specialized materials is more promising. However, permeable concrete has insufficient compressive strength to be implemented in many impervious surfaces and need more maintenance [10].

This research aims to fill this pressing literature gap which this paper fills by building a high-strength permeable concrete which can compete effectively with non-permeable concrete. The hypothesis is that the incorporation of novel reinforcements and strategic mix designs will improve compressive strength without significantly impacting the porosity.

II. Literature Review

A. Chemistry and Structure of Concrete

Concrete is a composite material composed of cement, coarse and fine aggregates, chemical admixtures and reinforcement. Concrete's strength is gained from the hydration reaction of $2CaO \cdot SiO_2\ (Alite)$ and $3CaO \cdot SiO_2\ (Belite)$ present in cement which form calcium silicate hydrate fibers and calcium hydroxide [11].

At the micro-level the internal structure of concrete is mainly composed of coarse aggregates which are the main load carrying components. The spaces between coarse aggregates are filled by fine aggregates, and hardened cement paste binds all the aggregates together. Between the aggregates and the cement paste is an interfacial transition zone (ITZ), around $50\mu m$ thick which is most vulnerable to cracking. Some of the unreacted alite or belite crystals remain in the cement contributing to the long-term increase in the concrete's compressive strength.

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2. DOI : 10.1109/ICIH67754.2025.

Water can percolate through interconnected void in concrete bricks [12]. Air voids typically occupies 2% of the concrete post mechanical compaction. Capillary voids occupy 10-15% of concrete volume, they are irregularly shaped and represent the space originally occupied by the water used up in the hydration reactions [13]. Due to the fundamental composite nature of concrete, it inevitably has some interconnected void spaces which facilitates the percolation and drainage of water [14]. However, the addition of fine aggregates like sand in non-permeable concrete reduces its permeability.

B. Importance and Composition of Cement

Cement is a major component of concrete as a binding agent, composed of calcium, silicon, aluminum and iron which are commonly sourced from limestone quarries [15]. Exact composition and mechanical properties of cement varies based on availability of local minerals and geographical conditions.

Cement manufacture has a significant environmental footprint as it is responsible for 5% of global carbon emissions and effluent pollution affecting worker and vegetation health [16], [17]. To ameliorate this environmental impact pozzolans including fly ash, bagasse ash, slag cement etc. have been investigated as partial replacement for cement [18]. Pozzolans are waste products from the thermal energy, steel production and agriculture sectors hence their constructive utilization helps create a circular economy [19]. Pozzolans also increase the durability and total strength of the cement by reducing the total pore volume, hence positively affecting the compressive strength of concrete [20].

C. Process of Concrete Manufacture

In the process of manufacturing concrete conventionally, a paste is made by mixing water, cement, admixtures, coarse and fine aggregates. The properties of the paste are determined by the size of aggregates, water to binder ratio (w/b) and ratio of concrete constituents. This paste is compacted to obtain a dense and homogenous layer of concrete and prevent formation of air pockets [21].

Concrete gains its strength during the curing process, where moisture and temperature is maintained to facilitate the hydration reactions of cement components.

D. Challenges in Permeable Concrete

Permeable concrete is a special type of concrete which allows rainwater to percolate through it. It is made by reducing the amount of fine aggregates used in the cement slurry during the mixing phase [22]. Most permeable concretes cannot exceed 12–15 MPa without sacrificing porosity; this study aims to bridge this trade-off [23], [24]. This is because, porosity and compressive strength have a negative relationship [25]. In fact, permeable concrete with compressive strength greater than 12MPa has drastically reduced porosity (around 11-25%) affecting their ability prevent urban waterlogging [26]. Typically permeable concrete is utilized for building sidewalks, driveways and patios but cannot be used for building roads or industrial dockyards [27].

E. Methods to Increase Compressive Strength of Concrete

Reinforced concrete refers to concrete in which steel is embedded to enhance concrete’s compressive strength. There are three main types of reinforcements – rebar, wire mesh and fiber reinforcement. A comparative evaluation reveals that fiber reinforcement and rebar are most effective in improving the compressive strength of concrete while wire mesh is ideal for improving the flexural strength [28]. However, wire mesh reinforcement can improve the effective compressive strength of concrete by spreading the stress and preventing formation of cracks [29]. Among the different fiber reinforcement materials available steel has the greatest positive effect on compressive strength [30].

Superplasticisers are chemical admixtures polymers which reduce the water requirement for cement hydration while maintaining the cement’s workability hence reducing the formation of capillary pores. Adding superplasticisers in optimal dose significantly boosts compressive strength by reducing water content from 25-35%, however, excessive usage of superplasticisers can reduce their compressive strength [31], [32].

III. Methodology

A. Building the Concrete Samples

Samples A, B, C and E had a mix design of 3:0:9; the control had a 1:0:1 ratio. In sample D and F the mix design was 3:1:9.

