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DISCHARGE CAPACITY AND CLOGGING EFFECTS IN PERVIOUS CONCRETE: A FINITE VOLUME MODELING APPROACH

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Abstract. Pervious concrete, characterized by its composition of coarse aggregate embedded in cement paste without fine aggregates, creates a network of interconnected pores that enable water flow within the material's internal structure. This paper presents an analysis of the unsaturated flow behavior within pervious concrete elements specifically designed as entrance filters in sewage systems for pedestrian and light traffic areas. The study employs finite volume modeling techniques, incorporating experimental data obtained from physical tests, to simulate these pervious concrete elements and evaluate their discharge capacity relative to the flow generated by a design storm event. By accurately representing the flow dynamics, valuable insights into the performance and functionality of pervious concrete as an innovative solution for sustainable urban drainage systems are provided. The behavior of water within the porous structure is analyzed through the solution of Richard's equation, which governs the multiphase flow in porous media. The pervious concrete is considered as an unsaturated homogeneous medium, the water is treated as an incompressible fluid and a capillarity model utilizing the Van Genuchten parameters is incorporated to capture the capillary phenomena occurring within the porous network. The detrimental effects of clogging on the permeability are investigated by simulating pore clogging through the variation of permeability in specific regions, enabling the assessment of its influence on the discharge capacity. The enhanced understanding of the hydraulic performance, unsaturated flow and clogging mechanisms of pervious concrete elements provide critical insights for optimizing their design and implementation in urban drainage systems, contributing to the development of improved stormwater management strategies that promote sustainable and resilient urban environments.

1 INTRODUCTION

Permeable concrete has a well-defined pore structure, where these are interconnected, allowing the flow of water or other liquids through its structure. The aggregates are completely covered by cement paste and are adhered to each other. However, the amount of cement mortar is so low that the spaces between the aggregates are not completely filled. Figure 1 (left) illustrates the material's structure in a computed tomography image. The use of permeable or draining concrete in construction elements related to urban drainage is relatively recent in Argentina, mainly employed in permeable pavements, making use of its ability to allow water to pass through its structure.

In addition to the high permeability that characterizes this material, studies have been conducted to assess its performance in retaining contaminants carried by the water flowing through it, aiming to reduce environmental impact of the stormwater runoff. Retention can occur through mechanical retention, physical adsorption, chemical reaction, or biodegradation. From this, it can be deduced that the mechanical retention of solids will lead to a clogging effect in the structure, decreasing the material's permeability and consequently reducing its efficiency in water discharge.

By making use of both its permeability and its capacity to retain contaminants, a structure based on modules were designed to be used at the entrances of urban stormwater drainage structures. Its porous structure will allow the flow produced by the storm to enter the sewer system, but part of the contaminants will remain retained in the module, thereby improving the quality of the discharged water (Chandrappa and Biligiri, 2016).

Two computational models were conducted in order to simulate and evaluate how the phenomenon of clogging would affect the discharge capacity of the modules. Initially, a model was created assuming an impermeable area on the upper face that reduces the surface through which water can enter into the structure, aiming to replicate the clogging effect. A second model was based on the variation of permeability caused by the occurrence of clogging, relying on values from previous tests to determine parameters such as the depth of clogging.

Additionally, by performing these simulations, the need for extensive physical experimentation is reduced, decreasing material waste and energy consumption associated with trial and error methods. This aligns with sustainability initiatives, emphasizing resource efficiency and environmental stewardship.

