TESIS DOCTORAL

Análisis del comportamiento hidráulico y ambiental a largo plazo de pavimentos permeables y de su potencial para el control de microplásticos en la gestión avanzada de escorrentías urbanas

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Abstract / Resumen / Resum

Abstract

Permeable pavements, considered a part of Sustainable Urban Drainage Systems (SUDS), are characterised by an efficient water quality and quantity treatment of stormwater runoff. The layered structure allows water filtration, and infiltration to the underlying soil, or to be stored for subsequent use or discharge. The review of the main Spanish and international references for the design of permeable pavements, dealt with in Chapter II, has revealed certain lack of information related to the hydrological and hydraulic functionality, associated with a possible clogging of the structure, and additionally, to the capacity to manage certain pollutants present in stromwater runoff. This situation can generate some mistrust among the technicians responsible for the implementation of permeable pavements, representing an obstacle to the standardisation of their use. With the aim of tackling this challenge, this Thesis seeks to deepen our knowledge of the behaviour of permeable pavements subjected to sediment inputs, from the hydrological, hydraulic and environmental points of view, placing special emphasis on the management of emerging pollutants such as microplastics.

The analysis of the hydrological, hydraulic and environmental long-term behaviour of a permeable surface subjected to clogging by different sediment characteristics, developed in Chapter III, has demonstrated the high treatment capacity of this type of SUDS, achieving significant reductions in the concentration of pollutants in the filtered water, such as COD (96%), TN (76%), PT (79%) and TSS (98%). From a hydrological and hydraulic point of view, various factors related to the sediment itself (granulometry, organic matter content and the rate of surface accumulation), in addition to rainfall frequency, or the lack of surface maintenance, favour the clogging process of the structure, leading to the production of runoff. Maintenance measures at a frequency of less than 6 months could help to mitigate the potential dispersal of pollutants accumulated on the surface during periods of dry weather into the natural environment.

Among the wide variety of pollutants carried by stormwater runoff, microplastics (anthropogenic plastic particles smaller than 5 mm in size) are among the most abundant. Microplastics can come from a variety of sources, including wear and

tear from larger plastic objects such as bottles, tyres, synthetic fibre clothing and others. The recent declaration of stormwater runoff as a significant source of microplastic pollution of the oceans, has sparked particular interest in their research, with the aim of helping to mitigate their impact on the natural environment. In the last 10 years, the first studies focused on the use of SUDS for the control of microplastics have emerged. As a result of the review and analysis of existing studies to date, discussed in Chapter IV, it can be stated that SUDS based on treatment processes such as sedimentation (ponds and wetlands) and filtration (bioretention elements and permeable pavements) have a high capacity to retain microplastics. The literature review highlights the desirability of further research in this field, mainly in the development of a common methodology for sampling and identification of microplastics, as well as in refining the structural design of SUDS in order to retain those particles that are more difficult to retain.

The limited number of studies focusing on permeable pavements, combined with the high capacity of this technique to retain suspended solids, which have a significant correlation with microplastics, has motivated the study of this type of SUDS. As described in Chapter V, the high microplastic retention efficiencies obtained in the effluents of several pilot permeable pavement structures (78-97%), demonstrate that these structures are powerful tools for the management of this emerging pollutant. The analysis of the distribution of microplastics in the structure of a permeable pavement highlights the importance of two of its components in the retention of this pollutant: the permeable surface and the geotextile. The structure and configuration of these layers allow an efficient capture of a large amount of fibre-type particles (in the geotextile) and fragments (on the surface), which underlines their importance in the management of microplastic contamination. In addition, the pioneering study on the integration of adsorbent material in a permeable pavement has shown promising results in the capture of microplastics from tyre particles smaller than 0.1 millimetres.

Resumen

Los sistemas de pavimento permeable consisten en una de las medidas estructurales que engloban los Sistemas Urbanos de Drenaje Sostenible (SUDS). Entre otros aspectos, los pavimentos permeables se caracterizan por realizar una gestión de la escorrentía urbana eficiente en términos volumétricos y ambientales. Su estructura, configurada como una superposición de capas permeables, permite que el agua se filtre a través de ellas hacia el suelo subyacente, o bien, se almacene en las capas subsuperficiales para su posterior uso o descarga. La revisión de las principales referencias españolas e internacionales para el diseño de pavimentos permeables, abordada en el capítulo II, ha revelado cierta falta de información relacionada, en primer lugar, con la funcionalidad hidrológica e hidráulica asociada a la posible colmatación de la estructura, y, en segundo lugar, con la capacidad para gestionar determinados contaminantes presentes en las escorrentías urbanas. Esta situación puede generar cierta desconfianza entre los técnicos responsables de su implementación, representando un obstáculo para la normalización de su uso. Con el objetivo de abordar este desafío, la presente Tesis Doctoral trata de profundizar en el conocimiento del comportamiento de los pavimentos permeables sometidos a aportes de sedimentos, desde los puntos de vista hidrológico, hidráulico y ambiental, poniendo especial énfasis en la gestión de contaminantes emergentes como los microplásticos.

El análisis del comportamiento hidrológico, hidráulico y ambiental, a largo plazo de una superficie permeable sometida a colmatación por sedimentos de diferentes características, desarrollado en el capítulo III, ha demostrado la elevada capacidad depurativa de esta tipología de SUDS, consiguiendo importantes reducciones en la concentración de contaminantes en el agua filtrada, como DQO (96%), NT (76%), PT (79%) y SST (98%). Desde el punto de vista hidrológico e hidráulico, diversos factores relacionados con el propio sedimento (granulometría, contenido de materia orgánica y la tasa de acumulación superficial), además de la frecuencia de los eventos de lluvia, o la falta de mantenimiento de la superficie, favorecen el proceso de colmatación de la estructura, dando lugar a la producción de escorrentía. Adoptar medidas de limpieza con una frecuencia inferior a 6 meses podría ayudar a mitigar la posible dispersión hacia el medio natural, de los contaminantes acumulados en la superficie durante periodos de tiempo seco.

Entre la amplia variedad de sustancias contaminantes que transportan las escorrentías urbanas, los microplásticos (partículas plásticas de origen antrópico de tamaño inferior a 5 mm), figuran como uno de los elementos más abundantes. Los microplásticos pueden proceder de diversas fuentes, incluyendo el desgaste de objetos plásticos más grandes como botellas, neumáticos o ropa de fibra sintética entre otros. La reciente declaración de la escorrentía urbana como fuente significativa de contaminación de los océanos por estas partículas, ha suscitado un especial interés en su investigación, con el objetivo de ayudar a mitigar su impacto en el medio natural. En los últimos 10 años emergen los primeros estudios

centrados en el empleo de SUDS para el control de microplásticos. Fruto de la revisión y el análisis de los estudios existentes hasta la fecha, abordados en el capítulo IV, puede afirmarse que los SUDS basados en procesos de tratamiento como la sedimentación (estanques y humedales) y en la filtración (elementos de biorretención, y pavimentos permeables), poseen gran capacidad de retención de microplásticos. La revisión bibliográfica pone de manifiesto la conveniencia de continuar investigando en este campo, principalmente en el desarrollo de una metodología común en la fase de toma de muestras y de identificación de microplásticos, así como en perfeccionar el diseño estructural de los SUDS con el objetivo de en retener aquellas partículas más complicadas de retener.

La limitada cantidad de estudios centrados en los pavimentos permeables, combinada con la alta capacidad de esta técnica para retener sólidos en suspensión, los cuales poseen una correlación significativa con los microplásticos, ha motivado el estudio de este tipo de SUDS. Tal y como se describe en el capítulo V, las altas eficiencias de retención de microplásticos obtenidas en los efluentes de varias estructuras piloto de pavimento permeable (78-97%), sitúan a estas estructuras como potentes herramientas para la gestión de este contaminante emergente. El análisis de la distribución de los microplásticos en la estructura de un pavimento permeable destaca la importancia de dos de sus componentes en la retención de este contaminante: la superficie permeable y el geotextil. La estructura y configuración de estas capas permiten capturar eficientemente una gran cantidad de partículas de tipo fibra (en el geotextil) y fragmento (en superficie), lo que subraya su importancia en la gestión de la contaminación por microplásticos. Además, el estudio pionero sobre la integración de material adsorbente en un pavimento permeable ha arrojado resultados prometedores en la captura de microplásticos procedentes de partículas de neumáticos de tamaño inferior a 0.1 milímetros.

Resum

Els sistemes de paviment permeable consisteixen en una de les mesures estructurals que engloben els Sistemes Urbans de Drenatge Sostenible (SUDS). Entre altres aspectes, els paviments permeables es caracteritzen per realitzar una gestió de l'escorrentia urbana eficient en termes volumètrics i ambientals. La seua estructura, configurada com una superposició de capes permeables, permet que l'aigua s'infiltre a través d'elles cap al sòl subjacent, o bé, es emmagatzeme en les capes subsuperficials per al seu posterior ús o descàrrega. La revisió de les principals referències espanyoles i internacionals per al disseny de paviments permeables, abordada en el capítol II, ha revelat certa falta d'informació relacionada, en primer lloc, amb la funcionalitat hidrològica i hidràulica associada a la possible colmatació de l'estructura, i, en segon lloc, amb la capacitat per a gestionar determinats contaminants presents en les escorrenties urbanes. Aquesta situació pot generar certa desconfiança entre els tècnics responsables de la seua implementació, representant un obstacle per a la normalització del seu ús. Amb l'objectiu d'abordar aquest desafiament, la present Tesi Doctoral tracta de profunditzar en el coneixement del comportament dels paviments permeables sotmesos a aportacions de sediments, des dels punts de vista hidrològic, hidràulic i ambiental, posant especial èmfasi en la gestió de contaminants emergents com els microplàstics.

L'anàlisi del comportament hidrològic, hidràulic i ambiental, a llarg termini d'una superfície permeable sotmesa a colmatació per sediments de diferents característiques, desenvolupat en el capítol III, ha demostrat l'elevada capacitat depuradora d'aquesta tipologia de SUDS, aconseguint importants reduccions en la concentració de contaminants en l'aigua filtrada, com DQO (96%), NT (76%), PT (79%) i SST (98%). Des del punt de vista hidrològic i hidràulic, diversos factors relacionats amb el propi sediment (granulometria, contingut de matèria orgànica i la taxa d'acumulació superficial), a més de la freqüència dels esdeveniments de pluja, o la falta de manteniment de la superfície, afavoreixen el procés de colmatació de l'estructura, donant lloc a la producció d'escorriment. Adoptar mesures de neteja amb una freqüència inferior a 6 mesos podria ajudar a mitigar la possible dispersió cap al medi natural, dels contaminants acumulats en la superfície durant períodes de temps sec.

Entre l'àmplia varietat de substàncies contaminants que transporten les escorrenties urbanes, els microplàstics (partícules plàstiques d'origen antròpic de mida inferior a 5 mm), figuren com un dels elements més abundants. Els microplàstics poden provenir de diverses fonts, incloent l'erosió d'objectes plàstics més grans com ara ampolles, pneumàtics o roba de fibra sintètica entre altres. La recent declaració de l'escorrentia urbana com a font significativa de contaminació dels oceans per aquestes partícules, ha suscitat un especial interès en la seva investigació, amb l'objectiu d'ajudar a mitigar el seu impacte en el medi natural. En els últims 10 anys emergeixen els primers estudis centrats en l'ús de SUDS per

al control de microplàstics. Fruit de la revisió i l'anàlisi dels estudis existents fins a la data, abordats en el capítol IV, es pot afirmar que els SUDS basats en processos de tractament com la sedimentació (estanys i aiguamolls) i en la filtració (elements de biorretenció i paviments permeables), tenen gran capacitat de retenció de microplàstics. La revisió bibliogràfica posa de manifest la conveniència de continuar investigant en aquest camp, principalment en el desenvolupament d'una metodologia comuna en la fase de presa de mostres i d'identificació de microplàstics, així com en perfeccionar el disseny estructural dels SUDS amb l'objectiu de retenir aquelles partícules més complicades de retenir.

La limitada quantitat d'estudis centrats en els paviments permeables, combinada amb l'alta capacitat d'aquesta tècnica per a retenir sòlids en suspensió, els quals tenen una correlació significativa amb els microplàstics, ha motivat l'estudi d'aquest tipus de SUDS. Tal com es descriu en el capítol V, les altes eficiències de retenció de microplàstics obtingudes en els efluents de diverses estructures pilot de paviment permeable (78-97%), situen aquestes estructures com a potents eines per a la gestió d'aquest contaminant emergent. L'anàlisi de la distribució dels microplàstics en l'estructura d'un paviment permeable destaca la importància de dos dels seus components en la retenció d'aquest contaminant: la superfície permeable i el geotèxtil. L'estructura i configuració d'aquestes capes permeten capturar eficientment una gran quantitat de partícules de tipus fibra (en el geotèxtil) i fragment (en superfície), el que subratlla la seua importància en la gestió de la contaminació per microplàstics. A més, l'estudi pioner sobre la integració de material adsorbent en un paviment permeable ha donat resultats prometedors en la captura de microplàstics procedents de partícules de pneumàtics de mida inferior a 0,1 mil·límetres.

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Autorización

Dr. Ignacio Andrés Doménech, Profesor Titular de Universidad de la Escuela Técnica Superior de Ingeniería de Caminos, Canales y Puertos, adscrito al Departamento de Ingeniería Hidráulica y Medio Ambiente de la Universitat Politècnica de València,

Dra. Carmen Hernández Crespo, Profesora Asociada de la Escuela Técnica Superior de Ingeniería de Caminos, Canales y Puertos, adscrita al Departamento de Ingeniería Hidráulica y Medio Ambiente de la Universitat Politècnica de València,

AUTORIZAMOS:

La presentación de la Tesis Doctoral titulada "Análisis del comportamiento hidráulico y ambiental a largo plazo de pavimentos permeables y de su potencial para el control de microplásticos en la gestión avanzada de escorrentías urbanas", realizada por Eduardo García Haba, y presentada en forma de compendio de artículos, bajo nuestra dirección y supervisión, en el Programa de Doctorado en Ingeniería del Agua y Medioambiental de la Universitat Politècnica de València.

