LABORATORY TESTING AND MODELLING OF THE HYDROLOGIC PERFORMANCE OF A RESIN GRAVEL PERMEABLE PAVEMENT

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KEY POINTS:

- *Laboratory tests were performed to assess the hydrological performance of permeable pavements under different rainfall intensity and slope conditions.*
- *Measurements are analysed using the first- and second-order step response functions of dynamical systems.*
- *Results, summarized in terms of performance indices as a function of the rainfall intensity and slope, allow the transferability of the solution to different morphological and climatic contexts.*

1 INTRODUCTION

The expansion of urbanization in the last decades resulted in extending the impermeable surfaces, as roofs and roads, with increasing the annual runoff generation, flood volumes and flood peaks (*Jinkang Du et al.*, 2012). Traditional drainage techniques appear increasingly inadequate, and innovative stormwater management strategies are required. Sustainable urban drainage systems (SUDSs) are a set of technologies aimed at restoring the natural flow regime configuration of a site with the objective to reduce flooding and improve water quality (*Fletcher et al.*, 2015). SUDSs include green infrastructures like green roofs, sand filters, rain gardens, urban green areas, permeable pavements, etc. (see e.g., *Palla et al.*, 2010; *Fioretti et al.*, 2010). Most of the research on SUDSs focuses on green walls and roofs, urban vegetation and street trees and addresses different functions, such as pollution mitigation, temperature regulation and stormwater management, although additional quantitative studies are still necessary to evaluate the post-implementation performance (*Vidya Anderson et al.*, 2023). Among SUDSs, permeable pavements (PP) are simple systems with structures formed by open spaces that facilitate the passage of water and air to allow rainwater infiltration, storage and dispersion of runoff while simultaneously permitting the vehicular and/or pedestrian use of the urban surfaces (*Ferguson*, 2005). The main roles of PPs are the reduction of stormwater runoff volume and of the peak flows and the improvement of the water quality by infiltration and adsorption through the pavement stratigraphy (*Brattebo & Booth*, 2003; *Imran et al.*, 2013; *Marchioni & Becciu*, 2014).

The hydraulic performance of PPs were addressed by numerous research works using field tests, laboratory tests or software modelling. *Dreelin et al.* (2006) observed the hydraulic behaviour of a permeable parking lot, in Georgia, USA, compared to a traditional asphalt parking lot built on clay soils, under nine low-intensity precipitation events, obtaining that the PP produced 93% less runoff than the traditional one even though located on a clay-rich soil. The laboratory study of *Dai et al.* (2021) investigated the drainage capacity of four types of prefabricated PPs in parking lots, simulating three rainfall intensity values (0.5, 1, and 2 mm/min) and three event durations (one, three and seven days). Results revealed that the initial runoff time of each PP is not less than 36 min when the rainfall interval is one day, and the levelling layer material has an important impact on the hydrological response. The impact of the rainfall intensity and the installation slope on the hydrological response of a laboratory plot equipped with four different PP technologies was investigated by *Palla et al.* (2015) using a dimensionless volume and a timing index. Monitoring of inflow, runoff, and subsurface outflow revealed good results for all the PPs investigated, with no runoff observed until a rainfall intensity of 98 mm/h. Many studies in the literature have focused on modelling the behaviour of PPs using dedicated software like e.g., HYDRUS (*Brunetti et al.*, 2016). *Turco et al.* (2017) proposed a procedure to describe the hydraulic response using the HYDRUS-2D model. The mathematical model correctly interprets the measured hydrograph of three PPs monitored under different rainfall intensity and duration scenarios in laboratory tests.

The present work investigates the response hydrograph of a continuous resin gravel pavement used in the reconversion project of the former military area “Caserma Gavoglio”, in the district of Lagaccio (Genova, Italy). The results of the laboratory tests were interpreted using a mathematical model based on the analogy of the step response of the first- and second-order dynamical systems. From this analysis, synthetic performance indices and their functional dependencies were obtained.

2 METHODOLOGY

2.1 Laboratory tests

A sample of the resin gravel pavement solution employed in the Gavoglio area was tested in the hydraulic laboratory of the Department of Civil, Chemical and Environmental Engineering (DICCA – University of Genova). A small-size testbed (1 × 2 m) was equipped with a slope adjustment system, a rain simulator device, and an automatic monitoring system for the measurement of the inflow and outflow. Measurements are based on real-time acquisition of the water level on two reservoirs located upstream and downstream to the testbed by means of ultrasonic probes having a resolution of 0.2 mm (Figure 1a). The stratigraphy (Figure 1b) is composed of 28 cm of compacted quarry gravel and a 5 cm cellular support filled with the same material. The resin gravel top layer, with a thickness of 1.8 cm, has a large percentage of voids and a high permeability.