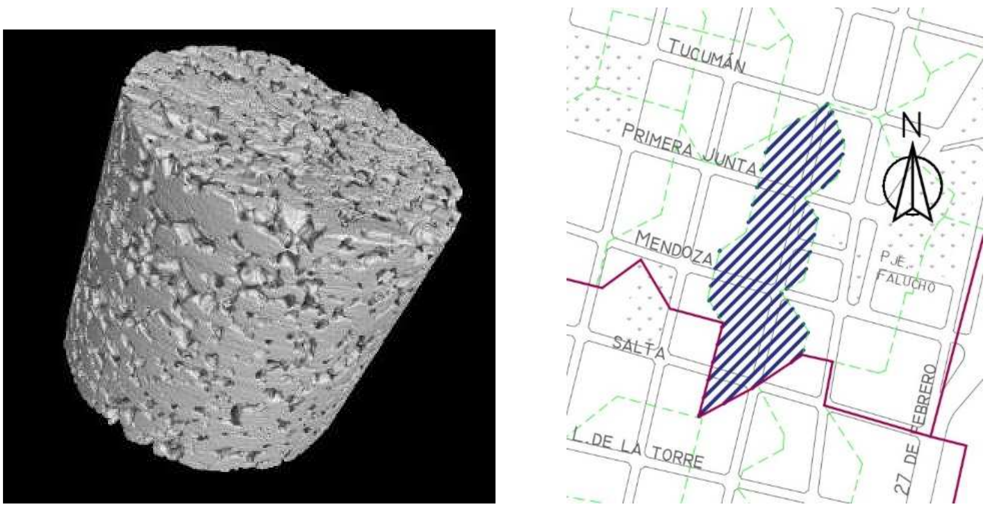

Figure 1: Left, computed tomography 3D image. Right, reference sub-basin.

2 MATERIALS AND METHODOLOGY

First, the design storm, the dimensions of the projected modules, the material characteristics, the equations governing the phenomenon, and other relevant aspects will be defined.

2.1 Hydrological parameters

The design storm depends on the values of frequency, intensity, and duration, which are specific to each region. The frequency adopted by the Secretary of Water Affairs and Risk Management of the City of Santa Fe for the verification of the stormwater drainage system is 5 years. The highest rainfall intensity for this recurrence is chosen, which is 186.1 mm/h, in order to verify the structure with the highest possible intensity allowing the lower ones to also be adequately discharged. A duration of 5 minutes is selected.

The precipitation will fall onto a specific surface, generating a peak flow for that highest intensity. Based on data obtained from the same public department, the drainage sub-basin to be intervened was identified, see Fig. 1 (right). The model is suitable for this drainage sub-basin located in the central area of the City of Santa Fe, where the impermeabilization factor is 100%, consequently, all the precipitation converts into surface runoff. Considering 1-meter-long strips and a total width between building lines of 13 meters, the peak flow per linear meter is calculated for designing an efficient stormwater management system. This parameter guides the sizing of drainage infrastructure to handle peak rainfall volumes, reducing flood risk. This calculation is pivotal for ensuring the system's resilience and effectiveness in adverse weather, contributing to urban safety and sustainability. Additionally, it informs decisions on materials, structure sizing, and inlet/outlet design, vital for a robust system. The peak flow to be discharged per unit meter Q can be determined as a function of the precipitation intensity i and the surface S, computed as the maximum influence width per unit meter,

$$Q = i\,S = 5.1694 \times 10^{-5}\ \frac{\mathrm{m}}{\mathrm{s}} 13\ \mathrm{m}\ 1\ \mathrm{m} = 6.72 \times 10^{-4}\ \frac{\mathrm{m}^3}{\mathrm{s}} \quad (1)$$