En cumplimiento de la legislación vigente, firmamos esta autorización en València.

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Actividades específicas

En este apartado se citan las principales actividades derivadas de la elaboración de la Tesis Doctoral. Estas actividades se agrupan según publicaciones de artículos en revista, participaciones en congresos, seminarios y cursos impartidos, y realización de estancias en otros centros de investigación.

A. Artículos en revistas

Artículo 1. Análisis de los actuales estándares de diseño de estructuras de pavimento permeable y futuras consideraciones.

García-Haba, E., Rodríguez-Hernández, J., Andrés-Doménech, I., Hernández-Crespo, C., Anta, J., & Martín, M. (2022). Diseño de pavimentos permeables en España: situación actual y necesidades futuras. Ingeniería Del Agua, 26(4), 279–296. https://doi.org/10.4995/ia.2022.18290

Artículo 2. Influencia de los sedimentos urbanos en el comportamiento hidráulico de la superficie porosa de una estructura de pavimento permeable, y en la calidad del agua infiltrada durante el proceso de colmatación.

García-Haba, E., Naves, J., Hernández-Crespo, C., Goya-Heredia, A., Suárez, J., Anta, J., & Andrés-Doménech, I. (2023). Influence of sediment characteristics on long-term hydrology and water quality behaviour during the clogging process of a permeable asphalt. Journal of Water Process Engineering, 53, 103658. https://doi.org/10.1016/J.JWPE.2023.103658

Artículo 3. Revisión del estado del arte de los SUDS como medida de control de microplásticos en escorrentías urbanas.

García-Haba, E., Hernández-Crespo, C., Martín, M., & Andrés-Doménech, I. (2023). The role of different sustainable urban drainage systems in removing microplastics from urban runoff: A review. Journal of Cleaner Production, 411, 137197. https://doi.org/10.1016/J.JCLEPRO.2023.137197

Artículo 4. Evaluación de la eficiencia de retención de microplásticos de un pavimento permeable.

García-Haba, E., Benito-Kaesbach, A., Hernández-Crespo, C., Sanz-Lazaro, C., Martín, M. and Andrés-Doménech, I. (2024). Removal and fate of microplastics in permeable pavements: An experimental layer-by-layer analysis. Science of The Total Environment. Volume 929, 172627, ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2024.172627

B. Participación en congresos

Conferencia 1. Evaluación de la capacidad de un pavimento permeable para el tratamiento de escorrentía urbana y de su gestión para reutilización.

García-Haba, E., Hernández-Crespo, C., Martín, M., Albentosa, E., & Andrés-Doménech, I. (2021). Can permeable pavements act as water storage systems? evaluation of water treatment capacity and reuse. 4th International Congress SMALLWAT 2021v Wastewater treatment in small communities. Abstract book (pp. 461-465). ISBN: 978-989-331964.

Conferencia 2. Estudio del efecto del fango deshidratado de potabilizadora en la capacidad de tratamiento de un pavimento permeable.

García-Haba, E., Hernández-Crespo, C., Martín, M., & Andrés-Doménech, I. (2021). Addition of drinking water treatment sludge into permeable pavements for phosphorus control in infiltrated runoff water. Proceedings of the 2nd IAHR Young Professionals Congress (pp. 37–38). IAHR-YPN.

Conferencia 3. Gestión de escorrentías urbanas mediante pavimentos permeables para su reutilización.

García-Haba, E., Hernández-Crespo, C., Martín, M., Albentosa, E., & Andrés-Doménech, I. (2021). Permeable pavements as stormwater storage systems for water reuse in a Mediterranean city and evaluation of their treatment capacity. Proceedings of the 15th International Conference on Urban Drainage.

Conference 4. Eficiencia de un pavimento permeable para la retención de microplásticos en escorrentía urbana.

García-Haba, E., Hernández-Crespo, C., Martín, M., Benito- Kaesbach, A., Sanz-Lazaro, C., Andrés-Doménech, I. (2023). Permeable pavements for microplastic pollution control: a laboratory analysis under mediterranean rainfall conditions. Novatech 2023 11e Conférence internationale sur l'eau dans la ville, Graie, Jul 2023, Lyon, France.

Conferencia 5. Pavimentos permeables para la captura de microplásticos en escorrentía urbana.

García-Haba, E., Hernández-Crespo, C., Martín, M., Benito- Kaesbach, A., Sanz-Lazaro, C., Andrés-Doménech, I. (2023). Eficiencia de los pavimentos permeables para la retención de microplásticos de la escorrentía urbana. VII Jornadas de Ingeniería del Agua Libro de resúmenes (pp.359-362). ISBN:978-84-17853-72-3.

Conferencia 6. Influencia de la colmatación a largo plazo de un pavimento permeable en su respuesta ambiental e hidrológica.

García-Haba, E., Naves, J., Hernández-Crespo, C., Goya-Heredia, A., Suárez, J., Anta, J. and Andrés-Doménech, I. (2024). Long-term laboratory analysis of the impact of sediment characteristics on the clogging process of permeable asphalt and its hydrological and water quality response. 8th IAHR Europe Congress. June 2024, Lisbon, Portugal. (comunicación oral aceptada)

C. Seminarios y cursos impartidos

Seminario 1

Participación como expositor en el taller virtual de “Sistemas de drenaje urbano sostenible”, desarrollado el 10 de marzo de 2023, organizado por la Sociedad de Ingenieros de Bolivia Departamental Chuquisaca y la ABIS Chuquisaca.

Seminario 2

Participación como expositor en la Jornada Técnica "SUDS - Sistemas Urbanos de Drenaje Sostenible: Tecnología, implantación, avances y experiencias" realizada el 28 de marzo de 2023, organizada por AGUASRESIDUALES.INFO.

Curso 1

Docencia Universitaria Impartida en cursos de formación continua y permanente durante el curso académico 2022/2023. Curso “Implementación de soluciones basadas en la naturaleza en el ámbito urbano: humedales para el tratamiento y sistemas urbanos de drenaje sostenible”, promovido por Instituto Universitario de Ingeniería del Agua y del Medio Ambiente (IIAMA), de 36 horas presenciales. Docencia dedicada de 8 horas. Responsable de la actividad: Miguel Martín Monerris.

D. Estancias en otros centros de investigación

Estancia 1. Centro de Innovación Tecnológica en Edificación e Enxeñaría Civil (CITEEC).

Centro de Innovación Tecnológica en Edificación e Enxeñaría Civil (CITEEC), Universidade da Coruña, colaborando con el “Grupo de Enxeñaría del Agua y del Medio Ambiente (GEAMA). Duración: 1 mes (del 25/03/2023 al 28/04/2023). Temática: monitorización de SUDS y organización de jornadas de difusión en el ámbito de los SUDS. Investigador anfitrión: Jose Anta Álvarez.

A Mauro y Valeria, mis hijos

Contenido

Capítulo I

Introducción

I.1 Contexto

En la actualidad, cerca del 56% de la población mundial reside en las ciudades. Según las estimaciones, se espera que este porcentaje se eleve hasta casi el 70% para el año 2050. Este hecho podría propiciar la expansión del suelo urbano siguiendo un desarrollo insostenible, ejerciendo una enorme presión sobre el consumo de los recursos naturales y aumentando la generación de residuos. A medida que crecen las ciudades, éstas aumentan su exposición a riesgos y desastres climáticos como inundaciones, agravadas a consecuencia del cambio climático (Banco Mundial, 2024). Precisamente, en periodos en los que se producen eventos de precipitación, el incremento de la superficie impermeable afecta de forma directamente proporcional a la generación de escorrentía, la cual se encuentra altamente contaminada (Andrés-Doménech et al. 2018).

El modelo actual de drenaje urbano, basado en una gestión del agua de lluvia centralizada en una estación de tratamiento, y desagregada en sumideros (captación), conducciones (transporte), tanques de tormenta (laminación/dilución) …, puede presentar grandes dificultades a la hora de solventar problemas asociados a la cantidad y calidad de las escorrentías urbanas. En ciertas ocasiones, durante episodios de precipitaciones, una insuficiente capacidad hidráulica del sistema de drenaje, dando lugar a inundaciones (Ellis et al. 1989). En este escenario, la escorrentía superficial y las Descargas de Sistemas Unitarios (DSU) alcanzan las masas de agua, transportando cargas importantes de contaminantes (Richard, 1982). La desconexión entre las planificaciones hidráulica y urbanística, la contaminación de las escorrentías, y el impacto medioambiental en los medios receptores, han suscitado interés social en transformar el modelo actual. Este nuevo enfoque, basado en un modelo de desarrollo sostenible, integra los aspectos hidráulico, medioambiental, urbanístico y social, descentralizando la gestión del agua de lluvia. Los Sistemas Urbanos de Drenaje Sostenible (SUDS), representan medidas para la gestión sostenible y resiliente de las aguas pluviales. Los SUDS engloban un conjunto de técnicas que tratan de replicar el ciclo hidrológico natural en entornos urbanos, favoreciendo procesos relacionados con la cantidad (infiltración, evaporación, retención, detención), la calidad (filtración, adsorción, sedimentación, degradación biológica); y potenciando aspectos como la biodiversidad, el uso recreativo, y la mejora del paisaje urbano desde el punto de vista estético.

Particularmente, los sistemas de pavimento permeable se encuentran entre las técnicas de SUDS más empleadas y estudiadas a nivel mundial, debido a su gran versatilidad y multifuncionalidad. En España, se ha realizado un notable esfuerzo desarrollando actividad investigadora en torno a los pavimentos permeables, propiciando la creación de una base científica sólida y ampliando el conocimiento sobre estas estructuras. Como resultado, la información sobre los sistemas de pavimento permeable se ha incrementado sustancialmente en guías y manuales de diseño de SUDS, consolidándose como herramientas de diseño útiles y accesibles.

I.2 Motivación de la investigación

A pesar del esfuerzo invertido en producir documentación orientada a facilitar y regular la implementación de los SUDS, todavía existen múltiples barreras que impiden consolidar su aceptación y dificultan su generalización. (Andrés-Doménech et al. 2021). En el contexto de los pavimentos permeables, pese a que viene demostrándose su eficacia para la gestión de cantidad y de la calidad de las aguas pluviales desde los últimos 40 años (Castro-Fresno et al. 2013), todavía se detecta cierto escepticismo entre los actores responsables de su implementación, motivado fundamentalmente por dos factores.

Por un lado, la existencia de limitaciones físicas que puedan comprometer el rendimiento y la funcionalidad de los pavimentos permeables (Hoang y Fenner, 2015). La escorrentía superficial moviliza el sedimento acumulado sobre las superficies urbanas, ocupando los huecos del pavimento permeable. Este proceso puede llegar incluso a sellar completamente la estructura, provocando la pérdida de permeabilidad, y disminuyendo su capacidad de infiltración (Haynes et al. 2020). Por otra parte, la falta de información disponible desde la perspectiva ambiental, impide que se considere la instalación de pavimentos permeables con el propósito de mejorar la calidad de las escorrentías urbanas. La superficie urbana representa un reservorio significativo de una amplia variedad de sustancias contaminantes integradas en el sedimento, como aceites, metales pesados, nutrientes, sólidos en suspensión, productos químicos orgánicos y contaminantes emergentes, que pueden acabar en el medio receptor, afectando negativamente al medio ambiente.

Según Sañudo-Fontaneda et al. (2018), la superficie de un pavimento permeable es susceptible de colmatarse completamente tras el intervalo de 8 a 10 años de operación. Hasta el momento, estudios previos han simulado la entrada de sedimento en el pavimento permeable, aplicando lluvia o escorrentía sintética (Fernández-Gonzalvo et al. 2020; Guthrie et al. 2010; Tan et al. 2003), con una granulometría previamente estructurada, y un contenido de contaminantes controlado (Mahmoud et al. 2020; Aberle et al. 2017). Por tanto, resulta interesante estudiar el comportamiento de esta tipología de SUDS utilizando diferentes tipos de sedimento urbano real, con diferentes grados de contaminación y distinta granulometría. Precisamente, uno de los vectores que contribuyen significativamente al proceso de colmatación, es la presencia de contaminantes (sólidos en suspensión, metales pesados, nutrientes, materia orgánica, aceites, hidrocarburos) en la escorrentía urbana (Luke y Beecham, 2013). Evidencias científicas demuestran que ciertas tipologías de SUDS permiten retener sólidos en suspensión eficientemente (Nandi et al. 2019), destacando los pavimentos permeables (Hernández-Crespo et al. 2019a; Fernández-Gonzalvo et al. 2021; Razzaghmanesh y Borst, 2019). No obstante, se desconoce cómo actúan frente a otros contaminantes, también de naturaleza particulada y presentes en la escorrentía urbana, como los microplásticos. Investigaciones realizadas por Wang, Q. et al. (2020) y Calzadilla-Cabrera et al. (2023), observaron la existencia de una correlación lineal significativa entre microplásticos y sólidos en suspensión. Este hecho sugiere que los SUDS, y los pavimentos permeables en particular, podrían desempeñar un papel muy similar en el control de microplásticos. Por lo tanto, se plantea la necesidad de explorar esta hipótesis.

Considerados como contaminantes emergentes, los microplásticos se definen como partículas de plástico insoluble en agua, de tamaño inferior a 5 mm, que tienen su origen en las actividades humanas (ISO 2020). Se trata de un contaminante que abunda en el sedimento urbano, que ha despertado recientemente un especial interés en la sociedad por sus efectos adversos en la salud humana y en los ecosistemas acuáticos (Sharma et al. 2023; Prata et al. 2021; Thompson et al. 2004). Según el modo en el que se originan, los microplásticos se clasifican como primarios (fabricados con fines industriales, de tamaño inferior a 5 mm), o secundarios (proceden de la descomposición de plásticos de mayor tamaño) (GESAMP, 2015). Según su forma, se catalogan habitualmente como esferas, fibras, *films*, fragmentos, *foams* o láminas (Figura I.1).