TABLE I CONCRETE SAMPLE DETAILS

<table>
<tr><th rowspan="2">Sample</th><th colspan="3">Coarse Aggregates Diameter (m)</th><th colspan="3">Fine Aggregate Diameter (m)</th></tr>
<tr><th>Min</th><th>Max</th><th>Avg.</th><th>Min</th><th>Max</th><th>Avg.</th></tr>
<tr><td>Control</td><td>0.032</td><td>0.040</td><td>0.036</td><td colspan="3" rowspan="4">NA</td></tr>
<tr><td>A</td><td>0</td><td>0.006</td><td>0.003</td></tr>
<tr><td>B</td><td>0.008</td><td>0.010</td><td>0.009</td></tr>
<tr><td>C</td><td>0.022</td><td>0.030</td><td>0.026</td></tr>
<tr><td>D</td><td>0.022</td><td>0.030</td><td>0.026</td><td>0</td><td>0.006</td><td>0.003</td></tr>
<tr><td>E</td><td>0.032</td><td>0.040</td><td>0.036</td><td colspan="3">NA</td></tr>
<tr><td>F</td><td>0.032</td><td>0.040</td><td>0.036</td><td>0</td><td>0.006</td><td>0.003</td></tr>
</table>

The locally procured coarse aggregates were filtered according to their size using sieves. For each permeable concrete design, 4.50±0.01kg of coarse aggregates were mixed with 1.50±0.01kg of cement. Water was added incrementally to the slurry until the desired consistency was obtained. This consistency was tested by checking whether a ball made with the slurry was able to maintain its shape.

This slurry was added to a 0.15m x 0.15m x 0.15m mold in 4 layers of 0.038m height. Between each layer reinforcement

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of 0.0016m radius steel wires was placed and manual pressure was applied. This was a limitation as compaction with industrial apparatus can greatly increase the compressive strength of concrete. These samples were left undisturbed for 12 hours, de-molded and immersed in water for curing. After the 7th day the concrete samples were left to dry.

B. Permeability Test

The 4 lateral faces of the concrete sample were covered with water-tight insulation tape to control water leakage and spillage. A water-tight square pipe of dimensions 0.15m x 0.15m x 0.45m was constructed using acrylic sheets and insulation tape. The concrete sample was fixed into the square pipe and the desired water level was marked.

The pipe was placed under a source of regulated water flow, first the concrete sample was allowed to soak in water for 90s minutes to control for cement's water absorption. Then the water flow was regulated until the desired water level was maintained. The volume of water percolating through the sample was measured for 60s. To ensure precision these trials were triplicated.

C. Compressive Strength Test

After the permeability test, the concrete samples were placed under a Compressive Strength Testing Machine and an increasing hydraulic load was applied on its surface. When the hydraulic pressure applied became constant, it indicated that the maximum load the sample. To control for the irregular surfaces of the permeable samples, this load was determined after the maximum load did not fluctuate for 10s. This pressure measured is the serviceable pressure – the maximum pressure with which the samples can be exposed to without failure.

IV. Results & Discussions

A. Compressive Strength Results

Global standards evaluate the compressive strength of concrete at a 7 day (for early testing) and 28 day curing period. Due to resources constraint samples were evaluated at 7 days only. Future efforts must address this limitation. Empirical equations obtained from experimental and AI based research papers were used to project compressive strength at 28 days [33], [34].

During these experiments, negligible compaction could be applied due to the lack of apparatus. Literature review reveals that negligible compaction in permeable concrete can leave an estimated 8-12% entrapped air volume due to absence of fine aggregate and low cement usage [35]. It is a common thumb rule that 1% of entrapped air causes 5% loss in compressive strength [36], [37]. Therefore, with proper compaction using vibration tables the compressive strength of all permeable samples could increase by 66.7% to 150%.

TABLE II COMPRESSIVE STRENGTH RESULTS

Sample	**Compressive Strength (± 0.01MPa)**		
	7-day	***28-day***	***Compacted 28-day***
Control	27.94	33.79	45.05
A	4.62	10.63	26.58
B	7.66	13.65	34.13
C	5.20	11.21	28.02
D	7.02	13.01	32.54
E	3.97	9.99	24.97
F	3.48	9.50	23.75

B. Porosity Results

The superficial velocity of runoff down the permeable concrete was calculated from the volumetric flow rate. It was plugged in the Ergun Equation to calculate the porosity with the known constants of pressure drop, average particle diameter, fluid viscosity and density. The Ergun Equation combines Darcy's Law and Forchheimer's to consider both laminar and turbulent flow.

To calculate the porosity from the non-linear Ergun Equation the Brent-Dekker method of hybrid root finding was used [38]. The porosity derived was also substituted into the Ergun Equation for verification.

TABLE III POROSITY RESULTS

Samples	***Volumetric Flow ($\pm 0.003 m^3s^{-1}$)***	***Superficial Velocity ($\pm 0.003 ms^{-1}$)***	***Porosity ($\pm 2\%$)***
Control	0	0	0
A	0.02	1.04	85
B	0.02	0. 77	65
C	0.03	1.39	50
D	0.01	0.66	43
E	0.03	1.74	58
F	0.03	1.60	57.40

C. Discussion

1) Compressive Strength

Compressive strength and coarse aggregate size have a weak negative correlation of -0.29. Compressive Strength is maximum in sample B which has an average particle diameter of 0.009m. It tends to decrease with an increase in the aggregates size, because at higher coarse aggregate sizes the packing density decreases resulting in a weaker ITZ allowing cracks to forms. A coarse aggregate diameter of 0.009m is the optimal as the coarse aggregates are able to bear high compressive loads while having higher packing density. The compacted strength of Sample B is projected to be 34.13MPa.