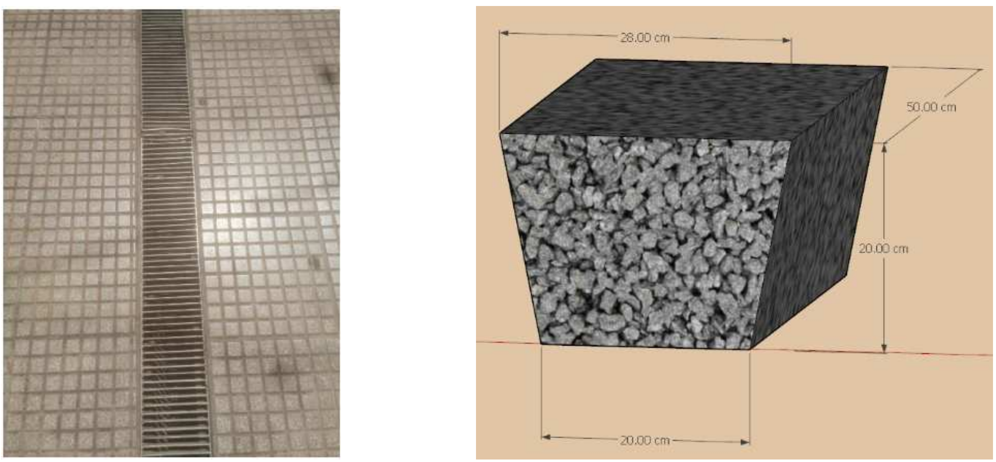

Figure 2: Drainage structure at the pedestrian zone of Santa Fe (left). Modulus geometry (right).

Given that this sub-basin is situated above the pedestrian zone in Santa Fe, and that the dimensions of the existing structure designed to capture runoff are 20 cm in width and 30 cm in depth at its shallowest section, a permeable concrete structure based on modular units was designed to conform to this geometry. This approach aims to minimize intervention, thereby reducing costs and construction time.

2.2 Module design

A trapezoidal isosceles section is proposed in order to allow for easy placement without the need for support structures, relying on the existing walls on either side for support. The module length is set at 0.5 meters, taking into account the maximum allowable values for manual lifting of loads according to argentinian regulations, such that without mechanical assistance, procedures should be carried out in such a way that the distributed weight does not exceed 25 kg per person.

The material characteristics were derived from data provided by the Permeable Concrete Research Group at CECOVI (Centro de Investigación y Desarrollo para la Construcción y la Vivienda) of the National Technological University, Regional Faculty of Santa Fe. It was determined that for permeable concrete with a water-cement ratio of 0.35, coarse aggregate 3-9 mm, 0% fine aggregate, and a theoretical void volume of 20%, the permeability is 1.31 cm/s, which is the key feature for the analyzed case (Aguirre and Argento, 2021).

2.3 Governing equations

The flow in the partially saturated permeable medium is governed by the Richards equation, written as follows (Horgue et al., 2015a),

$$C(h)\frac{\partial h}{\partial t} - \nabla \cdot \left[K_S(h)\nabla\left(h+z\right)\right] = 0 \tag{2}$$

where $K_S(h)$ is the hydraulic conductivity, h is the head pressure of the fluid, θ the volumetric moisture, t the time and z the elevation angle, being the intrinsic permeability

$$K = \frac{\mu_\theta K_S}{\rho_\theta ||\mathbf{g}||_2} \tag{3}$$

i.e., it is related to the permeability of the medium and fluid characteristics. The behavior of the permeable medium in terms of water content is described in this case by the Van Genuchten model, in which permeability is a function of saturation θ. Here, the saturated water content is θ_s, the residual water content is θ_r, the inverse capillary length is α, and pore size distribution is represented by n, with $m = 1 - 1/n$. The variation in saturation is given by

$$\theta(h) = \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha\,|h|)^n\right]^m} + \theta_r \tag{4}$$

On the other hand, the hydraulic conductivity is computed as

$$K_r(h) = \frac{\left[1 - (\alpha h)^{n-1}\left[1 + (\alpha h)^n\right]^{-m}\right]^2}{\left[1 + (\alpha h)^n\right]^{m/2}} \tag{5}$$

Meanwhile, the capillary capacity is:

$$C(h) = \frac{\alpha m(\theta_s - \theta_r)}{1-m}\theta_e^{1/m}\left(1 - \theta_e^{1/m}\right)^m \tag{6}$$

where $\theta_e^{1/m} = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r}$ represents the effective saturation. The boundary conditions are given in terms of either the potential h or the fluid velocity in the permeable medium u.