A principios de la década anterior aparecen los primeros estudios que relacionan la escorrentía urbana con los microplásticos, considerándola como una fuente principal de contaminación difusa por este tipo de material (Lee et al. 2013; Moore et al. 2011). Los microplásticos pueden alcanzar el medio natural como consecuencia del vertido directo de las escorrentías que no ha recibido un tratamiento previo, o a través de las DSU. Es importante destacar que la gestión de las escorrentías mediante sistemas convencionales de depuración de aguas, permite reducir eficientemente los microplásticos de la línea de agua (Prata, 2018). Sin embargo, una concentración significativa de microplásticos permanece en los fangos generados en el proceso de tratamiento. Estos lodos pueden representar una seria amenaza para el medio ambiente. El empleo de fangos procedentes de EDAR en la agricultura, supone una vía de entrada de microplásticos en las masas de agua, a consecuencia del efecto lavado de la escorrentía superficial (Calzadilla et al. 2023; van den Berg et al. 2020).

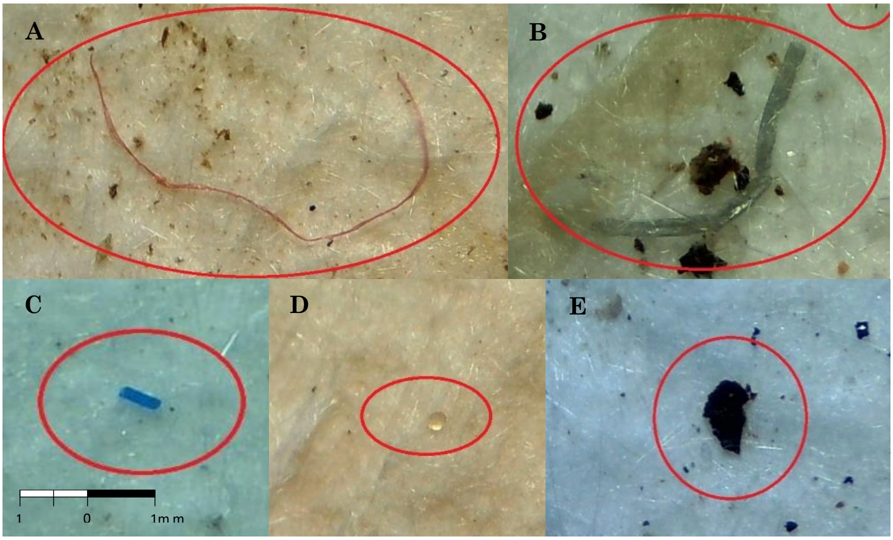

Figura I.1. Formas de microplásticos recogidos en muestras de efluentes de agua en pavimentos permeables (A, fibra; B, *film*; C, fragmento; D, esfera; E, partícula de neumático). Elaboración propia.

Abordar el tratamiento de las escorrentías superficiales mediante modelos de gestión sostenible, como los SUDS, se presenta como un importante desafío para mitigar su impacto ambiental. Durante los últimos 10 años, se han llevado a cabo las primeras investigaciones centradas en el estudio de la capacidad de retención de microplásticos empleando diferentes tipologías de SUDS (Bodus et al. 2024). Los resultados demuestran que los sistemas basados en los procesos de sedimentación, como los humedales o estanques, y los basados en la filtración, como los elementos de biorretención, retienen eficientemente un número significativo de microplásticos (García-Haba et al. 2023b). Coincidiendo con la fase final de la elaboración de la Tesis, únicamente se han detectado 3 estudios que traten el problema de la gestión de microplásticos en escorrentía mediante pavimentos permeables. Este hecho subraya la relevancia y la necesidad de profundizar en este campo de estudio, representando el principal estímulo para el desarrollo de este trabajo de investigación.

I.3 Objetivos

A partir de los antecedentes descritos en los puntos anteriores, la presente Tesis Doctoral tiene como objetivo general profundizar en el conocimiento del comportamiento hidráulico de los pavimentos permeables, así como de su capacidad para el tratamiento de la escorrentía urbana, poniendo especial énfasis en el control de microplásticos. Para ello se han establecido los siguientes objetivos específicos:

Objetivo 1. Examinar el estado actual de las normas y criterios de diseño de estructuras de pavimento permeable que recogen las principales guías básicas españolas para el diseño de SUDS. Este objetivo se aborda en el capítulo II del documento.

Objetivo 2. Estudiar el comportamiento hidrológico e hidráulico (permeabilidad, volúmenes infiltrados, y de producción escorrentía) a largo plazo de una superficie permeable durante el proceso de colmatación producido por sedimentos de diferentes características. Este objetivo se aborda en el capítulo III del documento.

Objetivo 3. Analizar a largo plazo la calidad del agua filtrada por una superficie permeable durante el proceso de colmatación producido por sedimentos de diferentes características. Este objetivo se aborda en el capítulo III del documento.

Objetivo 4. Evaluar el potencial de los SUDS para el control de microplásticos presentes en la escorrentía urbana, para identificar posibles brechas todavía por estudiar e investigar. Este objetivo se aborda en el capítulo IV del documento.

Objetivo 5. Determinar experimentalmente la capacidad y eficiencia de los pavimentos permeables para la retención de microplásticos. Este objetivo se aborda en el capítulo V del documento.

Objetivo 6. Estudiar la influencia de las distintas capas que conforman la estructura integral de un pavimento permeable en su capacidad para la captura de microplásticos. Este objetivo se aborda en el capítulo V del documento.

Objetivo 7. Analizar experimentalmente la influencia de la incorporación de un material adsorbente en la estructura de un pavimento permeable en la retención de microplásticos. Este objetivo se aborda en el capítulo V del documento.

I.4 Estructura de la Tesis

La Tesis Doctoral se presenta en formato por compendio de los siguientes artículos publicados en las revistas que se indican a continuación:

Artículo 1: García-Haba, E., Rodríguez-Hernández, J., Andrés-Doménech, I., Hernández-Crespo, C., Anta, J., & Martín, M. (2022). Diseño de pavimentos permeables en España: situación actual y necesidades futuras. Ingeniería Del Agua, 26(4), 279–296. https://doi.org/10.4995/ia.2022.18290

Artículo 2: García-Haba, E., Naves, J., Hernández-Crespo, C., Goya-Heredia, A., Suárez, J., Anta, J., & Andrés-Doménech, I. (2023). Influence of sediment characteristics on long-term hydrology and water quality behaviour during the clogging process of a permeable asphalt. Journal of Water Process Engineering, 53, 103658. https://doi.org/10.1016/J.JWPE.2023.103658

Artículo 3: García-Haba, E., Hernández-Crespo, C., Martín, M., & Andrés-Doménech, I. (2023). The role of different sustainable urban drainage systems in removing microplastics from urban runoff: A review. Journal of Cleaner Production, 411, 137197. https://doi.org/10.1016/J.JCLEPRO.2023.137197

Artículo 4: García-Haba, E., Benito-Kaesbach, A., Hernández-Crespo, C., Sanz-Lazaro, C., Martín, M. and Andrés-Doménech, I. (2024). Removal and fate of microplastics in permeable pavements: An experimental layer-by-layer analysis. Science of The Total Environment. Volume 929, 172627, ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2024.172627

El documento de tesis se articula en siete capítulos tal y como se detalla a continuación.

El **Capítulo I** describe el contexto y la motivación de la investigación, los objetivos generales y específicos de la Tesis, y la estructura del propio documento.

El **Capítulo II** se corresponde con el *Artículo 1* y revisa el estado actual de las normas y criterios de diseño de estructuras de pavimento permeable que recogen las principales guías básicas españolas para el diseño de SUDS. Además, discute las principales y más recientes innovaciones llevadas a cabo en España en el ámbito de esta técnica. Por último, se identifican las principales barreras que impiden formalizar la implementación de los pavimentos permeables en las ciudades, y propone una serie de recomendaciones para ser incorporadas a los documentos de referencia para el diseño de estas estructuras.

Con el objetivo de contribuir a resolver las limitaciones identificadas en el capítulo anterior, el **Capítulo III,** que corresponde al *Artículo 2*, examina el comportamiento hidrológico y ambiental de un pavimento permeable de asfalto poroso, sometido a colmatación prolongada en el tiempo, empleando sedimentos reales de diferentes características físicas y ambientales. Finalmente, se estudia la movilización (distribución y destino) de los sedimentos empleados en la investigación, en función de los procesos de filtración, retención y producción de escorrentía superficial.

Los SUDS se confirman como herramientas eficaces en la gestión de contaminantes presentes en las escorrentías urbanas. El reciente descubrimiento de la fuerte correlación entre uno de los contaminantes que más eficientemente retienen (sólidos en suspensión), y los microplásticos, plantea la cuestión sobre cómo responderán ante la presencia de este contaminante emergente. El **Capítulo IV,** que se corresponde con el *Artículo 3,* ofrece una exhaustiva revisión y recopilación del potencial de las diferentes tipologías de SUDS para la gestión de microplásticos presentes en la escorrentía urbana. Además, se analiza la capacidad de retención de microplásticos de las técnicas estudiadas, así como la distribución de partículas en su estructura. Por último, se identifican posibilidades de mejora en su diseño.

A pesar de que todavía falta mucho por investigar en este campo, cada vez son más los trabajos que estudian los SUDS como herramienta de control de microplásticos. Humedales artificiales, estanques, o elementos de biorretención y filtración, son las tipologías de SUDS más analizadas hasta el momento, siendo muy escasos los estudios que se han centrado de los pavimentos permeables. Con el objetivo de ampliar y contribuir al conocimiento respecto de esta técnica, el **Capítulo V**, correspondiente al *Artículo 4*, examina de manera experimental el comportamiento de varias estructuras piloto de pavimento permeable para el control de microplásticos. Se analiza, a nivel global y capa por capa, la influencia de varios aspectos como el modo de captación de agua y entrada de microplásticos, el tipo de superficie permeable, el número de capas de geotextil dispuestas, y la incorporación de material adsorbente, en la capacidad de retención de partículas.

El **Capítulo VI** presenta una discusión integrada de los resultados obtenidos en los capítulos anteriores.

Por último, el **Capítulo VII** resume las principales conclusiones extraídas de los artículos que conforman la Tesis Doctoral.

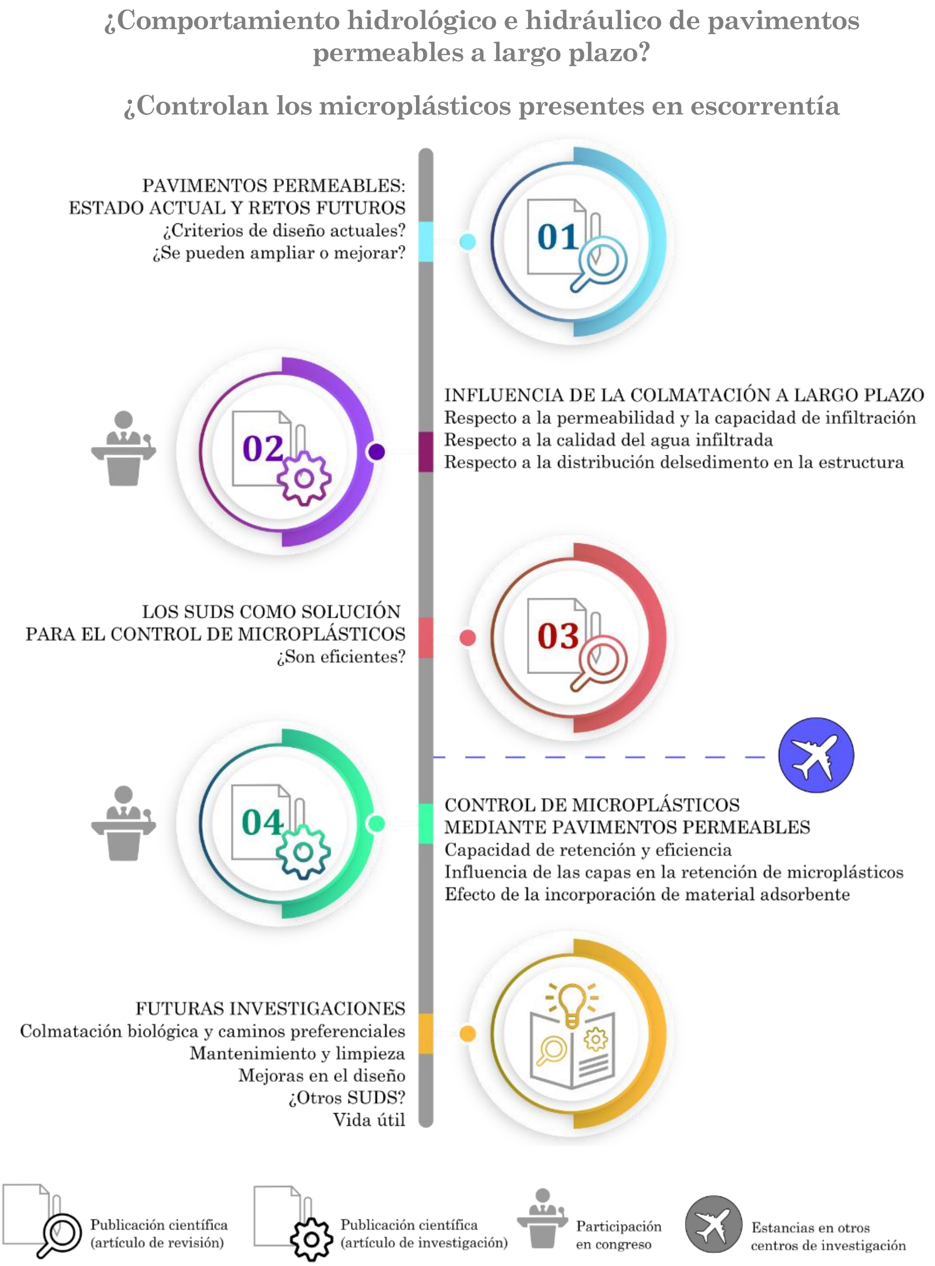

Figura I.2. Resumen gráfico del desarrollo de las principales actividades y logros conseguidos durante la elaboración de la Tesis, haciendo referencia a los artículos científicos publicados, participaciones en congresos y estancias en otros centros de investigación.