The duration of each rainfall test was set to 15 minutes, according to *FLL (2008)*, with antecedent dry periods of 24-hours intervals after a wetting cycle of 15 min (150 mm/h) so that each test is characterized by the same initial conditions. Three rainfall intensity values and three bed slopes were used, as follows:

1. Rainfall intensity (*RI*): 108.0 mm/h, 145.7 mm/h and 177.2 mm/h (corresponding to an equivalent flow rate, Q, equal to 3.6 l/min, 4.9 l/min e 5.9 l/min) associated with a return period of 2, 5 and 10 years according to the Depth Duration Frequency (DDF) curves derived from the meteorological station of “Genova Università” located close to the Gavoglio area;
2. Slope (*s*): 0%, 2%, 4%, according to the most common values adopted in the Gavoglio area.

2.2 Analytical model

To perform a regression of the experimental results, the step response functions of a first- (linear reservoir) and second-order “critically dumped” dynamical system (Figure 1c) were used. The measurements of the inflow and outflow, from the ultrasonic probes, were recorded every 10 seconds and then filtered with a 10-values moving average (Figure 2a) per each of the test configurations (Figure 2b).

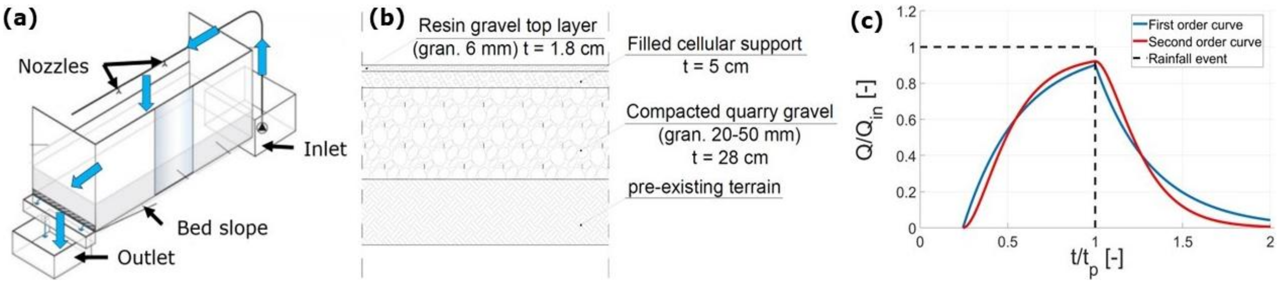

Figure 1. (a) Laboratory testbed, (b) stratigraphy of the PP under test, (c) sample first- and second-order step response function.

The rising limb of the outflow hydrograph can be modelled as the response of a second-order “critically dumped” dynamical system (Figure 1c), starting after the occurrence of a significant “dead time” (t_0) - defined as the time window where the rainfall event has already started but no outflow discharge is yet observed – in the form:

$$Q_{up}^{II}(t) = AK \cdot \left(1 - \left(1 + \frac{t - t_0}{\tau}\right) e^{-\frac{t - t_0}{\tau}}\right) \qquad t \le t_p \tag{1}$$

where t_p is the rain duration, τ is the time constant characterizing the dynamical system and *AK* is a modulation coefficient. For each test, the values of t_0, τ, *AK* are obtained from the least square interpolation and the mean value of the dead time ($\bar{t_0}$) was calculated. With this value, the rising limb for every test was fixed using as parameters: $\bar{t_0}$, *AK* and τ. The falling limb and the recession curve were divided in three segments (see Figure 2a). The first is a second-order function, $Q_{dwn}^{II}(t)$, having the same parameters (AK and τ) as derived from the rising limb. Assuming continuity at the junction point (t_p) with the rising limb, the equation assumes the following form:

$$Q_{dwn}^{II}(t) = Q_{up}^{II}(t_p) \cdot \left(1 + \frac{t - t_p}{\tau}\right) e^{-\frac{t - t_p}{\tau}} \qquad t_p \leq t \leq t_\beta \tag{2}$$

The first-order approximation of the second part of the falling limb (Q_{dwn}^{I}) and of the recession curve (Q_{rec}^{I}) can be described as:

$$Q_{dwn}^{I}(t) = Q_{dwn}^{II}(t_\beta) \cdot \left(e^{-\frac{t - t_\beta}{k_\beta}}\right) \qquad t_\beta \leq t \leq t_\gamma \tag{3}$$

$$Q_{rec}^{I}(t) = Q_{dwn}^{I}(t_\gamma) \cdot \left(e^{-\frac{t - t_\gamma}{k_\gamma}}\right) \qquad t \geq t_\gamma \tag{4}$$

where k_β and k_γ are the time constants (linear reservoir parameters) derived from the least-squares regression while t_β and t_γ are the junction points separating the three parts of the falling limb. The junction points were fixed and calculated as the mean values each set of tests performed at a fixed bed slope (Figure 2c). The second junction point is obtained from a sensitivity analysis on the starting point of the recession curve t_γ. A comparison of the Pearson coefficient (always higher than 0.99) with varying the instant t_γ was performed.