The numerical solution for this case is obtained through a finite volume discretization in OpenFOAM, using the solver *groundwaterFoam*, developed as part of the *porousMultiphaseFoam* package (Horgue et al., 2015b).

3 NUMERICAL RESULTS

3.1 Numerical data

The parameters required for the computational models performed pertain to the material, system behavior, and fluid characteristics are detailed below.

The hydraulic conductivity adopted from Aguirre and Argento (2021) is $K_S = 1.31 \times 10^{-2}$ m/s, the fluid density and viscosity are $\rho = 1000$ kg/m^3 and $\mu = 0.001$ Pa s, respectively, and the gravity acceleration $g = 9.8$ m/s^2, such that the intrinsic permeability computed with Eq. (3) is $K = 1.34 \times 10^{-9}$ m^2.

The following Van Genuchten parameters are adopted, $\theta_s = 0.25$, $\theta_r = 0.025$, $\alpha = 0.145$ and $n = 2.68$, taken from reference results of Rayane de Aguiar Costa et al. (2020). An incompressible, viscous and isothermal fluid flow is assumed.

The finite volume method (FVM) will be employed, as it is considered suitable for evaluating the current problem. The model creation procedure begins with the generation of the geometry and mesh in Salome, which allows for domain discretization and the definition of faces where boundary conditions are assigned. An hexahedral discretization is employed, given that the geometry allows for working with regular elements of such volume shape. As can be observed in Fig. 3, the volumes exhibit a certain degree of uniformity. The distribution is even, with no areas of distortion or elongated elements.

In order to address the problem, specific boundary conditions must be specified at the faces of the modulus, as well as an initial value for some variables. While specific boundary conditions for each model will be detailed separately later on, those that will be uniformly applied in both cases are presented here. Based on the observation of the actual system's behavior, the boundary conditions for the problem are identified, and groups of faces are created to input them into the model. This aims to ensure that the model behaves approximately in line with the real-world case. Pressure and flow velocities, referred to as "h" and "$Utheta$", respectively, must be determined along with flow conditions for some faces of the model. The flow velocity is calculated by dividing the total flow generated by the design storm on the contributing surface by the discharge area of the module: From Eq. (1), and the free discharge area of the module given by 0.20 m $\times$ 1 m, the inlet velocity is $v_i = 3.36$ m/s. This value is imposed as a boundary condition on the upper face, with the velocity in the vertical downwards direction.

On the supporting side faces, a zero flow condition is set, as they will be resting on material considered impermeable. This means that the water flow will be directed towards the bottom face. Finally, on both front and back faces, as there is no horizontal flow in the designed model, null flow is assumed.

3.2 Model 1: surface clogging

For the first model, an impervious area was introduced on the upper face of the module, through which the discharge flow enters. This area has a variable width for each case, simulating an increase in the clogged percentage by augmenting the impermeable area on the surface, see Fig. 4 (left). This subsequently reduces the flow entering into the module. In Fig. 4 (right), streamlines can be observed for the case with 50% clogged, along with corresponding colors indicating the velocity scale. A central zone is noticeable where no flow enters, aligning with the specified boundary condition. The fluid's path primarily descends in a vertical direction, increasing in velocity upon entry due to the reduced inlet area. It subsequently increases again on the lower face, due to the progressive reduction of the cross-sectional area resulting from the trapezoidal shape of the module. At the bottom, the flow is characterized as "zerogradient",

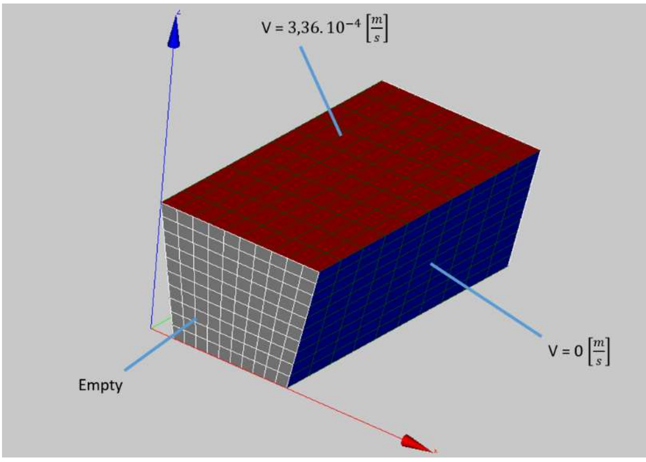

Figure 3: Finite volume discretization and boundary conditions.

setting the value of the variable at the patch equal to the internal value in the nearest cell.

