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Experimental evaluation of pervious concrete designed based on the Excess Paste Theory: Strength and water permeability

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KEYWORDS

Pervious concrete
Excess paste theory
Compressive strength
Drainage
Permeability

ABSTRACT

Urbanization increases impervious areas, requiring sustainable stormwater management like pervious concrete (PC). Standardized PC design methods are limited in Vietnam. This study evaluated the Excess Paste Theory, based on coating aggregates without filling voids to maintain permeability, for designing PC for pedestrian areas targeting ~40 % void ratio and 7.5-10 MPa compressive strength. Experimental samples exhibited high interconnected porosity and efficient drainage. Average 7-day compressive strength was 8.5 MPa, meeting the target pedestrian traffic area. Variability was noted (manual mixing, lack of equipemnt for vibration and compaction of 10 kPa for concrete), with failure in the cement paste layer. Initial results indicate the method's potential. Future work should enhance paste strength (e.g., via fine aggregate and/or reduced Dmax) for uniformity. PC design requires balancing porosity and strength.

1. Introduction

Socio-economic development and urbanization have significantly altered natural landscapes, converting permeable surfaces into impervious ones such as roads and parking lots, leading to disrupted hydrological processes and increased stormwater runoff that carries pollutants [1-3]. This runoff can overwhelm drainage systems, causing urban flooding and contamination of water bodies [7]. Conventional solutions, like collection ponds and treatment facilities, are often costly and environmentally impactful [3]. Furthermore, impervious surfaces hinder groundwater recharge and exacerbate the Urban Heat Island (UHI) effect [4]. These challenges highlight the need for sustainable urban infrastructure solutions.

Pervious concrete (PC), with its high void ratio of 15-35 %, is an effective material for addressing these issues [10-15]. Its interconnected pore structure allows for rapid rainwater infiltration, aiding groundwater recharge, reducing runoff, and potentially mitigating the UHI effect. PC also contributes to noise reduction and pollutant removal through filtration, making it an essential component of stormwater management and sustainable development [13].

However, PC is relatively new in regions like Vietnam, where its implementation faces challenges due to a lack of comprehensive guidelines and standardized mix designs [13-18]. Current methods, such as those by ACI, Zouaghi, and Zheng, often rely on empirical approaches and do not sufficiently address factors like the water-to-ratio or compaction, leading to trial-and-error experimentation [16-18].

A method based on the excess paste theory, developed by Nguyen et al. [9], offers a theoretically grounded approach. It ensures that paste only coats the aggregate particles, leaving inter-particle voids open for permeability, distinguishing it from conventional concrete design. This method includes a binder drainage test to optimize the water-to-cement ratio and prevent clogging of pores.

To evaluate the applicability of this method in Vietnam, a preliminary study was conducted. The research aimed to create pervious concrete mixes with high drainage capacity and compressive strength between 7.5-10 MPa, suitable for pedestrian traffic areas like parks and parking lots. The targeted void ratio for high drainage was approximately 40 %. While the impact of mechanical compaction was omitted due to equipment limitations, concrete samples were prepared and assessed through compressive strength testing and visual drainage capacity evaluation. This study provides preliminary findings to support future research and the broader adoption of pervious concrete in sustainable urban infrastructure solutions.

2. Overview of the theoretical basis of the “Excess Paste Theory” design method

The design method for pervious concrete mixes based on the Excess Paste Theory is an approach developed by Nguyen and colleagues [9] at Normandy University in France, which systematically combines theoretical principles with experimental investigation. Therefore, only the general principle and key theoretical design steps are presented here. For detailed information on the design method, please refer to [9].

2.1. General principle

The theoretical basis of the “Excess Paste Theory” for pervious

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concrete is based on the principle that paste should only coat the surfaces of aggregate particles, without filling the voids between them. This approach is crucial for maintaining a continuous network of interconnected voids, which is necessary for effective drainage. The design goal is to determine the optimal amount of paste needed to bind the aggregates together, while preserving porosity. Unlike traditional concrete design, which focuses on filling voids to create a dense, strong mass, the Excess Paste Theory emphasizes the precise definition of the required "excess" paste to achieve both strength and permeability.

