



PAVEMENTS AS ACTIVE THERMOHYDRAULIC SYSTEMS FOR SAFETY AND SUSTAINABILITY IN HOSPITAL ENGINEERING

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Abstract

The external areas of healthcare complexes represent potential sources of significant safety, thermal, hydrological and acoustic criticalities. Conventionally conceived as static infrastructural elements, these spaces are increasingly recognized as strategic components of the hospital organism. Consequently, a new design perspective is emerging, one that reinterprets pavements as active systems capable of contributing to patient safety, environmental quality and operational resilience. The present study investigates the performance of an innovative pavement solution conceived as an Active ThermoHydraulic System. The system aims to mitigate thermal loads, optimize stormwater management and enhance acoustic comfort, while maintaining the mechanical durability and safety required in healthcare environments. Highpermeability structures eliminate hazardous surface water films, ensuring skid resistance and reducing the risk of accidents for vulnerable users. Concurrently, the combined effect of high surface reflectance and evaporative cooling contributes to the mitigation of the Urban Heat Island (UHI) effect, improving microclimatic comfort in outdoor hospital spaces. A comprehensive laboratory campaign was conducted to evaluate the mechanical, hydraulic, thermal and acoustic behavior of a porous wearing course produced with a transparent ecocompatible binder and light-colored aggregates. The results demonstrate that the mixture achieves the required structural performance while providing substantial environmental benefits. The findings support the feasibility of integrating pavements as active components within sustainable healthcare infrastructure, promoting safety, resilience and improved environmental quality.

Keywords: pavement materials, porous asphalt, hospital engineering, thermohydraulic systems, cool pavements

1 Introduction

Pavement engineering is undergoing a significant paradigm shift driven by the increasing vulnerability of urban areas due to climate change. Within this context, the external spaces of healthcare facilities including emergency access routes, parking areas, cycle paths and pedestrian walkways must no longer be regarded as passive transit zones. Instead, they constitute an integral component of the hospital system, directly influencing operational safety, microclimatic conditions and the overall effectiveness of care delivery. The present study proposes the reconceptualization of the road surface as an Active ThermoHydraulic Pavement System, capable of responding dynamically to environmental, hydraulic and acoustic stresses, as well as with the mechanical stresses related to traffic.

According to the World Health Organization, healthcare facilities are the “first and last line of defense” in climate emergencies [1], serving as first responders and the last resilient stronghold when urban systems fail. Ensuring uninterrupted accessibility under standard and adverse conditions is therefore a strategic priority to increase the effectiveness of healthcare treatments and the usability of external spaces. Hence, hospital outdoor areas require advanced pavements, footpaths and bike lanes that maximize safety and operational resilience, especially for vulnerable users, based on four performance pillars:

- Hydraulic safety and resilience: high permeability pavements reduce surface water, maintain friction during heavy rainfall and abate contamination risks [1, 2].
- Thermal mitigation and UHI reduction: materials with high Solar Reflectance Index (SRI) and evaporative cooling capacity stabilize the microclimate in accordance with the most common outdoor wellbeing criteria [3].
- Acoustic comfort: a microporous surface structure attenuates tire - pavement noise, and absorbs the incident noise, supporting quieter healing environments [4].
- Circular water management: porous layers act as active drainage systems, enabling storm-water filtration, storage and reuse in line with the most common urban NatureBased Solutions principles [5].

The proposed paving innovation integrates an unbound permeable base with a wearing course produced using a transparent eco-compatible binder and light-colored aggregates. Through a comprehensive experimental program, the study demonstrates the feasibility of combining structural durability with the stringent functional requirements of modern healthcare infrastructure, positioning the paving solution as a strategic element for hospital safety and sustainability.

2 Theoretical framework and state of the art

2.1 Thermophysics of high albedo and porous pavements

The thermal behavior of urban pavements depends on the balance between absorbed solar radiation and emitted thermal energy. Conventional dark bituminous surfaces, characterized by low albedo, absorb most incident radiation and store it as sensible heat [6]. The proposed system employs a transparent eco-compatible binder that preserves the reflectance of light-colored aggregates, increasing the SRI. The macroporous structure also supports thermal mitigation through moisture retention and evaporative cooling during post-precipitation phases [3]. These combined mechanisms are particularly relevant in healthcare environments, where stabilizing the right microclimate conditions helps to reduce thermal stresses for vulnerable patients and users [1].