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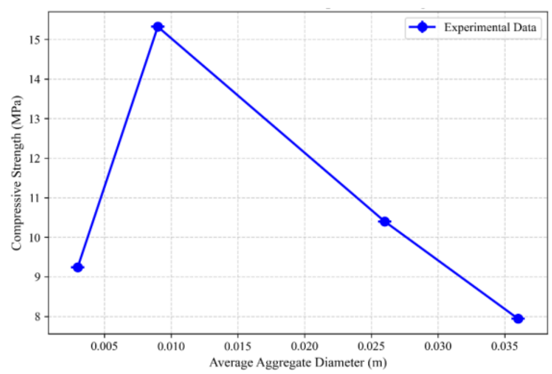


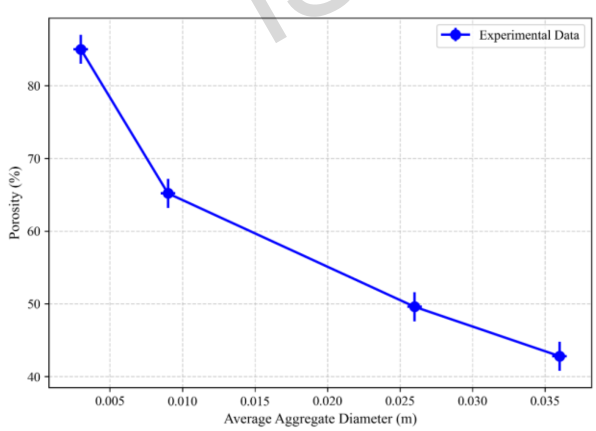
Fig. 1 Compressive strength versus coarse aggregate size

Analyzing differences between samples C and D and samples E and F reveals the complex effect of adding finer aggregates. While sample D has higher compressive strength than C the opposite is observed in between sample F and D. The addition of fine aggregate is expected to boosts the compressive strength of a concrete sample as more void spaces are filled as evident between sample C and D. The anomaly of sample F and D can be accounted to the irregular geometry of larger coarse aggregates which disturbs the homogeneity of the concrete.

2) Porosity

Coarse aggregate diameter and the porosity have a moderately strong negative relationship with a Pearson correlation coefficient of -0.66. This trend contradicts literature which predicts that finer aggregates would fill the voids more effectively reducing porosity. However, in these samples the presence of steel mesh wire reinforcements

Fig. 2 Porosity versus coarse aggregate size



causes finer aggregates to settle on the wires leaving localized voids. Additionally, coarser aggregates are more jagged and non-spherical, this geometry prevents smooth interlocking between aggregates creating more voids. The rate of porosity decline with coarse aggregate size is not uniform, hence an optimal coarse aggregate diameter can be identified. This paper adds evidence to trend observed in [39].

Addition of fine aggregates at this low proportion does not have a major impact on the porosity of samples as seen in the porosity data between samples C and D and E and F.

Compressive strength and porosity have a non-linear relationship in reinforced permeable concrete. The reinforcement of steel wires is likely to have played a major role in increasing the compressive strength of the permeable concrete even when there is high porosity since literature suggests that both variables share an inverse linear relationship [40], [41].

V. Conclusion

This paper successfully developed a viable permeable concrete sample with compressive strength higher than current permeable concrete [42]. With sufficient compaction, present in concrete industrial manufacture setups the permeable compressive strength is projected to rise to 34.14MPa which can be leveraged to build roads according to global standards.

The mechanism outlined by this paper can be feasibly implemented in all countries as it is not dependent on chemical additives like superplasticisers or specialized technologies. Locally available materials can be incorporated for pozzolans or aggregates creating a cyclical economy. In the future, concrete samples with higher ratio of cement can also be developed to increase compressive strength with slightly reducing porosity.

Hence this design permeable is sufficiently strong to be used in the construction of high and low-volume roads, sports fields, pavements, the sub-layers of asphalt and concrete roads and other urban surfaces globally [43]. This technology will be extremely helpful to developing countries like India who have launched ambitious concretization projects and face heavy seasonal rains.

The material developed can be incorporated in integrated urban watershed management, smart city initiatives and green infrastructure planning. In the future the material must be piloted to test its durability under real-world conditions and viability.

Acknowledgment

The author would like to thank Dr. Ravi Mariwala, the founder and CEO of SMAART Water, for his mentorship and for unique insights in permeability and fluid dynamics. I am grateful to Mr. Vishal Singh, Dr. Shalini Ghosh, Mr. Mahesh Chavan and Mr. Sandeep Keskar for their support.

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1. 979-8-3315-5644-0/25/$31.00 ©2025 IEEE
2. DOI : 10.1109/ICIH67754.2025.