2.2. Key theoretical design steps

(1) Determination of aggregate volume:

This determination is based on the following assumptions:

- A#1: Aggregate particles are assumed to be spherical (Figure 1)

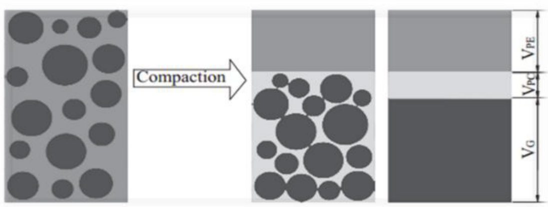

Fig 1. Mode of concrete structure [9].

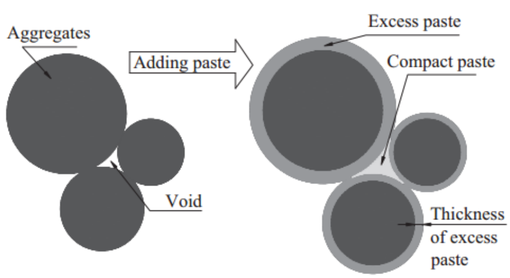

Fig 2. Illustration of excess paste theory [9].

- A#2: The volume of compact paste (V_{PC}) is assumed to be equal to the void volume among dry and compacted aggregate grains (V_V). $V_{PC} = V_V$. So, the thickness of the excess paste can be considered negligible when compared to the size of the coarse aggregate particles. Therefore, the presence of this excess paste does not affect the porosity between the aggregate particles (the air voids between the particles). These voids will be filled with compacted paste (Figure 2).

- A#3: The thickness of the excess paste, e_i (Figure 3), is proportional to the size of the aggregate particles according to the factor k. The factor k is determined by the ratio of the diameter of the aggregate particle covered by the excess paste l, $D_i + 2e_i$, to the diameter of the uncoated aggregate particle, D_i (Figure 4). For a given volume of excess paste, coarse aggregates have a smaller total surface area compared to fine aggregates. Therefore, the thickness of the excess paste on coarse aggregates is always greater than that on fine aggregates. Thus, for an aggregate with a diameter D_i and an excess paste thickness e_i, the factor k is defined as:

$$\frac{D_1 + 2e_1}{D_1} = \frac{D_2 + 2e_2}{D_2} = \cdots = \frac{D_i + 2e_i}{D_i} = \cdots = \frac{D_n + 2e_n}{D_n} = k \quad (1)$$

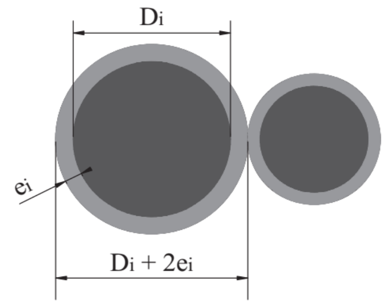

Fig3. Thickness of excess paste [9].

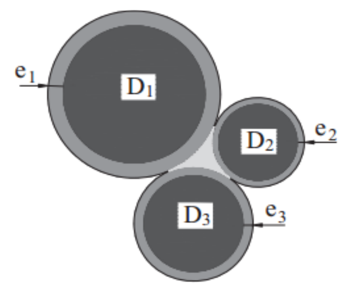

Fig 4. Thickness of excess paste proportional to the diameter [9].

- A#4: A pervious concrete structure is considered "ideal" when aggregate particles are just sufficiently coated by the excess paste to achieve the required strength, and the voids between aggregate particles are kept empty for water to pass through. According to this assumption, the volume of compact paste (V_{PC}) is zero (Figure 5).

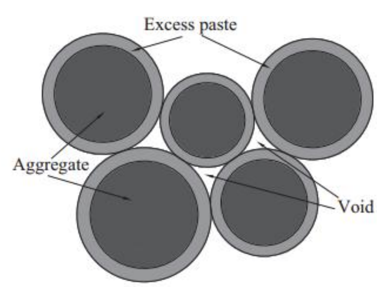

Fig 5. Illustration of the theory of excess paste [9].