Capítulo II

Pavimentos permeables: estado actual y retos futuros

Los sistemas de pavimento permeable son una de las técnicas de drenaje urbano sostenible mejor consideradas para la gestión sostenible de las aguas pluviales. El presente capítulo tiene como objetivos destacar y analizar las referencias internacionales y nacionales más importantes para el diseño de sistemas de pavimento permeable. Innovaciones recientes desarrolladas en España reflejan que el ajuste y la mejora de su diseño puede optimizar su funcionamiento. Por ejemplo, la consideración de volúmenes de gestión de lluvia adaptados a las condiciones climatológicas del lugar de instalación, la incorporación de materiales reactivos para el control de contaminantes, la elección de superficies permeables más apropiadas o la ejecución de un proceso de mantenimiento mejorado. El conocimiento generado por la investigación, apoyado con información gráfica adaptada a la normativa municipal, debe promover el desarrollo de manuales y guías de diseño, exclusivas de sistemas de pavimento permeable, adaptadas a las singularidades de cada municipio.

García-Haba, E., Rodríguez-Hernández, J., Andrés-Doménech, I., Hernández-Crespo, C., Anta, J., & Martín, M. (2022). Diseño de pavimentos permeables en España: situación actual y necesidades futuras. Ingeniería Del Agua, 26(4), 279–296. https://doi.org/10.4995/ia.2022.18290

II.1 Introducción

El desarrollo de las ciudades genera importantes cambios en su cobertura superficial, interrumpiendo drásticamente el ciclo hidrológico natural. Particularmente, la impermeabilización del suelo y la reducción de superficie vegetal, limitan la capacidad de interceptar, almacenar e infiltrar en el subsuelo el agua de lluvia. En consecuencia, la producción de escorrentía durante eventos de precipitación se magnifica, provocando serios problemas de inundaciones, medioambientales y sociales (Woods-Ballard et al. 2015; Giménez-Maranges et al. 2020). La implementación de superficies permeables, entendidas como soluciones basadas en la naturaleza (SbN), se plantea como una firme estrategia para mitigar los impactos de estos problemas (Zölch et al. 2017). Por ejemplo, la adopción de infraestructuras verdes-azules o de Sistemas Urbanos de Drenaje Sostenible (SUDS), como parques y jardines inundables, cubiertas vegetadas, alcorques estructurales, o pavimentos permeables, contribuyen a la resiliencia del ecosistema urbano, a través del mantenimiento o restauración de las funciones hidrológicas naturales (Oral et al. 2020). Según la literatura, los pavimentos permeables, además de pertenecer a los conjuntos de sistemas y soluciones citados anteriormente, son también considerados como pavimentos biomiméticos o *cool pavements* en el ámbito anglosajón (Araque et al. 2021; Kappou et al. 2022), que basan su comportamiento en la propia naturaleza para hacer frente al fenómeno isla de calor, ayudando a disminuir el aumento de temperaturas en las zonas urbanas más densas y consolidadas).

El presente artículo se centra en los pavimentos permeables, conceptualizados como sistema integral de gestión de agua de lluvia, citando y analizando las principales referencias internacionales y españolas para el diseño de estas estructuras. Asimismo, discute las principales y más recientes innovaciones llevadas a cabo en España en el ámbito de esta técnica, cuyos resultados demuestran su elevada eficiencia a la hora de controlar y gestionar las escorrentías pluviales. Las guías y recomendaciones sobre SUDS que se pueden consultar actualmente en España, ofrecen información de partida suficiente para el diseño de los sistemas de pavimento permeable. Sin embargo, cuentan con el principal inconveniente de que los criterios de diseño se plantean para un ámbito de aplicación general, eludiendo las particularidades que cada municipio pueda contemplar en sus ordenanzas urbanísticas, cuando éstas existen y son lo suficientemente detalladas. La abundante información disponible debe servir de respaldo para el uso de los pavimentos permeables, además de fomentar que las administraciones públicas tomen decisiones e iniciativas como el desarrollo de instrucciones o guías de diseño y de aplicación, especialmente a nivel local.

Sistemas de pavimento permeable

Los sistemas de pavimento permeable están considerados como una herramienta eficaz para la gestión de las escorrentías urbanas en origen, interceptándolas, retrasando su cinética, y reduciéndolas en términos volumétricos, además de tratarlas desde el punto de vista de la calidad del agua (Pratt et al. 1989; Scholz y Grabowiecki, 2007; Drake et al. 2013). Concretamente, los procesos de tratamiento que se dan lugar en los sistemas de pavimento permeable son la filtración, adsorción, biodegradación y sedimentación, permitiendo la retención de sedimentos, algunos nutrientes, metales pesados, aceites y grasas (Beecham et al. 2015; Sambito et al. 2021).

Estas estructuras permiten la percolación del agua de lluvia a su través, al mismo tiempo que ofrecen el soporte apropiado para la circulación peatonal y de vehículos. El agua se retiene temporalmente bajo la superficie para posteriormente ser utilizada, infiltrada en el suelo o descargada aguas abajo hacia la red de drenaje o el medio natural de forma laminada. En general, la sección tipo de los sistemas de pavimento permeable está compuesta por un conjunto de capas superpuestas entre sí y apoyadas sobre la explanada natural o artificial (figura II.1). De arriba hacia abajo, las capas generalmente consisten en: pavimento permeable (formado por la propia superficie permeable y base), subbase y explanada. Adicionalmente, suelen ir complementadas con tuberías de drenaje y/o geosintéticos: geotextiles con funciones de filtro, protección, y separación entre capas; o geomembranas, con función de impermeabilización (Pratt et al. 2002; Sañudo-Fontaneda, 2014; Woods-Ballard et al. 2015).

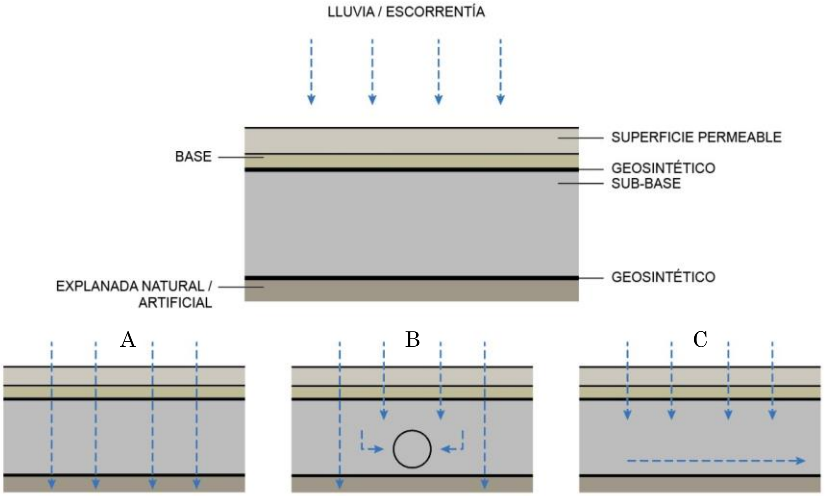

Figura II.1. Secciones tipo de sistema de pavimento permeable y posibles destinos del agua captada: A) El agua de escorrentía se infiltra en el terreno; B) Parte de la escorrentía se infiltra al terreno y parte se evacúa mediante un tubo drenante; C) La escorrentía se transporta a otro lugar para su tratamiento, almacenamiento o infiltración. (Adaptado de MITECO, 2019).

En la capa superficial pueden emplearse pavimentos permeables de césped reforzado, pavimentos porosos, o pavimentos impermeables con junta permeable, formados por adoquines y/o bloques. Por su parte, la base se ejecuta normalmente con material granular sin finos, mientras que la subbase se resuelve de nuevo con gravas o zahorras con bajo porcentaje de partículas finas, o mediante la instalación de cajas de plástico de alta resistencia e importante capacidad de almacenamiento de agua (Rodríguez-Hernández, 2008; Sañudo-Fontaneda, 2014; Jato-Espino et al. 2019; Castillo-Rodríguez et al. 2021).

II.2 Referencias internacionales para el diseño de sistemas de pavimento permeable

Sin duda, uno de los manuales más destacados y consultados en el ámbito de los SUDS a nivel internacional, es *The SUDS Manual*, elaborado por la *Construction Industry Research and Information Association* (CIRIA), de Reino Unido (Woods-Ballard et al. 2015). Este extenso y completo documento, está basado tanto en diferentes estudios llevados a cabo en todo el mundo, como en la experiencia de sus autores. La guía cubre varios aspectos como la planificación, diseño, construcción y mantenimiento de SUDS y, en consecuencia, de los sistemas de pavimento permeable. El manual contiene diferentes puntos dedicados a criterios de diseño de carácter general y específico (consideraciones hidráulicas, de calidad del agua, servicios para el ciudadano, biodiversidad, estructurales y paisajísticas), así como a los elementos de entrada y salida, y a las características de los materiales a emplear.

Resulta relativamente fácil encontrar guías y manuales de diseño de SUDS en la literatura técnica. Sin embargo, esto es más complicado cuando se requiere una guía focalizada en los sistemas de pavimento permeable. En este caso, sobresale la publicación específica elaborada por CIRIA (Pratt et al. 2002) y, como ejemplo de regulación local, la guía de pavimentos permeables de la ciudad de Rockville (Maryland) en Estados Unidos (City of Rockville, 2018). Esta última se centra en el uso de superficies de adoquín de hormigón con junta permeable en calles residenciales, y abarca consideraciones de óptima localización, diseño hidráulico, integración paisajística, materiales a emplear, construcción y mantenimiento. Adicionalmente, esta información está complementada con un conjunto de esquemas que incluyen secciones tipo recomendadas por la administración local.

II.3 Referencias españolas para el diseño de sistemas de pavimento permeable

En 2008, el Centro de Estudios y Experimentación de Obras Públicas (CEDEX) publicó el manual *Gestión de las aguas pluviales. Implicaciones en el diseño de los sistemas de saneamiento y drenaje urbano* (Puertas Agudo et al. 2008). El documento constituyó el primer intento por parte del entonces Ministerio de Fomento en la integración de las técnicas de drenaje urbano sostenible en la gestión urbana de las aguas pluviales. En él se recopila un amplio contenido de consideraciones para el diseño de pavimentos permeables, entre otras técnicas, basadas en referencias internacionales contrastadas. Fue en 2016 cuando la legislación española incorporó por primera vez el término SUDS en el Real Decreto 638/2016, estableciendo que los sistemas urbanos de drenaje sostenible, como las superficies permeables, deben ser incorporados en nuevas áreas industriales y futuros desarrollos urbanísticos (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016). En el periodo 2005-2019, y tomando como base este marco legislativo nacional, las comunidades autónomas de Euskadi, Galicia, Cataluña, Comunidad Valenciana, Canarias, Región de Murcia y Comunidad de Madrid, desarrollaron su propia regulación de implantación de SUDS. A pesar de la compleja organización territorial del país y las diferentes percepciones del modo de gestión de las aguas pluviales mediante SUDS (Andrés-Doménech et al. 2021), desde el año 2018, ciudades como Madrid (Ayuntamiento de Madrid, 2018), Barcelona (Ajuntament de Barcelona, 2020), València (De la Fuente et al. 2021) o Castelló de la Plana (Perales-Momparler et al. 2019), han elaborado guías y manuales locales que proporcionan una amplia visión de las técnicas SUDS, abordando los criterios de diseño, la fase de ejecución y el modo de explotación y mantenimiento. Complementariamente, en 2019, el Ministerio para la Transición Ecológica (MITECO) elaboró una guía descriptiva y orientativa de las técnicas SUDS a adoptar para mejorar la gestión de las aguas pluviales en las ciudades (MITECO, 2019). En el ámbito de los sistemas de pavimento permeable, la totalidad de estas guías describen y analizan esta técnica, además de proponer recomendaciones y criterios para su adecuado diseño.

Innovaciones recientes para la mejora del rendimiento de los sistemas de pavimento permeable

Según Jato-Espino et al. (2019), el origen de las investigaciones sobre pavimentos permeables en España se produce a mediados de la década de los años 90, obteniendo resultados que señalaban a estas estructuras como potenciales herramientas para el control de la cantidad y la calidad de la escorrentía urbana. Sin embargo, es a partir del año 2003 cuando comienzan a desarrollarse numerosos proyectos de investigación, centrados en los pavimentos permeable. El proyecto *FIDICA* (2003), liderado por el Grupo de Investigación GITECO de la Universidad de Cantabria (UC), estudió distintas secciones permeables de firmes biodegradantes de hidrocarburos, utilizando áridos reciclados (Castro-Fresno et al. 2005; Rodríguez-Hernández, 2008; Rodríguez-Bayón, 2008). En 2010, de nuevo GITECO-UC lideró el proyecto *VEA*, que tenía como objetivos analizar la capacidad de captación de agua de lluvia de los firmes permeables, además de desarrollar sistemas de almacenamiento para uso no potable o geotérmico (Andrés-Valeri et al. 2014; Sañudo-Fontaneda et al. 2014a; Sañudo-Fontaneda et al. 2014b). El proyecto *RHIVU* (2013), también liderado por GITECO-UC, analizó entre otros objetivos, el comportamiento mecánico e hidrológico de diferentes pavimentos permeables urbanos. Se estudió la influencia de los hidrocarburos asociados al tráfico de vehículos en la resistencia a la abrasión de diferentes mezclas asfálticas porosas (Jato-Espino et al. 2016; Rodríguez-Hernández et al. 2015; Rodríguez-Bayón et al. 2015). Otro caso de estudio es el proyecto *SUPRIS* (2016), coliderado por GITECO-UC y el Instituto de Ingeniería del Agua y Medio Ambiente (IIAMA) de la Universitat Politècnica de València (UPV), que estudió experimentalmente el comportamiento de diferentes pavimentos permeables bajo condiciones de cambio climático, desde los puntos de vista de la cantidad y la calidad (Elizondo-Martínez et al. 2019; Hernández-Crespo et al. 2019a; Fernández-Gonzalvo et al. 2021). En 2017, el proyecto *CerSUDS*, liderado por el Instituto de Tecnología Cerámica de Castelló de la Plana (ITC), se centró en el diseño de una superficie de pavimento permeable de bajo impacto ambiental, construido a partir de baldosas cerámicas con escaso valor comercial (figura II.2). Los resultados demostraron la idoneidad de este material desde los puntos de vista estructural, hidráulico, ambiental y de la seguridad (Castillo-Rodríguez et al. 2021; Life CerSUDS, s.f.).