2.2 Interface hydraulics and frictional stability

Hydraulic safety in hospital outdoor areas requires surfaces that promote vertical drainage and maintain friction for all kinds of users' safety. The high interconnected voids content of the wearing course enables rapid water dissipation and prevents the formation of surface films. According to the Darcy's law, the filtration velocity is governed by the permeability coefficient and hydraulic gradient [7], ensuring quasidry friction levels even during intense rainfall and supporting the directional stability of vehicles and walking devices [8]. In addition, infiltration reduces biofilm formation and enables possible stormwater harvesting for irrigating the nearby green areas, improving water efficiency and hydrological resilience [9, 10].

2.3 Acoustic comfort and noise mitigation mechanisms

Acoustic comfort is a recognized therapeutic factor, given that elevated noise levels can hinder patient recovery [11]. In hospital access roads, tire–pavement noise is dominated by airpumping, caused by the rapid compression and release of air within the contact patch – an effect amplified on densegraded surfaces [12]. The presence of a macroporous structure mitigates this mechanism by providing pressure relief pathways that dissipate compressed air within the surface layer thickness. Incident sound waves also undergo acoustic tortuosity, a process where energy is lost through viscous friction along the pore walls [13]. This dual mechanism helps to reduce noise reflections in urban settings and contributes to quieter outdoor environments in line with specific international guidelines on environmental noise [14].

3 Materials and experimental methodology

3.1 Characterization of components

The technical specifications and specific functions of the components selected for the porous surfacing mixture are summarized in table 1.

Table 1 Components of the porous mixture for the wearing course

Component	Description	Function
Transparent synthetic binder	Polyolefinbased thermoplastic binder	Binder transparency, adhesion to aggregate, mixture cohesion
Biancone anconetano aggregates	Lightcolored limestone rocks from central Italy	Mechanical strength of skeleton, light natural pavement color, high albedo, surface cooling
Limestone filler	Mineral filler	Mastic stability, rutting resistance

3.2 Mix design and specimen preparation

A gapgraded distribution was adopted to promote interconnected voids. The binder content was set at 5.4%, excluding the 0/4 mm size fraction to achieve 18–25% target porosity. Mixing was performed at 180 °C (UNI EN 1269735), and cylindrical specimens (100 and 150 mm in diameter) were compacted using a gyratory compactor (UNI EN 1269731) at 600 kPa for a maximum of 50 gyrations.

3.3 Volumetric characterization and air void analysis

The mix air voids content (V_m) was determined according to UNI EN 126978. Maximum density (ρ_m) was measured using the volumetric method (UNI EN 126975), while bulk density (ρ_p) was obtained through the geometric method (UNI EN 126976), suitable for highly porous bound mixtures.

3.4 Hydraulic characterization: vertical permeability

Vertical permeability was assessed using a constant head permeameter (UNI EN 1269719). After saturation, the permeability coefficient was calculated using the well-known Darcy's law:

$$K_v = \frac{4Q_v l}{h\pi D^2} \quad (1)$$

This test quantifies the capacity of the interconnected void system to convey water through the pavement layer.

3.5 Mechanical characterization: stiffness modulus and tensile strength

Stiffness Modulus (ITSM): measured in the IT-CY configuration with the well-known Nottingham Asphalt Tester (UNI EN 1269726) under dynamic loading at fixed temperature, to evaluate elastic response and load distribution capability.

Indirect Tensile Strength (ITS): determined at fixed temperature according to UNI EN 1269723 to assess the tensile resistance and binder–aggregate cohesion, particularly relevant for porous mixtures.

3.6 Functional characterization: skid resistance

Skid resistance was measured in the laboratory using the British Pendulum Tester (UNI EN 130364). The Pendulum Test Value (PTV), obtained as the mean of five wet surface measurements, provides an indicator of friction performance in hospital outdoor wet conditions.

3.7 Thermal analysis and thermographic monitoring

A dedicated and validated protocol was developed and used to assess the thermal behavior under controlled solar radiation. Specimens were conditioned at 20°C, irradiated for 180 minutes using a 250 W nIR/IR lamp (800–350 W/m²), and monitored through embedded thermocouples and periodic thermographic imaging. The procedure evaluates the contribution of the transparent binder layer to surface reflectance and the porous matrix to evaporative cooling.

3.8 Acoustic characterization: Impedance tube for noise absorption

Sound absorption was measured using a specific impedance tube, according to EN ISO 105342:2023. The transfer function method was applied to determine the absorption coefficient (α) across a range of frequencies, quantifying acoustic energy dissipation through viscous friction and tortuosity within the surface void network.