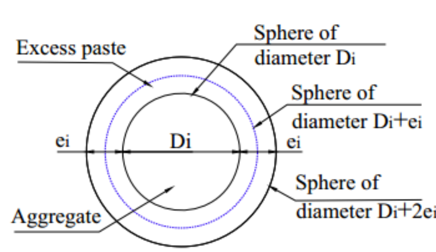

Fig 6. Scheme of grain aggregate covered by cement paste.

(2) Determination of cementitious paste volume:

$$V_P = \frac{3m_G(k-1)}{\rho_{specify}} \quad (2)$$

Where:

- m_G: masse of aggregate;
- k: factor definie above;
- $\rho_{specify}$: specify bulk density of the aggregate.

To be more precise, using Figure 6, Vp is deduced in accordance with formula (3):

$$V_p = \beta \times (1 - V_V)$$

with:

$$\beta = \frac{3(k-1)}{a \times (k^3 - 1) + 1 + b} \times \left(\frac{D_i + e_i}{D_i}\right)^2 = \frac{3(k-1)}{a \times (k^3 - 1) + 1 + b} \times \left(\frac{k+1}{2}\right)^2 \quad (3)$$

Determining the excess paste layer thickness "e_i":

$$e_i = \frac{1}{2}\left[\left(\frac{1+Q_x}{1+Q}\right)^{1/3} - 1\right] D_i$$

with:

$$Q = 1 - \frac{\rho_{dry,compacted}}{\rho_{specify}} \quad (4)$$

$$Q_x = \frac{1+u}{x} - 1$$

Where:

- u: total void volume/total solid volume,
- x: aggregate volume/total solid volume

Based on the formules obtained above, the factor "k" can be written as:

$$k = \left(\frac{1+Q_x}{1+Q}\right)^{1/3} \quad (5)$$

Pervious concrete is typically used for low-load-bearing structures that do not require high strength. Therefore, the amount of cement in the mixture should be reduced as much as possible. Furthermore, from the optimization study of the pervious concrete mix conducted in the laboratory, it was found that a low value of k, approximately 1.116, results in concrete with good water permeability. This value is similar to that established by Deo and Neithalath [16]. Thus, it is preliminarily recommended that k = 1.116. So, $e_i/D_i = 0.058$.

Adjusting aggregate and paste amount: The total porosity of the concrete (Pt), including inter-particle voids and paste porosity, is calculated based on the paste volume (Vp), paste porosity (Pp), and void volume (V_V) in accordance with formular (5):

$$P_t = \beta * P_P * (1 - V_V) + V_V$$

With:

$$P_P = P_o - 0.53.\alpha.(1 - P_o) \quad (5)$$

$$V_V = \frac{\beta * P_P - P_t}{\beta * P_P - 1}$$

(3) Determination of (w/c) ratio using the Binder drainage test:

An accurate w/c ratio is necessary to maximize strength without negatively impacting permeability characteristics. The relationship between strength and w/c ratio is not as clear as in traditional concrete because the paste content is much lower compared to the void volume. The binder drainage test is proposed to determine the appropriate w/c ratio. The objective is to find a w/c ratio at which the cement paste has sufficient viscosity to coat the aggregates and bind them, but not so liquid as to flow down and clog the voids under the action of vibration or compaction. The principle of the test involves observing the appearance or flow of cement paste through a layer of aggregate on a sieve under vibration. If the paste flows to the bottom of the sieve, that w/c ratio is too high. This test helps determine the "ideal" w/c ratio that does not cause void clogging. The diameter of the sieve holes is used to simulate the pervious concrete void size. Details of the binder drainage test procedure can be found in [9], the example of the binder drainage test is provided in Figure 7.

Preparation of concrete   Vibration of concrete in sieve

Fig 7. The binder drainage test [9].

3. Experimental validation of the excess paste theory mix design

3.1. Materials

3.1.1. Cement

The cement used for the mix design is PCB40, with the following specification:

Table 1. Specification for PCB 40.