Figura II.2. Detalle de la instalación sobre base de gravilla del adoquín cerámico CerSUDS (izquierda) y aspecto de superficie acabada junto a zona ajardinada (derecha). Elaboración propia.

Más recientemente, se han finalizado los proyectos *SAFERUP!* (2018) y *HOFIDRAIN* (2018), liderados por GITECO-UC y IIAMA-UPV respectivamente. El primero se centra en el diseño de pavimentos urbanos con múltiples objetivos, incluido el que funcionen de forma resiliente a las inundaciones, manteniendo su resistencia frente a cargas de tráfico. Paralelamente, otro de los objetivos del proyecto ha permitido el desarrollo inicial de una herramienta de localización y selección de pavimentos permeables de asfalto poroso en el entramado urbano (Gupta et al. 2021a; Gupta et al. 2021b; Gupta, 2022). Por su parte, el proyecto *HOFIDRAIN*, en el que participaron el IIAMA-UPV, GITECO-UC y el Grupo de Ingeniería del Agua y del Medio Ambiente de la Universidade da Coruña (GEAMA-UDC), abarca la caracterización hidráulica, ambiental y mecánica de secciones filtrantes en diferentes escenarios: considerando la colmatación del pavimento, la incorporación de materiales reactivos para potenciar la capacidad de tratamiento del sistema de pavimento permeable, o el empleo de diferentes aditivos para mejorar su vida útil y resiliencia. Además, se evalúa la idoneidad de utilizar pavimentos permeables como sistemas de almacenamiento de agua para reutilización en el medio urbano (García-Haba et al. 2021a; Goya et al. 2022).

II.4 Criterios de diseño

Las guías y manuales analizados incluyen una gran variedad de requerimientos técnicos con el fin de caracterizar los sistemas de pavimento permeable. Analizando los criterios de diseño que recogen las referencias españolas, éstos pueden catalogarse como hidrológicos e hidráulicos, ambientales y estructurales. A continuación, se recogen y discuten los principales a juicio de los autores.

Criterios hidrológicos e hidráulicos

Volumen de gestión

Los sistemas de pavimento permeable se diseñan con el objetivo de retener temporalmente y evacuar o infiltrar la escorrentía generada en la cuenca por un cierto volumen de precipitación. Este volumen de lluvia a gestionar viene definido habitualmente en las guías como el volumen del episodio de lluvia que no es superado, al menos, por el 80% de los eventos de precipitación (V_{80} o percentil 80% de la serie de episodios de precipitación). Mediante la gestión de este volumen de lluvia se logra el tratamiento de las primeras aguas de todos los eventos y de sus contaminantes asociados. En este sentido, la ciudad de València establece en su guía un amplio rango de volúmenes de gestión (desde V_{60} hasta V_{95}) según la tipología urbana, fundamentado en la oportunidad y flexibilidad de los espacios disponibles para la ubicación de los SUDS (De la Fuente et al. 2021). Así, se es más exigente en la implantación de SUDS en grandes áreas ajardinadas (V_{95}) que en zonas consolidadas de centro histórico (V_{60}) donde la realidad hace que la instalación de SUDS deba hacerse con criterios hidrológicos menos ambiciosos. El volumen efectivo de gestión viene determinado por la escorrentía superficial que se genera en la superficie impermeable que drena hacia la superficie de pavimento permeable, junto con la lluvia que precipita sobre la misma. A tal efecto, las guías recomiendan establecer una relación 2:1 para determinar la proporción entre área generadora de escorrentía (cuenca) y área de captación y tratamiento (pavimento permeable) (Woods-Ballard et al. 2015; Ayuntamiento de Madrid, 2018; Perales-Momparler et al. 2019; Ajuntament de Barcelona, 2020; De la Fuente et al. 2021).

Permeabilidad

A la hora de tratar la permeabilidad, los manuales hacen referencia a dos capas en concreto: el pavimento y la explanada sobre la que apoya la estructura de firme.

La permeabilidad del material que define al pavimento debe ser siempre superior a la intensidad de precipitación característica del lugar de aplicación. La guía de diseño de Barcelona sugiere una capacidad de percolación mínima del pavimento de 2000 mm/h (Ajuntament de Barcelona, 2020), mientras que las guías de Castelló de la Plana y València consideran un valor mínimo de 4500 mm/h (Perales-Momparler et al. 2019 y De la Fuente et al. 2021), afectados todos ellos por un factor de seguridad (FS=10) para tener en cuenta la colmatación del pavimento a largo plazo. Respecto a la permeabilidad del suelo, siempre y cuando la infiltración de la escorrentía al subsuelo sea un objetivo, debe ser superior o igual 10^{-6} m/s (3,6 mm/h). En el caso de que el proceso de infiltración no sea viable, se recomienda evacuar la escorrentía almacenada en la subbase, mediante la instalación de una tubería de drenaje en su fondo (Ayuntamiento de Madrid, 2018; Perales-Momparler et al. 2019; Ajuntament de Barcelona, 2020; De la Fuente et al. 2021). Por su parte, MITECO (2019) propone que la sección tipo del sistema de pavimento permeable se determine según las condiciones climáticas y de permeabilidad del lugar de instalación.

Pendiente

Cuando se pretende la instalación de un sistema de pavimento permeable en una superficie con pendiente importante (>3%), se recomienda la ejecución de terrazas o barreras transversales al flujo (Woods-Ballard et al. 2015; Ayuntamiento de Madrid, 2018; Perales-Momparler et al. 2019; De la Fuente et al. 2021). De esta manera se consigue maximizar el volumen de almacenamiento en la subbase y evitar problemas de erosión de la subbase debidos a una excesiva velocidad del flujo de agua bajo la superficie (figura II.3).

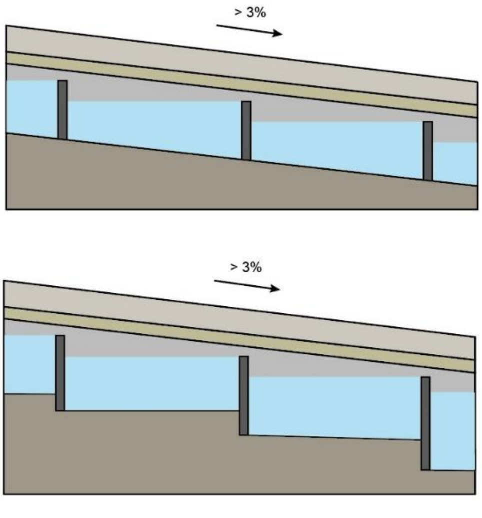

Figura II.3. Ejemplos de terrazas o barreras transversales en subbase de pavimento permeable. (Adaptado de Ayuntamiento de Madrid, 2018).

Como opción alternativa, se puede limitar la construcción de pavimentos permeables en pendiente, tal y como plantea la "Guia Tècnica per al Disseny de Sistemes de Drenatge Urbà sostenible SUDS" de Barcelona (Ajuntament de Barcelona, 2020), que reconoce la dificultad de ejecutar la solución anterior. Este documento recomienda el uso de pavimentos permeables únicamente cuando la superficie a drenar tenga una pendiente máxima del orden del 2-3% para evitar la necesidad de construir las terrazas necesarias que aseguren el correcto rendimiento del sistema.

Tiempo de vaciado

Con el fin de tener disponible el volumen de almacenamiento en previsión de eventos posteriores y por tanto, mantener la capacidad de gestión del sistema, se aconseja que el tiempo máximo para que se produzca el vaciado de la subbase sea, en general, de 48 horas (Ayuntamiento de Madrid, 2018; Perales-Momparler et al. 2019; De la Fuente et al. 2021). No obstante, este parámetro no se tendrá en cuenta cuando la función principal del sistema de pavimento permeable sea la de aljibe (Woods-Ballard et al. 2015), debiendo contar en cualquier caso con un desagüe de emergencia que evite la inundación de la superficie.

Criterios ambientales

Se ha demostrado que existe una fuerte correlación entre diversos contaminantes (materia orgánica, nutrientes y metales) con los sólidos en suspensión presentes en las escorrentías (Andrés-Doménech et al. 2018). Buena parte de los contaminantes se encuentran adheridos o formando parte de las partículas en suspensión, lo que se traduce en que, si los sólidos en suspensión (SS) son retenidos eficientemente en los sistemas de pavimento permeable, también lo serán los contaminantes asociados a ellos. Según la metodología de los índices de mitigación propuesta por CIRIA y adoptada por la guía de València, el nivel de tratamiento que proporcionan los sistemas de pavimento permeable frente a contaminantes como SS, metales pesados e hidrocarburos, es adecuado cuando los usos del suelo donde se instalan estas estructuras poseen niveles de riesgo de contaminación bajos y medios (Woods-Ballard et al. 2015; De la Fuente et al. 2021). Corresponden a estos usos caminos o viales con intensidades de tráfico muy bajas, pistas deportivas, zonas de uso lúdico, zonas de estacionamiento con poca renovación, zonas peatonales, entre otros.

En ciertas ocasiones, es posible el planteamiento de un sistema de pavimento permeable sobre un terreno con elevada capacidad drenante, cuya cuenca presente un elevado contenido de contaminantes susceptibles de ser lavados por las escorrentías. En estos casos, existe un gran peligro de contaminar el suelo subyacente, así como las aguas subterráneas, cuando éstas se encuentran a menos profundidad de la necesaria para asegurar el filtrado y retención de los contaminantes. Según Puertas et al. (2018), la distancia del fondo del sistema al nivel freático máximo estacional debe ser superior a 1,2 metros.

Técnicamente, una posible solución para prevenir los problemas de contaminación es la que viene propuesta por CIRIA y adoptada en las guías de València y Castelló de la Plana, la cual consiste en envolver el sistema de pavimento permeable mediante una geomembrana impermeable y flexible (Woods-Ballard et al. 2015; Perales-Momparler et al. 2019; De la Fuente et al. 2021). No obstante, como solución extrema, algunas referencias como Puertas et al. (2008); Ajuntament de Barcelona, (2018) directamente no recomiendan la implantación de sistemas de infiltración en zonas industriales o próximas a gasolineras, donde la potencial contaminación de las escorrentías superficiales es incompatible con una infiltración de éstas al subsuelo.

Criterios estructurales

Desde el punto de vista estructural, son dos los aspectos fundamentales a comprobar: en primer lugar la adecuación funcional de la tipología del pavimento superficial (en base a los esfuerzos tangenciales y la resistencia a la abrasión necesarias para hacer frente al paso de los neumáticos y las maniobras del tráfico previsto), y en segundo lugar el espesor de las capas que conforman el sistema (necesarias para repartir las cargas de tráfico a soportar de forma que lleguen suficientemente atenuadas a la explanada). Para ambos casos, deben tenerse en cuenta las cargas del tráfico que debe soportar la estructura del firme y la calidad de la explanada sobre la que se ejecutará, además de la localización y el uso al que va destinado para acotar el aspecto estético y acabado superficial del sistema.

La Guía Básica de Diseño de Sistemas de Gestión Sostenible de Aguas Pluviales en Zonas Verdes y otros Espacios Públicos de Madrid (Ayuntamiento de Madrid, 2018), ofrece una serie de fichas con detalles constructivos y secciones estructurales de firmes permeables, indicadas para uso peatonal en aceras y paseos (figura II.4). En ellas se recomienda el tipo de pavimento a emplear, los distintos espesores para cada capa del sistema y características de los materiales como la granulometría, resistencia o capacidad drenante.

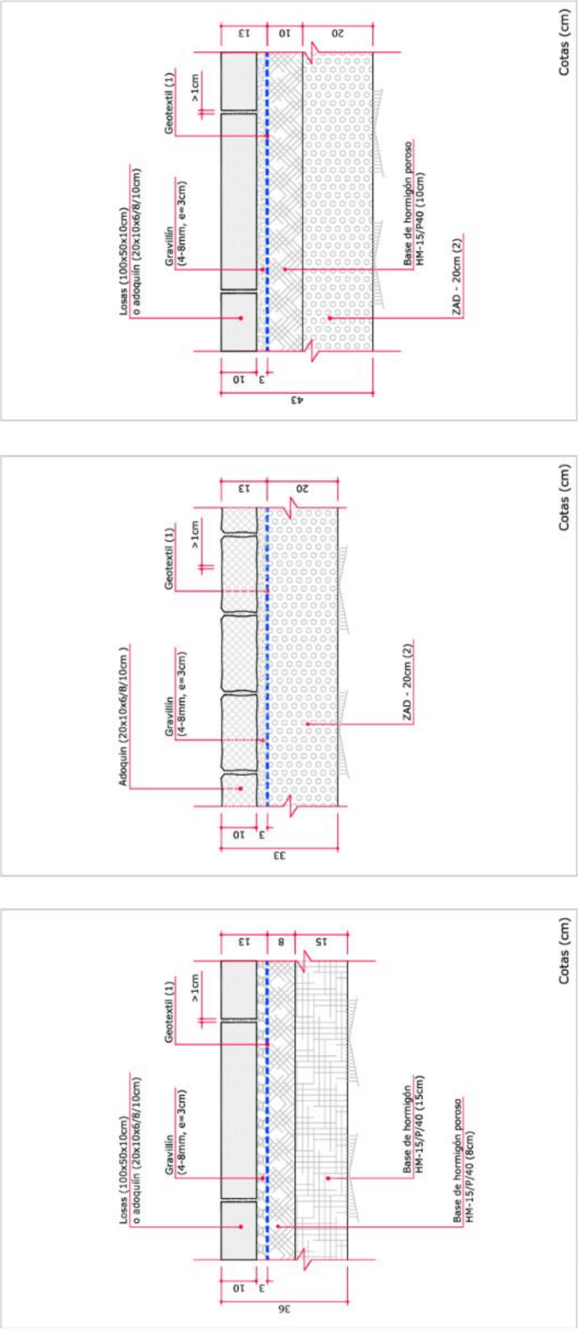

Figura II.4. Ejemplos de fichas con secciones estructurales de firmes permeables incluidas en la Guía Básica de Diseño de Sistemas de Gestión Sostenible de Aguas Pluviales en Zonas Verdes y otros Espacios Públicos de Madrid (Ayuntamiento de Madrid, 2018).