4 Results and discussion

This section presents the laboratory test results for the investigated mixture, whose performance characterization is summarized in table 2.

Table 2 Summary of the experimental results and performance characterization of the investigated mixture

Volumetric characterization	% Air void	18.39%
Hydraulic performance	Vertical permeability (K_v)	$2.26 \cdot 10^{-3}$ [m/s]
Mechanical characterization	Stiffness Modulus (ITSM)	3587 [MPa]
	Indirect Tensile Strength (ITS)	0.53 [MPa]
Surface friction	British Pendulum Tester (PTV)	46
Thermal analysis	Surface temperature (T)	41.2 °C
Acoustic characterization	Absorption coefficient (α)	0.511703

4.1 Volumetric characterization

The volumetric analysis confirms the effectiveness of the mix design in achieving a high-porosity structure. The light-colored mixture consistently reached air void contents within the 18–25% target range, ensuring the formation of an interconnected void network. This outcome is attributed to the gapgraded distribution of the white aggregates and the viscosity of the synthetic binder, which provides uniform coating without obstructing the macropores during compaction.

4.2 Hydraulic performance

The vertical permeability coefficient (K_v) exceeded the functional threshold of $5 \cdot 10^{-4}$ m/s, demonstrating excellent hydraulic conductivity. The porous matrix enables rapid rainwater infiltration and prevents the formation of surface water films, confirming that the synthetic binder does not clog the layer drainage channels and ensures high safety in the hospital external environment.

4.3 Mechanical characterization

Stiffness Modulus (ITSM): tests at 20°C showed a balanced elastic modulus, indicating adequate stress distribution capacity. The synthetic binder imparts sufficient flexibility to the mixture, mitigating the brittleness typically associated with highvoid systems in cold conditions.

Indirect Tensile Strength (ITS): the mixture exhibited strong internal cohesion, with effective bonding between the binder and limestone aggregates. This performance reduces the risk of raveling and supports longterm structural integrity of the wearing course, thus reducing maintenance interventions and service disruptions.

4.4 Surface friction

Skid resistance measurements using the British Pendulum Tester yielded PTV values consistently well above 36, the reference threshold for pedestrian and publicuse areas. Despite the reduced contact area typical of opengraded mixtures, the surface texture of the limestone aggregates combined with the synthetic binder ensures reliable friction performance under wet conditions.

4.5 Thermal analysis

Thermographic monitoring confirms the lower surface temperatures of the mixtures relative to conventional bituminous pavements, as illustrated in figure 1. The highalbedo aggregates, combined with the transparent binder and the porous structure, improve solar reflectance and heat dissipation, reinforcing the system’s role as an effective “Cool Pavement” solution.

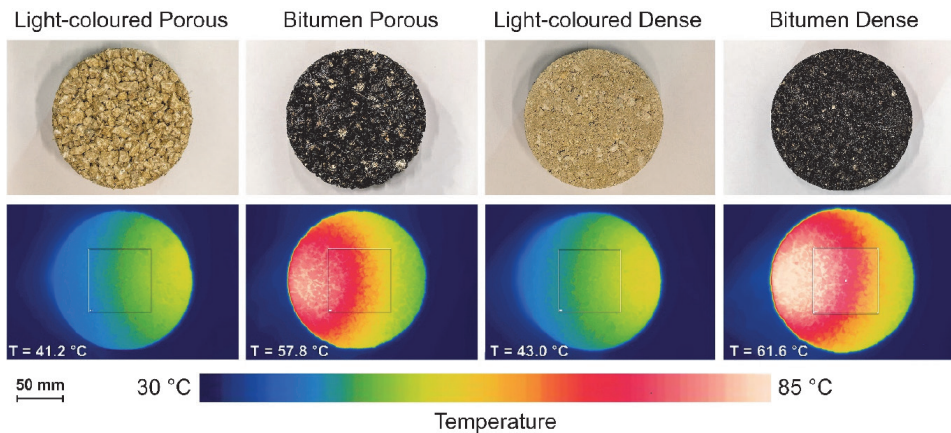


Figure 1 Thermographic and visual comparison of porous and dense mixtures, the thermographic analysis depicts the average surface temperature (T) recorded for each specimen, asymmetry is due to the lamp position

4.6 Acoustic characterization

The acoustic performance of the mixture was assessed using the impedance tube. The findings indicate that the porous structure effectively dissipates sound energy within its interconnected voids, in contrast to densegraded pavements, which predominantly reflect tire-pavement noise. The light-pavement porous matrix achieves a sound pressure reduction of approximately 3 to 6 dB, with the most significant attenuation observed between frequencies 500 and 800 Hz, where the highest sound absorption coefficients (α) are recorded. This dissipation through viscous friction enhances acoustic comfort in sensitive hospital areas, providing targeted mitigation at the critical frequencies associated with rolling and incident noise.