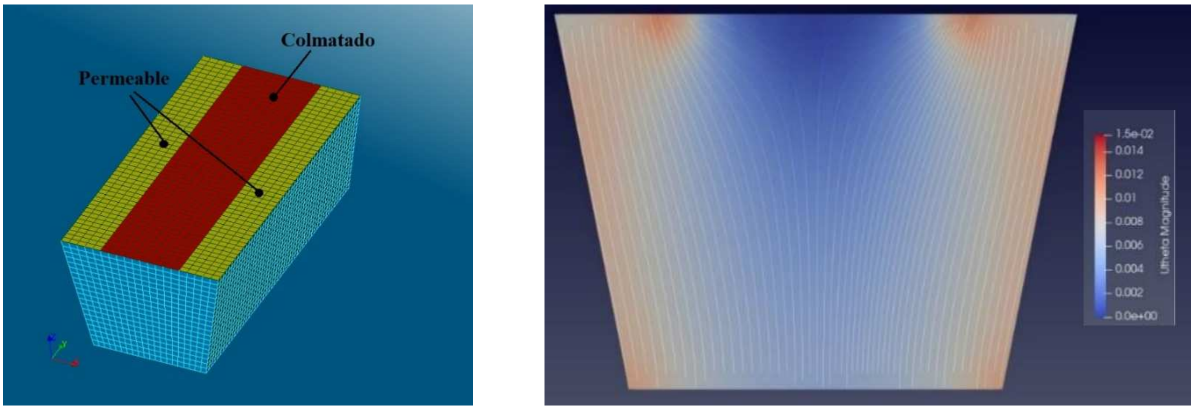

Figure 4: Model 1. Sketch of clogged surface (left). Streamlines and velocity magnitude, in cm/s (right).

Simulations were conducted for 9 cases, each with different percentages of clogged pores area, ranging from 10% to 90%. With knowledge of the area of the bottom face, the discharged flow was calculated for each case based on the obtained velocity values. This led to the graph presented in Fig. 5, displaying the variation of the flow passing through the module in relation to the clogging percentage. A line is used to denote the minimum flow value that should pass through the module in order to be capable of discharging the design storm. It is observed that approximately 80% clogging must be achieved for the design flow not to pass through correctly, highlighting the material's substantial infiltration capacity.

3.3 Model 2: width clogging

For the second model, in order to improve the simulation's approximation to reality the boundary condition of the impermeable area simulating the clogging percentage is replaced by a variation in the module's permeability. This variation is applied only at the top and into a certain depth. It is because, according to studies, clogging occurs only in the upper layers of permeable concrete, approximately up to a depth of 12.7mm or 1 inch (Kayhanian et al., 2012).

The input velocity is also variable due to the maximum flow that will be allow to pass through the internal structure of the material while the clogging percentage is increased. At the bottom,

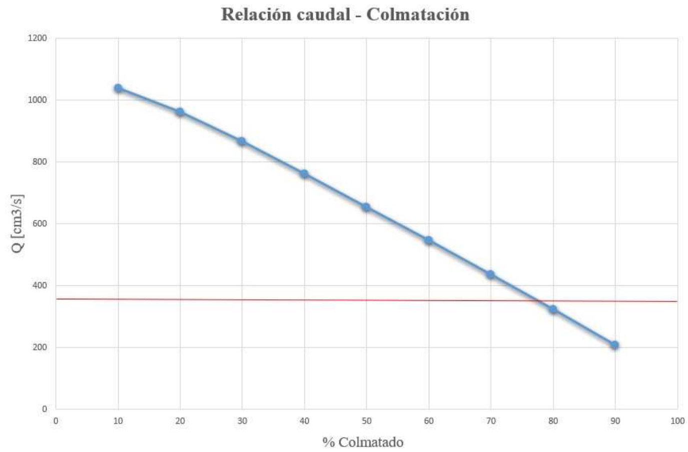

Figure 5: Model 1. Flow rate versus percentage of clogging.