De manera más concisa, las guías de Barcelona y del MITECO basan sus recomendaciones en que las capas deben ser capaces de resistir las cargas producidas por el paso de vehículos de emergencia pesados (2500 – 3000 kg). Para ello, en el caso de que el sistema incluya subbase granular, establecen que su espesor mínimo sea de 30 cm, debiendo calcularse explícitamente cuando haya previsión de superar las cargas anteriores (MITECO, 2019; Ajuntament de Barcelona, 2020).

Es también habitual que sean los propios fabricantes de superficies permeables o porosas, quienes ofrezcan recomendaciones acerca del diseño de estos sistemas. La figura II.5 recoge un ejemplo que incluye la descripción de las capas que componen la sección, así como sus espesores, e información relativa a la categoría de tráfico a soportar por el pavimento y la calidad de la explanada sobre la que se asienta. Como puede observarse, aunque la comparación no es directa, sí que existe cierta convergencia entre las secciones propuestas por el Ayuntamiento de Madrid para usos peatonales y aceras (figura II.4) y éstas últimas para la categoría C4/S1.

Figura II.5. Secciones de pavimentos permeables recomendadas según categoría de tráfico y calidad de explanada (Adaptado de Breinco, s.f.).

II.5 Recomendaciones sobre las operaciones de limpieza y mantenimiento

La exposición ambiental de los pavimentos permeables puede acarrear el deterioro y la pérdida de funcionalidad del sistema. Los sedimentos depositados directamente en la superficie o arrastrados por el viento o la escorrentía, procedentes de zonas adyacentes, provoca acumulaciones que pueden dar lugar a la colmatación de las distintas capas y, en consecuencia, la pérdida de permeabilidad en algunas zonas (figura II.6). Asimismo, el propio tráfico puede propiciar el desgaste y rotura del pavimento, dando lugar a problemas estructurales y de comodidad que requieran de actuaciones de bacheado o reparación de las superficies con materiales distintos de los originales (Sañudo-Fontaneda et al. 2018).

Figura II.6. Vistas de superficie (izquierda) y de sección (derecha) de una porción de pavimento poroso colmatado. Elaboración propia.

Por tanto, además de los criterios de diseño analizados anteriormente, es necesario prever y llevar a cabo un adecuado mantenimiento del sistema para garantizar un funcionamiento óptimo a lo largo del tiempo y prolongar su vida útil. Fundamentalmente, las tareas de mantenimiento se centran en el cuidado de la capa más superficial, siendo recomendable realizarlas en base a inspecciones periódicas cuya frecuencia varía en función de las precipitaciones y actividades llevadas a cabo en la zona (ej. si hay obras cercanas a los pavimentos permeables, deberán realizarse más inspecciones). Algunas de las principales consisten en el barrido o aspirado de la superficie permeable. Generalmente se recomienda su ejecución de forma semestral, especialmente durante la primavera y el otoño, pues son las estaciones del año en las que se puede producir arrastres con mayor aporte de material vegetal. Otro tipo de tareas consisten en restaurar y/o sustituir elementos estructurales dañados, así como corregir las posibles acumulaciones de vegetación o tierra en zonas adyacentes, evitando que queden elevadas sobre el nivel del pavimento. En estos casos se recomienda una frecuencia mínima de 5 años aproximadamente. Con menos frecuencia (cada 10-15 años) se recomienda la aspiración en profundidad de la superficie y subbase para recuperar la permeabilidad inicial si ésta se ha reducido significativamente a causa de la colmatación (Ayuntamiento de Madrid, 2018; Perales-Momparler et al. 2019; Ajuntament de Barcelona, 2020; De la Fuente et al. 2021). Por su parte, MITECO (2019) recomienda realizar al menos 3 operaciones de limpieza al año, preferiblemente al final de las diferentes épocas climatológicas.

II.6 Análisis de la situación actual y necesidades futuras

El número de guías y manuales de diseño de SUDS que se elaboran y forman parte de las normativas municipales es cada vez mayor ante la demanda creciente por parte de técnicos y administraciones de un marco de referencia. Dentro de los SUDS, los sistemas de pavimento permeable son una de las técnicas más interesantes de implementar, tanto por su gran eficiencia a la hora de gestionar agua de lluvia, como por su versatilidad estética y capacidad para integrarse en el ambiente urbano. La flexibilidad del diseño, junto con el amplio abanico de acabados de superficies permeables disponible, hacen que sean unas estructuras de firme totalmente personalizables y adaptables a la mayoría de las necesidades urbanas (De la Fuente et al. 2021). Consecuentemente, el diseño de una sección de firme permeable debe realizarse contemplando todos los condicionantes particulares de cada actuación (Rodríguez-Hernández, 2008).

Los criterios de diseño recopilados de las actuales guías y manuales disponibles en España pueden catalogarse según 3 criterios fundamentales: hidrológicos e hidráulicos, medioambientales y estructurales. La información extraída en base al primer criterio se resume en la tabla II.1. Los parámetros de diseño presentan homogeneidad en prácticamente todas las guías. Es especialmente importante que el diseño tenga en cuenta la climatología particular del lugar de aplicación (Fernández-Gonzalvo et al. 2021) y su conveniente adecuación a escenarios que contemplen los efectos del cambio climático. En este sentido, cabe destacar la adaptación del parámetro “volumen de gestión” a la precipitación de la zona. Así, en localizaciones con lluvias cortas e intensas, como la costa mediterránea, se puede pensar en aljibes o depósitos de almacenamiento acoplados al pavimento permeable, para que éste pueda seguir funcionando en medio no saturado y así ofrecer una mayor capacidad volumétrica. Un buen ejemplo de este sistema lo constituye el conjunto pavimento permeable-aljibe del proyecto *CerSUDS*, consistente en un pavimento permeable dispuesto sobre bases drenantes que percolan el agua al terreno, conduciendo el exceso a un depósito/canal situado bajo la superficie, que permite su recuperación para el riego de las zonas ajardinadas y que actúa también a modo de colector, laminando los caudales a la red municipal durante eventos de precipitación (Castillo-Rodríguez et al. 2021).

Un factor de preocupación que destaca es la posible pérdida de permeabilidad del sistema a lo largo del tiempo, la cual puede afectar a las capas superficial (debido al sellado de los huecos, habitualmente por acumulaciones de sedimentos o vegetación) e inferiores (por fracciones más finas de los sedimentos arrastrados). Es por ello fundamental realizar un estudio o caracterización inicial de los posibles aportes que pueden generarse en la cuenca, susceptibles de afectar el sistema. Por ejemplo, si se prevén grandes aportaciones de detritus vegetales procedentes de ajardinamientos próximos o arbolado, deberá analizarse cuidadosamente la idoneidad de este sistema, o adoptar las precauciones necesarias para que estos elementos no alcancen la superficie del pavimento (figura II.7). Si el nivel de riesgo es elevado, se diseñará un pavimento permeable con un coeficiente de seguridad adecuado, maximizando la permeabilidad de la superficie en previsión de su reducción a lo largo de la vida útil.

Figura II.7. Aporte de material vegetal superficial procedente de ajardinamiento contiguo (izquierda) y aporte de material vegetal procedente del arbolado (derecha). Elaboración propia.

Respecto a los criterios medioambientales (tabla II.1), en las guías se encuentra escasa información al respecto. Es fundamental el soporte de los trabajos de investigación que vienen desarrollándose para potenciar la funcionalidad de los sistemas de pavimento permeable desde el punto de vista de tratamiento y remoción de distintos contaminantes. Así, en el proyecto HOFIDRAIN se analizó en laboratorio la colmatación de dos tipos de pavimentos permeables (asfalto poroso y adoquines porosos) con cargas de hasta 5 kg/m^2 de sedimentos recogidos en el viario. Tras varios ciclos de acumulación-precipitación la cantidad retenida de sedimentos en la superficie y la sección de pavimento fue superior al 95% (Naves et al. 2021; Goya et al. 2022).

Tabla II.1. Resumen de criterios hidrológicos e hidráulicos, y ambientales.

	A	B	C	D
Criterios hidrológicos e hidráulicos				
Volumen de gestión	V_{80}	V_{80}	V_{80}	V_{60} - V_{95}
Relación área impermeable / área permeable	2:1	2:1	2:1	2:1
Permeabilidad:				
Del pavimento	≥ 2500 mm/h	≥ 4500 mm/h [i]	≥ 2000 mm/h	≥ 4500 mm/h [i]
De la explanada con objetivo de infiltrar	≥ 3,60 mm/h [ii]	≥ 3,60 mm/h [ii]	≥ 3,60 mm/h [ii]	≥ 3,60 mm/h [ii]
Pendiente del sistema	≤ 3% [iii]	≤ 3% [iii]	No recomienda su instalación cuando la pendiente de la cuenca drenante sea > 2-3%.	≤ 3% [iii]
Tiempo de vaciado	≤ 48 horas	≤ 48 horas	*	≤ 48 horas
Criterios ambientales				
Protección del suelo subyacente y de las aguas subterráneas	*	Mediante envoltura del sistema con geomembrana impermeable y flexible	*	Mediante envoltura del sistema con geomembrana impermeable y flexible

A: Ayuntamiento de Madrid, (2018); B: Perales-Momparler et al. 2019; C: Ajuntament de Barcelona, (2020); D: De la Fuente et al. (2021).

[i] Se aplica un factor reductor de 10

[ii] Evacuar la escorrentía almacenada mediante tubería de drenaje si no es posible la infiltración

[iii] Ejecutar terrazas o barreras transversales al flujo cuando la pendiente es > 3%

* Sin dato

También se está estudiando la instalación de barreras reactivas o la integración de agentes reactivos en el sistema de pavimento permeable mediante el empleo de biochar, utilizando materiales residuales o subproductos como el fango deshidratado de ETAP. De este modo, la adsorción y la inducción a los procesos de biodegradación de contaminantes orgánicos pueden resultar de gran utilidad para evitar la contaminación del suelo o de las aguas subterráneas (García-Haba et al. 2021b; Qi et al. 2021).

Otras actuaciones o reglas de gestión relacionadas con criterios ambientales, pueden ser la colocación de las tuberías de drenaje a cierta altura o con un codo para inducir la retención del agua durante cierto tiempo, favoreciendo así la eliminación de nitratos mediante el proceso biológico de desnitrificación y, por ende, reduciendo el riesgo de contaminación de las aguas subterráneas por nitratos (Brown y Borst, 2015). Esta retención del agua también puede favorecer la biodegradación de contaminantes orgánicos y fecales (Hernández-Crespo et al. 2019b; García-Haba et al. 2021a), fomentando así la posibilidad de reutilización de las aguas almacenadas en el propio sistema de pavimento permeable o en aljibes conectados al mismo.

Un condicionante ambiental que también debe ser considerado es el pH de las aguas filtradas por los pavimentos permeables. Estudios recientes han demostrado que el hormigón poroso puede provocar un incremento importante de esta variable de calidad de aguas, alcanzándose valores de hasta 12, teniendo como consecuencia un posible impacto negativo en el medio receptor (Hernández-Crespo et al. 2019a). Es conveniente destacar que estos altos niveles de pH se mantienen constantes durante los primeros meses de funcionamiento, y disminuyen con el lavado progresivo de material (Fernández-Gonzalvo et al. 2021). En este sentido se podría plantear un lavado controlado del propio material, previo a su instalación, con el fin de evitar que las aguas filtradas impacten negativamente sobre el medio ambiente. Como alternativa a este condicionante, sería optar por materiales que no provoquen estos efectos, como los adoquines con junta permeable (García-Haba et al. 2021b).

En cuanto a los criterios estructurales (tabla II.2), las guías ofrecen información generalmente bien definida en cuanto a los tipos de capa que componen la sección del sistema, así como acerca de los materiales de construcción a utilizar. Cuando se trata de definir los espesores de las distintas capas, especialmente de la subbase, el valor obtenido según el criterio hidrológico e hidráulico es generalmente mayor y prevalece sobre el criterio estructural (ej. el criterio estructural se cumple sobradamente en aceras y firmes con tráfico ligero con una base granular de 30 cm de espesor debido a criterios hidráulicos).

En cualquier caso, son los técnicos municipales, con ayuda de las empresas y marcas que comercializan los materiales que constituyen las superficies permeables, las que más información ofrecen al respecto, debiendo garantizar la adecuada resistencia de la superficie al tráfico esperado, además de comprobar la calidad y espesores de los materiales empleados en las capas inferiores, y también las condiciones de la explanada. A nivel municipal, el mayor detalle se encuentra en la guía básica de diseño de Madrid, siendo los planos de detalles de secciones tipo que incluye el documento, un ejemplo a seguir (Ayuntamiento de Madrid, 2018).

Es por tanto necesaria la elaboración de este tipo de información gráfica adaptada a la normativa municipal, para que sea incorporada en las prescripciones técnicas de los proyectos de urbanización. Para ello, se pueden tomar como referencia los catálogos de secciones de firmes existentes a nivel municipal, incluyendo aquellas secciones permeables que mejor se ajusten a las particularidades, necesidades y preferencias de cada ciudad.