1	Compressive strength, (N/mm^2)	- 3 days	29,75
		- 28 days	43
2	Finnest	- Retain in 0,09 mm, (%),	0,4
		- Blaine surface area, (cm^2/g),	4169
3	The initial setting time shall not be less than (minutes)		150
	The final setting time shall not exceed (minutes)		230
4	Volume stability (Le Chatelier method), (mm)		1,0
5	Sulfur trioxide (SO_3) content, (%),		1,8
6	Density of cement, kg/m^3		3150

3.1.2. Aggregate

The aggregates used for experimental validation were 5/10 gravel and 0/4 sand, with a mass of 7% of the 5/10 gravel mass. The specifications of the aggregate is presented in Table 2, and particle distribution is shown in Figure 8.

Table 2. Specification for aggregate and sand.

I	Aggregate 5/10	
1	Density, kg/m^3	2725
2	Water absorption, %	0,56
3	Los Angeles abrasion, %	22,85
4	Flat and elongated particle content, %	13,39
5	Crushing strength in a cylinder, %"	10,51
II	Sand 0/4	
1	Modul of finnest	2,75
2	Apperent specific gravity, kg/m^3	2,640
3	Water absorption, %	1,23

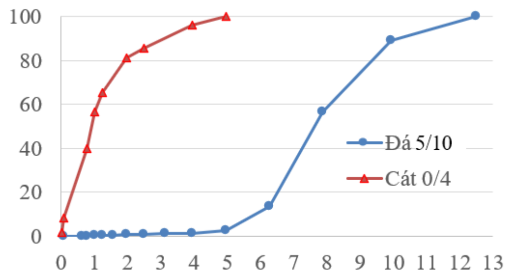

Fig 8. Thành phần hạt của Đá 5/10 và Cát 0/4.

3.2. Mix design

- The Inputs for mix design of pervious concrete are given in Table 3.

- The material composition for the mixture is calculated based on the design procedure outlined in section 2. The calculation results are presented in Table 4 below.

4. Results and discussions

4.1. Visual evaluation of the sample

The images of the test samples are shown in Figures 9 and 10 below.

Upon visual inspection of the sample after mold removal, it is evident that the sample appears relatively loose, coarse, and lacks smoothness. This can be attributed to the fact that the concrete is primarily composed of large 5/10 aggregate, and the mix design employed is an open gradation with very few fine aggregates. The amount of 0/4 sand in the concrete (49.3 kg per 1 m^3 of concrete) is minimal, with its primary function being to enhance the strength of the concrete and improve its mechanical properties. The combination of an open aggregate gradation and a large maximum aggregate size (Dmax) ensures a high interconnected porosity, facilitating efficient drainage.

Fig.9. Sample immediately after molding.

Fig.10. Sample after mold removal.

To improve the surface texture of the concrete, it is necessary to reduce the Dmax of the aggregates. However, in Vietnam, the two most common aggregate sizes available on the market are 5/10 and 10/20, with smaller aggregate sizes being virtually unavailable. Few suppliers produce aggregates smaller than 5/10, and obtaining smaller aggregates requires placing a special order for custom production.

Table 3. The mix design inputs for pervious concrete.

N°	Inputs	Values	Notes
1	Aggregate porosity (inter connected porosity), V_v, %	40 %	For the purpose of strong drainage of the pavement surface in used for the urban drainage system
2	Factor "k"	1.116	Based on the recommendation of the experimental study from the Normandy University, France.
3	Water absorption of 5/10 aggregate, %	0,56	
4	Percentage of aggregate larger than 80 mm in the aggregate mixture, *a*	1	The percentage of particles < 80 μm is too small and can be considered negligible.
5	Percentage of 0/4 sand contant in concrete, %	4,5	Based on the 5/10 aggregate content. The purpose is to create concrete that ensures porosity.
6	Shape and size of the sample, cm	15x15x15	Cube
7	Admixutre content, %	1	Based on the cement content

Table 4. Material composition for mix design.

V_v	1 m^3 of pervious concrete				W/C	Agg/cement	Sand/Agg.	V_p (m^3)
	Cement (kg)	Water (lít)	Agg. 5/10 (kg)	Sand 0/4 (kg)				
0,4	251	88	1095	49,3	0,35	4,36	0,045	0,168

4.2. Compressive strength

The image depicting the compressive strength test at 7 days of age is presented in Figure 11, with the corresponding strength values provided in Table 5 and Figure 12.