the flow is characterized as "zerogradient", setting the value of the variable at the patch equal to the internal value in the nearest cell.

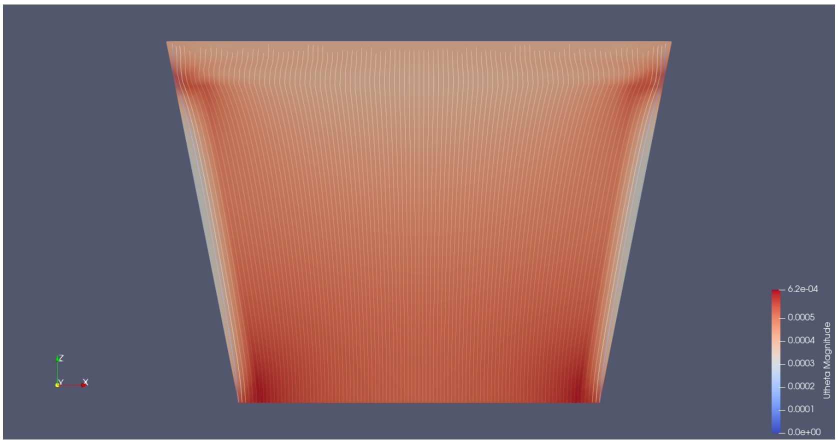

Figure 6: Model 2. Streamlines and velocity magnitude, in cm/s.

In Fig. 6, a disturbance in the streamlines can be observed, caused by the change in permeability of the material. Also there is an increment in velocities in that area and on the bottom face.

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Simulations were conducted for different decreasing permeability values. In each case, the evolution of the discharged flow was observed, resulting in a graph with the obtained flow values in relation to the variation of the clogging percentage, see Fig. 7.

An increase in the flow that can be discharged is observed, compared to the maximum allowed according to the material's permeability and the available area. This is because permeability, defined as the amount of fluid that can pass through the material per unit of time, depends on the applied pressure, among other factors. As the pressure increases due to the water accumulated on the upper part, the flow that can be discharged also increases.

In both graphs, a decrease in the discharged flow is observed as the clogging percentage increases, but with different behaviors. The result of the second model is a more straight line, indicating the linear behavior of the analyzed phenomenon. Nevertheless, it is just an approximation to the reality, where more variables are interacting.

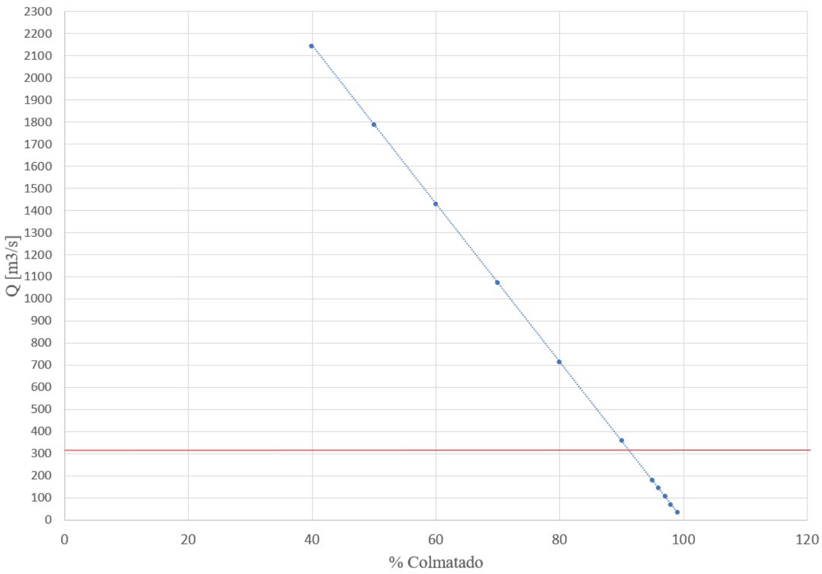

Figure 7: Model 2. Flow rate versus percentage of clogging.