Para garantizar el correcto funcionamiento del sistema de pavimento permeable, es necesario un adecuado plan de limpieza y mantenimiento (tabla II.3). En este aspecto, todas las guías muestran coherencia y homogeneidad en sus recomendaciones. Hay que destacar la atención que debe prestarse a las técnicas de barrido y aspirado, ya que el empleo de una u otra vendrá determinado por el tipo de superficie permeable. Según los medios de ejecución, puede ser manual mediante escoba, o mecánica empleando sistemas por aire o vehículos de limpieza por barrido y aspiración.

En el caso de pavimentos permeables por junta (adoquines), es recomendable la técnica de barrido manual o mediante soplador para evitar la pérdida del material granular contenido en las juntas. Por el contrario, para pavimentos porosos (asfalto poroso y hormigón poroso), se recomienda el empleo de vehículo de limpieza. Estudios recientes recomiendan reducir la frecuencia de las tareas de barrido y aspirado a 1 mes para evitar la generación de escorrentía, especialmente ante la llegada de eventos de lluvia de alta intensidad (Fernández-Gonzalvo et al. 2020). En el caso de pavimentos vegetales (césped reforzado) debe garantizarse un riego mínimo que dependerá de la especie vegetal utilizada (MITECO, 2019).

Tabla II.1. Resumen de criterios estructurales.

	A						B			C
Uso o tráfico a soportar	Acera tipo A	Acera tipo B	Acera tipo C	Aceras y paseos	Aparcamientos	Carril bici	Aceras y paseos	Parques y zonas de recreo, no accesibles a VP	Restringido a VP de emergencia	Restringido a VP de emergencia
Tipología de pavimento	AP			LP o AP	AA u HP	MPCP	PPJ	Pavimentos porosos	*	*
Material y espesor de las capas:										
**Capa de asiento	Gravillín - 3 cm					*	*	*	*	*
Base	Grava (15 cm)	HP (10 cm)	CD (>50 mm)	HP (10-15 cm)	HP (8 - 20 cm) o grava (35 cm)	HP (15 cm)	*	*	*	*
Subbase	*	ZAD (20 cm)	ZAD (20 cm)	HM (15 cm) o ZAD (20 cm)	HM (23 cm) o ZAD (20 cm)	ZAD (20 cm)	*	*	≥ 30 cm	≥ 30 cm

AA: Adoquín autoblocante; AP: Adoquín permeable por junta o por material; CD: Celdas drenantes; HM: Hormigón en masa; HP: Hormigón poroso; LP: Losa permeable; VP: Vehículos pesados; PPJ: Pavimentos permeables por junta; ZAD: Zahorra artificial drenante; MPCP: Mezcla bituminosa en caliente porosa; A: Ayuntamiento de Madrid, (2018); B: MITECO, (2019); C: Ajuntament de Barcelona, (2020).
* Sin dato; ** En superficies de tipo adoquín, la cama de asiento se puede considerar como base.

Tabla II.2. Resumen de tareas de mantenimiento.

	A	B	C	D	E
Inspección del estado general	*	Regularmente. Preferiblemente después de lluvias intensas	6 meses	Una al mes durante los 3 primeros meses y posteriormente cada 6 meses	6 meses
Eliminación de sedimentos y residuos sólidos (barrido o aspirado de la superficie)	A demanda	3 veces al año	6 meses	6 meses	6 meses
Eliminación de vegetación no deseada	*	3 veces al año	1 año	3 años	
Corrección de niveles de tierra o vegetación en áreas colindantes	*	*	5 años	5 años	A demanda
Reparación de adoquines, depresiones o grietas	*	*	5 años	5 años	A demanda
Aspiración en profundidad de la superficie y la capa de subbase	Al cabo de los años	*	10-15 años	15 años	10-15 años
Reemplazo del material de las juntas	*	*	*	*	A demanda
Mantenimiento de la vegetación	*	3 veces al año	*	*	*

A: Ayuntamiento de Madrid, (2018); B: MITECO, (2019); C: Perales-Momparler et al. 2019; D: Ajuntament de Barcelona, (2020); E: De la Fuente et al. 2021

* Sin dato

II.7 Conclusiones

Los sistemas de pavimento permeable constituyen una de las técnicas SUDS más completa, versátil, multifuncional y estudiada en todo el mundo. También en España viene realizándose un gran esfuerzo en la actividad innovadora, propiciando la generación de una base científica sólida y ampliando los conocimientos sobre estas estructuras de firmes que son resilientes al paso del agua. Como consecuencia, cada vez se encuentra más cantidad de información acerca de los sistemas de pavimento permeable en las guías y manuales de diseño de SUDS. Estos documentos se están consolidando como herramientas de diseño muy útiles y completas, de fácil acceso para los técnicos competentes. Sin embargo, existe la necesidad de ampliar los recursos disponibles que sirvan de base e impulsen la creación de normativa municipal sobre SUDS adaptadas a cada caso particular. Únicamente de este modo será posible incluir secciones permeables en los catálogos de firmes de cada ciudad, de forma que la implementación de los sistemas de pavimentos permeables quede debidamente integrada según las necesidades y particularidades de cada municipio.

Capítulo III

Influencia de la colmatación a largo plazo

En el presente capítulo se simula y analiza en el comportamiento hidráulico y ambiental de un asfalto permeable, sometido a colmatación producida por seis tipos distintos de sedimentos. En el experimento se midieron variables como la permeabilidad del pavimento de asfalto, además de los volúmenes y calidad del agua filtrada por el pavimento, y de la escorrentía superficial. Los resultados mostraron reducciones significativas de la permeabilidad (22-99%) para cargas superficiales de sedimentos a partir de 1 kg/m^2, excepto para sedimentos muy finos (<125 µm) (1%). Tras la limpieza de los pavimentos, se observó una recuperación de la permeabilidad original entre el 8% y el 100%. Tanto la granulometría como el contenido en materia orgánica del sedimento, junto con la secuencia de eventos de lluvia, influyeron directamente en la pérdida y recuperación de permeabilidad, así como en la calidad del agua filtrada. Se estimó una eficiencia de filtración de casi el 100% de la precipitación aplicada para cargas de sedimento por debajo de 4 kg/m^2. Para cargas superiores a este valor se producía escorrentía superficial. La eficiencia de la losa para la eliminación de contaminantes fue del 96% para DQO, 76% para NT, 79% para PT, y 98% para SST.

García-Haba, E., Naves, J., Hernández-Crespo, C., Goya-Heredia, A., Suárez, J., Anta, J., & Andrés-Doménech, I. (2023). Influence of sediment characteristics on long-term hydrology and water quality behaviour during the clogging process of a permeable asphalt. Journal of Water Process Engineering, 53, 103658. https://doi.org/10.1016/J.JWPE.2023.103658

III.1 Introduction

Sustainable Urban Drainage Systems (SUDS) are becoming a common solution to address the increase in flow discharges, runoff volumes and pollutants concentrations caused by urban expansion (Woods-Ballard et al. 2015). Among them, the use of permeable pavements (PP) is nowadays wide-spreading due to their demonstrated effectiveness in managing and treating stormwater at source. Porous asphalt is a common material that performs the surface layer of PP structures, which is successfully tested to implement this type of SUDS (Rodríguez-Hernández et al. 2015). Even though in many countries SUDS are more and more being integrated into the usual urban drainage scheme (Gimenez-Maranges et al. 2020). However, technical challenges related to clogging and water quality aspects need to be further studied in order to achieve a successful city-wide implementation of PP and SUDS in general, ensuring a high social acceptance (Andrés-Doménech et al. (2021); García-Haba et al. (2022)).

Clogging is the process by which PP lose its capacity for rainwater infiltration, due to the interception and accumulation of solid particles within the pavement layer. Solid particles can be sediments eroded from surrounding areas or from the pavement itself, debris from road surfaces or from other areas and carried by vehicles, organic matter from vegetation, etc (Kia et al. 2017). In addition, some fluids, such as hydrocarbons and oils, or biofilm growth, can accelerate the clogging process. Furthermore, clogged PP deteriorate at a faster rate than those remaining unclogged (Guthrie et al. 2010). Different methods can be used for clogging evaluation, including the measurement of permeability with standard permeameters (Sañudo-Fontaneda et al. 2018), the measurement of porosity in core samples (Kayhanian et al. 2019), and full-scale infiltration methods (Boogaard and Lucke, 2019). The previous methods are usually employed in full-scale PP, whereas at lab-scale, the use of physical models with rainfall simulators and road-deposited sediments dosage is a well-established practice to assess clogging processes and their influence on hydraulic efficiency and water quality of filtrated water (Kamali et al. (2017); Kia et al. (2018)).

The novelty of this article is the strengthened role of real sediment used under laboratory conditions. Previous studies focusing on the water quality of filtrated flows, usually introduced pollutants through the application of synthetic rainwater or runoff on the PP (Han et al. (2021); Kamali et al. (2017); Zheng et al. (2022)). However, in many cases, the accumulation of pollutants occurs directly on the own pavement surface and not through runoff from impervious pavements. In this case, the application of real sediments collected from urban areas and non-polluted rainwater, simulates a more realistic scenario to improve knowledge about the influence of rainfall intensity on pollutants mobilisation (Fernández-Gonzalvo et al. 2021). In this sense, it is interesting to check potential different behaviours of filtrated water considering sediments collected from different urban areas which can present different properties (such as particle size distribution, organic matter content or pollutant concentration), and accordingly, to suggest appropriate cleaning strategies. Most studies generally use synthetic runoff or prepared sediments with clay, sand and mixtures of them (Tan et al. 2003), while very few studies use real samples of sediment or runoff, or even different gradation openness of the pavement to evaluate clogging in PP (Aberle et al. (2017); Neuper et al. (2021); Tan et al. (2003); Burgin et al. 2017)). The present study aims at covering this gap of knowledge.

Therefore, the objective of this research is to improve the knowledge about how porous asphalt behaves as it becomes clogged with different particle size distributions, with a special emphasis on real sediments. Under a holistic approach, the research looks at the hydraulic performance but also at the filtrated water quality and runoff when it may occur, under synthetic rainfall laboratory-controlled conditions. The hypotheses set to develop the research are: experimental setups built in different universities can be used in a coordinate way to obtain complementary information; sediments taken from different urban areas have different properties and can affect differently to the hydraulic and water quality performance of porous asphalt; and, the study of filtrated water quality in clogging experiments can provide decisive information for recommendations on cleaning and maintenance frequencies. Section 2 describes the experimental setup and the procedure followed during the tests. The tests carried out at the Universidade da Coruña (UDC) focus on analysing the influence of granulometry on the clogging of the permeable pavement, while the experiments carried out at Universitat Politècnica de València (UPV) aim to evaluate in detail the behaviour of the porous asphalt in terms of pollutant reduction for different degrees of clogging. Section 3 presents and discusses results, focusing on the permeability evolution of porous asphalt and its reduction by clogging; the hydraulic efficiency of the pavements in terms of volume and flow rates managed; the water quality of filtrated water; and, finally, the mass balance analysis of sediment masses within the different flow components.

III.2 Materials and methods

The experimental setup is introduced in section III.2.1, first by describing the rainfall simulators in section III.2.1.1. The porous asphalt slabs and the variable head permeameter are described in sections III.2.1.2 and III.2.1.3. Then, the characteristics of the different sediment classes distributed over the asphalt slabs are presented in section III.2.1.4. Finally, the procedure followed during the tests is explained in detail in section III.2.2.

III.2.1 Experimental setup

III.2.1.1 Rainfall simulators

Two rainfall simulators have been used to assess the hydrological performance of the permeable pavement. First, a tailored rainfall simulator of 1 m^2 (Figure III.1a) was built in the hydraulics laboratory of CITEEC at Universidade da Coruña (UDC). It consists of a drippers-based rainfall simulator that can generate uniform and realistic rainfalls as described in Naves et al. (2020a, b). A rainfall intensity of 80 mm/h was simulated in this work, with an associated value of the Christiansen's uniformity coefficient of 93.5%. Then, the permeable pavement is installed below the drippers over an impervious surface with a 2% slope (Woods-Ballard et al. 2015). The rainwater that is filtered through the system is collected in a circular tank at the lateral of the experimental bench through a collecting funnel for online measuring of water discharge. In the same way, as the pavement gets clogged by sediment, runoff is generated and conducted to a second tank (Figure III.1b). Both filtered and runoff flow discharges are estimated from the level variation in the tanks using SN-SR04T ultrasonic probes previously calibrated.

Figure III.1. General views of the UDC (a) and UPV experimental setup (d). Detail of the asphalt slab installed in the test area of each rainfall simulator and including the runoff collection system (b and c, respectively). Own elaboration.

A second rainfall simulator is placed at Universitat Politècnica de Valéncia (UPV). This facility uses the same methodology to simulate rain over a surface of 0.25 m^2, and the filtrated water is collected vertically below the pavement with a funnel and weighted in a precision balance (Figure III.1d). The surface runoff generated when the asphalt starts clogging, is collected laterally and monitored in an additional tank in the same way that the first facility at UDC (Figure III.1c). A detailed description of this rainfall simulator can be found in Fernández-Gonzalvo (Fernández-Gonzalvo et al. 2021). The tests carried out at UDC focus on analysing the influence of sediment particle size distribution on the clogging of permeable pavement, while the experiments carried out at UPV aim to evaluate in detail the behaviour of pavements in terms of pollutant reduction for different degrees of clogging.