Fig 11. a- Compressive strengthe test; b,c,d - damaged samples after test.

The average compressive strength at 7 days for the four pervious cement concrete samples is 8.5 MPa, which exceeds the 7.5 MPa required for traditional fired bricks. As illustrated in Figure 11 and Table 5. However, it is important to note that there is considerable variation in the compressive strength values at 7 days among the four samples, when compared to the average strength. This disparity can be attributed to the sample preparation process, where manual mixing failed to ensure a uniform mixture.

Table 5. Compressive strength at 7 days of age.

Sample N°	Faillure load (kN)	Load - bearing Area (cm^2)	Compressive strength (MPa)
1	149.9	225	6.7
2	196.2	225	8.7
3	179.5	225	8.0
4	241.9	225	10.8

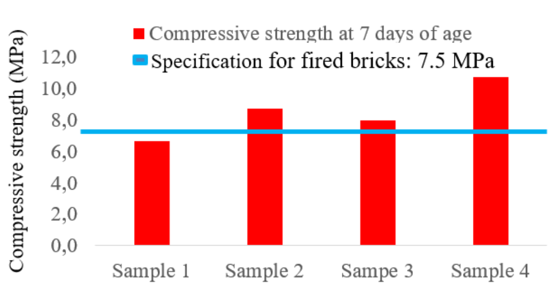

Fig.12. Compressive strength of pervious concrete at 7 days of age.

The failure of the samples, as observed in Figures 11b, 11c, and 11d, demonstrates that the concrete failed in a fragmented and disintegrated manner. The crushed stone particles remained intact, without breaking. This indicates that the pervious cement concrete failed primarily in the cement paste layer, at the point where the cement paste binds and surrounds the aggregate.

To enhance the strength of pervious cement concrete, it is crucial to improve the strength of the cement paste layer that binds and surrounds the aggregate particles. This can be achieved by increasing the sand content to introduce finer mineral particles that reinforce the cement paste layer, while simultaneously reducing the maximum aggregate size (Dmax). This would increase the surface area of the aggregates, allowing the high-strength cement paste layer to more effectively coat the aggregate.

4.3. Drainage Test

Due to the inability to design and fabricate a testing device for measuring water permeability as illustrated in Figure 13, the author was only able to conduct this experiment through visual observation. The figure 13 depicts the drainage test, where water is poured directly onto the surface of the sample. Upon observing the bottom of the sample, water is seen flowing through in a steady stream, confirming that the designed water permeability of the concrete has been achieved.

Fig. 13. Drainage Test.

The design of pervious cement concrete requires a balance between two key factors: porosity and strength. To achieve rapid drainage, a higher porosity is necessary; however, this can lead to a reduction in strength. Conversely, to increase strength, porosity must be reduced. Therefore, depending on the specific application and the material's performance in practice, an appropriate mix design should be selected to meet the required specifications.

5. Conclusions

This study experimentally evaluated the applicability of the Excess Paste Theory mix design method for pervious cement concrete, a method positing that cement paste should primarily coat aggregate surfaces without filling inter-particle voids to maintain permeability. The research aimed to produce pervious concrete suitable for pedestrian areas, targeting high drainage (around 40 % void ratio) and compressive strength between 7.5 and 10 MPa.

Visual assessment revealed a relatively loose, coarse appearance, consistent with the open gradation and large aggregate used, but successfully created high interconnected porosity, confirmed by efficient drainage observed as water flowed through samples in a steady stream. Mechanically, the concrete achieved an average 7-day compressive strength of 8.5 MPa, exceeding the target minimum for pedestrian use. However, significant strength variation among samples was noted, likely due to manual mixing inconsistencies. Failure analysis showed samples failed in the cement paste layer binding aggregates, while aggregates remained intact.

These initial results suggest the Excess Paste Theory method can design pervious concrete achieving target drainage and strength. To enhance performance and reduce variability, future mixes should consider increasing fine aggregate content and reducing maximum aggregate size to strengthen the paste layer. The study underscores the fundamental balance required in pervious concrete design between porosity for drainage and strength for structural integrity, with the optimal mix dependent on application needs. Despite manual limitations, the study provides initial support for the theoretical design approach.

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