4 CONCLUSIONS

The assessment of clogging is of paramount importance when determining the durability of permeable concrete for flow discharge purposes, prior to any maintenance activities. The combination of various numerical simulations and characteristic analyses can contribute to the mutual verification of multiple methods, thereby improving the accuracy of the results.

Two models were employed to simulate the clogging phenomenon in permeable concrete, which established that the design flow can be discharged normally until clogging reaches approximately 80% or higher. This demonstrates the significant infiltration capacity of the material and the safety margin present in the design, as it will take a considerable amount of time for these levels of clogging to develop.

From the graphs it can be observed that in the second model, the clogging has to increase more than 90% in order to be under the minimum required while in the first model, this value is reached between 70 and 80%. It indicates that the discharge capacity of the module will be more affected if part of its area is covered than if its permeability decreases. So, maintenance tasks to keep the surface unobstructed would be of vital importance.

Both simulations resulted in different variations in flow, differing from the results obtained in tests conducted by Garat et al. (2019) on similar concrete dosifications, indicating that the models should be adjusted to align more closely with the curves yielded by physical experiments. This can be achieved by incorporating parameters that should improve the model, such as pore size, aggregate size, or sediment characteristics (e.g., sand, silt, etc.), among others, which allow for a more accurate simulation of the phenomenon under analysis.

REFERENCES

Aguirre D. and Argento R. Hormigón drenante como regulador de excedentes pluviales. 2021. PFC - Universidad Tecnológica Nacional - Fac. Reg. Santa Fe.

Chandrappa A.K. and Biligiri K.P. Pervious concrete as a sustainable pavement material – Research findings and future prospects: A state-of-the-art review. *Construction and Building Materials*, 111:262–274, 2016. ISSN 0950-0618. doi:10.1016/j.conbuildmat.2016.02.054.

Garat M.E., Palacio A.J., Larenze G.R., and Sota J.D. Desempeño hidrológico y propiedades físico mecánicas de hormigones porosos elaborados con áridos de la Provincia de Entre Ríos. *Revista Tecnología y Ciencia*, 36:81–104, 2019. doi:10.33414/rtyc.36.81-104.2019.

Horgue P., Franc J., Guibert R., and Debenest G. An extension of the open-source porousMultiphaseFoam toolbox dedicated to groundwater flows solving the Richards' equation. *arXiv preprint arXiv:1510.01364*, 2015a.

Horgue P., Soulaine C., Franc J., Guibert R., and Debenest G. An open-source toolbox for multiphase flow in porous media. *Computer Physics Communications*, 187:217 – 226, 2015b. ISSN 0010-4655. doi:10.1016/j.cpc.2014.10.005.

Kayhanian M., Anderson D., Harvey J.T., Jones D., and Muhunthan B. Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots. *Journal of Environmental Management*, 95(1):114–123, 2012. ISSN 0301-4797. doi: 10.1016/j.jenvman.2011.09.021.

Rayane de Aguiar Costa I., Paiva Coutinho A., Gico Lima Montenegro S.M., Carvalho de Gusmão A.E. Martins dos Santos Neto M., Alves E.M., and Dantas Antonino A. Sensitivity of hydrodynamic parameters in the simulation of water transfer processes in a permeable pavement. *Brazilian Journal of Water Resources*, 25, 2020.

Salome. SALOME–plataform. www.salome-platform.org, 2023.