4.7 Comparative cost analysis of production and laying

To complement the performance characterization, a preliminary economic evaluation was conducted to compare the mixture under study with a standard porous asphalt pavement. The comparison is based on the substitution of modified bituminous binder (PMB) with a light-colored synthetic binder, while maintaining the same aggregate grading and laying procedures. Since logistics, paving operations with a finisher, and compaction are technically equivalent for both technologies, the price discrepancy is exclusively attributable to the cost of the binder. Based on 2025/2026 market prices in the Northern Italy for wearing courses with a thickness of 4 cm, the following indicative values are reported:

- standard porous asphalt (PMB): 18.00 – 24.00 €/m²
- light-colored binder mixture: 38.00 – 50.00 €/m².

5 Innovation in healthcare infrastructure

The experimental results confirm that the transparent binder porous system is well aligned with the functional and environmental requirements of modern, resilient, user-centered healthcare facilities. Its contribution can be articulated through three key performance pillars: safety, sustainability and maintenance efficiency.

5.1 Safety

Outdoor safety is a critical requirement in hospital environments, where especially vulnerable users, such as elderly patients and individuals with reduced mobility, are particularly exposed to slip risks and lack of accessibility. The high vertical permeability ($k_v > 5 \times 10^{-4}$ m/s) enables the rapid drainage of rainfall, preventing water film formation and the associated “mirror effect”, thereby preserving depth perception for visually impaired users (ISO 21542:2021). Furthermore, the combination of high-albedo aggregates and the transparent binder ensures PTV values well above 36, providing secure driving and walking conditions and reducing the likelihood of slip-and-fall accidents [8].

5.2 Sustainability

The system contributes to environmental and operational sustainability through its thermal and microclimatic performance, especially in hot weather conditions. The observed surface temperature reduction of over 20°C limits passive heat gain in adjacent hospital wards, lowering the thermal load on building envelopes and reducing HVAC energy demand [6]. Moreover, a more stable outdoor microclimate enhances the comfort of recovery and waiting areas, supporting the principles of healing-oriented design and environmental wellbeing [11].

5.3 Maintenance

Durability and continuity of service are essential for healthcare infrastructures, where access routes must possibly remain fully operational at all times. Mechanical characterization (mainly ITS and ITSM) confirms adequate stiffness and strength, reducing the risk of raveling and ensuring long-lasting smooth surfaces, guaranteeing in-time vibration-free ambulance routes and even surfaces for all users [9]. The mixture’s resistance to dynamic loads minimizes maintenance interventions, ensuring uninterrupted access to emergency docks and optimizing lifecycle costs, while preserving recyclability of materials [9].

6 Conclusion

The conceived pavement and the completed simple experimental program demonstrate that the proposed light-colored porous wearing course is a suitable and robust solution for road infrastructures in sensitive healthcare environments. The combination of a transparent synthetic binder and light-colored aggregates enables a resilient pavement capable of addressing key requirements related to safety, environmental performance, continuous operability and aesthetics. The system provides clear multifunctional advantages over conventional pavement technologies:

- Hydraulic efficiency: high vertical permeability ensures rapid infiltration and stable friction levels (PTV > 36) during intense rainfall.
- Thermal mitigation: the elevated albedo of the mixture significantly lowers surface temperatures, contributing to UHI reduction and improved outdoor comfort.
- Acoustic comfort: the interconnected voids structure enhances sound absorption, reducing rolling noise effects and supporting quieter hospital surroundings.

The findings confirm that the mixture functions as an active pavement system, interacting dynamically with environmental inputs. By controlling water, heat and sound, the surface acts as an environmental mitigation tool aligned with the principles of sustainable and resilient healthcare design.

Future work will investigate the integration of the porous wearing course with the previously mentioned unbound permeable road bases to optimize hydraulic drainage and storage as well as structural performance, and will include longterm monitoring through an instrumented full-scale laboratory box-test to assess the evolution of reflectance and permeability over time, as well as the mitigation of possible leachates and ecotoxic elements by means of synthetic interlayers.

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