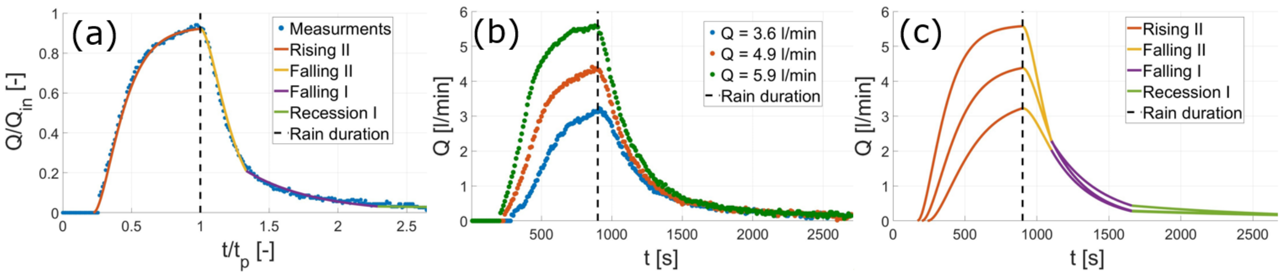

Figure 2. (a) Sample of a modeled outflow hydrograph against experimental data, (b) experimental hydrographs at a fixed slope (s = 2%) for various equivalent flow rates (Q) and (c) final modeled hydrographs for the same configuration.

3 RESULTS

The hydrological response of the permeable pavement was quantified using the following indices. The outflow coefficient, ϕ_{15} [-], is defined as the ratio between the outflow volume after 15 minutes and the inflow volume over the same duration. The damping coefficient, α [-], is defined as the ratio between the outflow peak and the equivalent reference inflow. The time constant, 2τ [s], is the time at which the outflow is equal to 59.4% of the peak outflow (with τ the inflection point of the raising limb). The retention coefficient, r [-], is calculated as the complement of the outflow coefficient calculated 12 hours after the onset of rainfall.

Results are summarized in Figure 3, where each index is plotted as a function of the inflow value per each bed slope configuration. The outflow and damping coefficients (Figures 3a,b) increase by increasing the slope of the testbed and the inflow value, while the opposite occurs for the time constant and the retention coefficient (Figures 1c,d). For all performance indices, a change in behaviour from s = 0% and any inclined installations is observed.

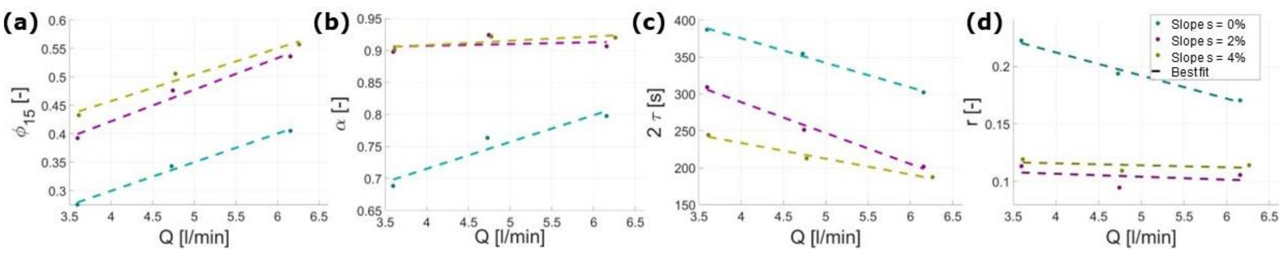

Figure 3. (a) Outflow coefficient, ϕ_{15}, (b) damping coefficient, α, (c) time constant, 2τ, and (d) retention coefficient, r, as a function of the equivalent flow rate, Q, per each bed slope configuration.

4 CONCLUSIONS

The present study quantifies the hydrological response of a resin gravel continuous permeable pavement, following standardized laboratory tests (according to the FLL roofing guideline), as a function of the slope of the site and the rainfall intensity. Results from the testbed laboratory study show the absence of surface runoff even for the maximum intensity (177.2 mm/h), confirming a high infiltration capacity.

The response hydrograph of the PP was modelled using the conceptual formulation of the step response of a first- and second-order dynamical systems. The rising limb of the outflow hydrograph was modelled as a "critically damped" second-order response function. However, the falling limb and the recession curve at s=0% had an exclusively first-order behaviour, while in tests performed at s=2% and s=4%, the first part of the falling limb is again compliant with a second-order response function.

The functional dependency of some synthetic performance indices, derived from the observed hydrological response, allows to extend the results obtained in laboratory tests in terms of discharge and slope ranges, so that they can be used in different morphological and climatic contexts than those analysed in this work.

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