III.2.1.2 Porous asphalt

The permeable pavement used in this investigation is a Spanish PA-16 porous asphalt use (Figure III.1b). Pavement slabs with 22.6% void-ratio, 4.03% of bitumen, and dimensions of 0.44 m x 0.40 m x 0.06 m in case of tests performed at UDC and 0.49 m x 0.49 m x 0.04 m for UPV tests. This pavement has been used because it is standardized in the Spanish national road design instructions (Ministerio de Fomento, 2019). The slabs were installed in the rainfall simulators with the perimeter completely sealed to force rain and sediment loads to pass through the pavement or be drained laterally with the runoff flow generated once the slab becomes clogged. At UDC tests, a two-centimetre-height slot has been left along the bottom part of one side of the slab to allow lateral drainage of the filtered flow over the impervious base into the corresponding tank. Above this open boundary condition, the slab was kept sealed to force rainfall vertical infiltration in the vicinity of that side. A new asphalt slab was used for each of the three tests carried out at UDC where the influence of particle size distribution on the clogging process was studied. After testing the possibility of recovering the initial conditions of the slab by washing it thoroughly between tests, an asphalt slab was used for the remaining three tests carried out at UPV to evaluate the pollutant reduction capacity for different levels of clogging and different sediment classes.

III.2.1.3 Variable head permeameter

A variable head permeameter has been used to measure the permeability of the porous asphalt for different grades of clogging during the tests following the Spanish standard NLT-327/00 (CEDEX, 2000), similar to EN 12697-40 (European Standard, 2020). This standardized variable head permeameter estimates permeability in one point of the surface from the time it takes the water level in a vertical cylinder to descend between two marks as the pavement drains. A single permeability measurement was made instead of the two indicated by the standard because it has been observed that the pulse of water generated by the permeameter can partially flush the sediment trapped in the PP, disturbing the second measurement. The procedure indicated in the standard is motivated to moisten dry pavements in field measurements. In our tests, measurements were performed 30 minutes after the end of the rain event once the slab has completely drained water, but the pavement is still wet. Three points separated 75 mm between them were marked on the centre of the asphalt slabs to be used as control points to monitor the variations on permeability produced by the different sediment loads and sediment classes distributed during the tests.

III.2.1.4 Sediment classes

Three sediment classes have been used first to investigate the influence of particle size distribution on the long-term hydraulic performance of the porous asphalt as it progressively clogs. These sediments were obtained from road dust collected from parking lots in the UDC campus. The sediment was first calcined at 550ºC and prepared to be classified into three different sediment classes: fine (UDC-1), coarse (UDC-2), and realistic (UDC-3). The calcination aims to remove organic matter reducing the uncertainty that cohesivity may introduce in the process and focusing this part of the research in the influence of particle size distribution on the clogging process. UDC-1 (63-125 µm) and UDC-2 (250-500 µm) have a uniform particle size distribution with a mean diameter d_{50} of 104 µm and 391 µm, respectively. UDC-3 represents a realistic graded road deposit sediment with a d_{50} of 282 µm. This third sediment class was created by sieving the road dust using blind, 63, 125, 250 and 500 µm sieves and composing it in a proportion of 10%, 15%, 25% and 30% following the particles size distribution found in Deletic and Orr (2005), Vaze and Chiew (2002), Viklander (1998), and Zafra (2008). In this process, the coarser fraction retained in the sieve of 1 mm was not considered since it was preliminary observed that these particles cannot be introduced into the pavement due to the pore size of the asphalt and thus, they do not contribute to the clogging process of slabs (Mishra et al. 2013). Figure III.2a shows the particle size distribution of these three sediment classes measured using a laser coulter counter (Beckam-Coulter LS 13 320) and compared to literature values.

Three additional sediment classes have been tested at UPV facility to assess in detail variations in pollutant removal efficiency as pavement gets clogged. First, as the content of organic matter has been removed in the previous sediment classes and considering that cohesivity may play an important role in both the water quality of the effluents and the clogging of permeable pavements, the realistic graded sediment class (UDC-3) was replicated without calcinating (UDC-4). The behaviour of this material was then compared with two additional sources of sediments collected from the UPV campus and from a residential area in the Benicalap district of València (BEN). Sediments UPV and BEN were collected by mechanical vacuum-sweepers (Yang et al. 2022) and sieved to a size of 5 mm. In this case, particles larger than 1 mm have been considered because, although they do not contribute to the clogging process due to the maximum pore size of the pavement, they may be of interest because they can contain contaminants that are washed during rain events (Burton and Pitt, 2002; Duong and Lee, 2014; Durand et al. 2003; Hernández-Crespo et al. 2019). Figure III.2b shows the particle size distribution of the three sediment classes tested in this part of the research at UPV.

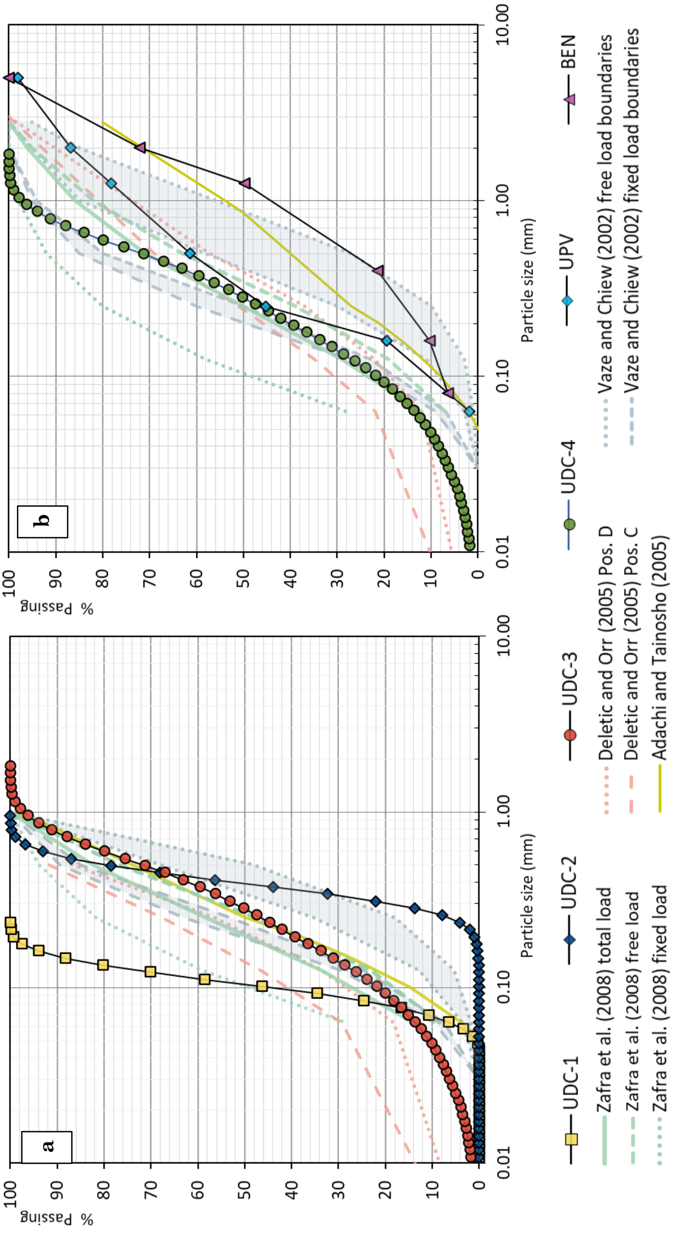

Figure III.2. Particle size distribution of the six sediment classes analysed compared to reference values found in the literature (Adachi and Tainosho, (2005); Deletic and Orr, (2005); Vaze and Chiew, (2002), Zafra et al. (2008)). The left graph (a) includes the sediment classes used to analyse in detail the effect of particle size on the clogging process (UDC-1, UDC-2 and UDC-3), which are limited to a maximum size of 1 mm. The remaining sediment classes (UDC-4, UPV and BEN) are shown on the right graph (b). Only the fraction less than 1 mm of the literature references has been considered in the left graph to be compared.

Note that the maximum size of 1 mm has been maintained for UDC-4 sediment to compare with previous tests analysing the influence of cohesivity on the clogging process. UPV and BEN sediments presented a lower content of fine material despite being collected with an effective technique for the finest fraction (Haynes et al. 2020), probably since these sediments were sieved at 5 mm.

Table II.1 includes a summary of all sediment classes used in this work indicating the rainfall simulator where the sediment class was used and its main characteristics. The influence of sediment characteristics on the results is analysed in next section.

Table III.1. Summary of sediments characteristics. Note: d.w.: dry weight; NA: not analysed; LOI: loss-on-ignition; Org. C: organic carbon; TN: total nitrogen; TP: total phosphorus.

Sediment class	d_{50} (µm)	d_{min}-d_{max} (µm)	Real density (kg/m^3)	LOI (% d.w.)	Org. C (% d.w.)	TN (g/kg d.w.)	TP (g/kg d.w.)
UDC-1	104	63-125	2931 ± 5	0	NA	NA	NA
UDC-2	391	250-500	2652 ± 4	0	NA	NA	NA
UDC-3	282	0-1000	2929 ± 4	0	NA	NA	NA
UDC-4	282	0-1000	NA	4.7	2.2 ± 0.3	0.2	0.05
UPV	300	0-5000	NA	8.2	2.4 ± 0.4	0.9	0.30
BEN	1125	0-5000	NA	33.2	4.9 ± 0.5	1.3	0.20

III.2.2 Experimental and analytical procedures

A total of 45 sediment load steps have been tested for 6 different sediment classes evaluating the variations of permeability and changes in the quantity and quality of drained hydrographs as the pavement becomes gradually clogged. Every load step represents the accumulation of sediment in time with no cleaning or maintenance. For each sediment class, the porous asphalt slabs are loaded by means of cyclical build-up and rainfall events. Deionised water (electrical conductivity [EC] of 10 µs/cm and pH of 7.1) is used to simulate rainwater. In each step of this procedure, a certain amount of the sediment tested was distributed homogeneously over the slab surface and a constant 80 mm/h and 30 minutes rainfall was simulated, waiting 24 h until the next step of load to allow the system to dry. The rainfall intensity used was chosen as the highest and most unfavourable in terms of clogging that the rainfall simulator is able to generate (Fernández-Gonzalvo et al. (2021, 2020); Hernández-Crespo et al. (2019)), with a duration enough to achieve a steady flow regime and to ensure that the material is able to penetrate the pavement as far as possible. Filtered and runoff drained flows were online monitored during the simulated rain events. The permeability of the slab was measured 30 minutes after the end of the rain at certain load steps using the variable head permeameter. The measurement was made at the three control points marked on the asphalt without any sediment load (blank), after 1 kg/m^2 cumulative load and with the maximum load tests to consider the heterogeneities of the slab. For the rest of measurements, only one of the three control points has been used each time alternatively so that the flush flow generated by the permeameter has the minimum effect on the slab clogging and thus on subsequent measurements. When the proposed maximum load stablished for each sediment class has been reached, the surface of the pavement was cleaned using an 1600W industrial vacuum cleaner (UDC) and 110W handheld vacuum cleaner (UPV) until it was observed that no more particles were able to enter the device. Then, an additional rain event was simulated the following day, measuring permeability and drained flow rates again to assess the potential recovery of initial conditions. Table III.2 summarizes the load steps tested for each sediment class indicating the cumulative sediment load distributed on the slab from the start of each test and the steps where permeability measurements and vacuuming were made. At the end of each battery of experiments, a mass balance was carried out by weighting the sediment load vacuumed from the surface of the slab and quantifying the mass of sediment dragged into the filtration and surface runoff tanks.

Table III.2. Accumulative sediment load tested in each step of each battery of experiments.

	Cumulative sediment load (kg/m^2)													
Sediment class	**D0**	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D10**	**D11**	**D12**	**D13**
UDC-1	0*	0.1	0.3	0.6	1.0*^{v}	V*	-	-	-	-	-	-	-	-
UDC-2	0*	0.1	0.3	0.6	1.0*^{v}	V*	-	-	-	-	-	-	-	-
UDC-3	0*	0.1	0.3	0.6	1.0*	1.5	2.0*	2.5	3.0*	3.5	4.0*^{v}	V*	4.5	5.0
UDC-4	0*	0.1	0.4	1.0	2.0*	3.5	5.5*^{v}	-	-	-	-	-	-	-
UPV	0*	0.1	0.4	1.0	2.0*	3.5	5.5*^{v}	-	-	-	-	-	-	-
BEN	0*	0.1	0.4	1.0	2.0*	3.5	5.5*^{v}	-	-	-	-	-	-	-

* Variable head permeameter measurement.
^{V} Vacuuming of the surface at the end of the test.
V New rain event after vacuuming the surface at the end of the previous day

Beyond this general procedure, in the tests using the realistic continuous granulometry within the analysis of the influence of particle size on the clogging process (sediment class UDC-3), the particle size distribution of the sediment collected at the end of the experiments for the mass balance was analysed by a laser coulter particle size analyser (Beckam-Coulter LS 13 320) to be compared with the sediment initially distributed and to assess the behaviour of the different particle sizes through the permeable pavement tested. In the case of the experiments that aimed at analysing in detail the quality of the effluents for different degrees of clogging (UDC-4, UPV and BEN), the drained mean concentration of different water quality variables was analysed. These variables were chemical oxygen demand (COD), biological oxygen demand at 5 days (BOD_5), total and volatile suspended solids (TSS and VSS), ammonium, nitrites, nitrates, total nitrogen (TN), phosphates, total phosphorus (TP), aluminium (Al), turbidity, hydrogen potential (pH), electric conductivity (EC), dissolved oxygen (DO), saturation percentage (%sat DO) and temperature. For sediments, humidity, apparent and real density, organic matter (loss-on-ignition (LOI) and oxidable carbon), total nitrogen (TN) and total phosphorus (TP) were also analysed. The standardized methods used for these physicochemical analyses are listed in Table III.S1 (Supplementary Material[1]).

III.3 Results and discusión

III.3.1 Permeability of porous asphalt and reduction by clogging

Permeability was measured by the variable head permeameter in the sediment load steps indicated in Table III.2. The results obtained for the initial permeability, 23559±5034 mm/h (Figure III.3), fall around the upper limit of the range reported for porous asphalt in a recent review study (300-30000 mm/h) (Razzaghmanesh and Beecham, 2018). As sediment load was increased on the system surface, the permeability was exponentially reduced for the different sediment classes, as showed in Figure III.3. Similar decreasing patterns have been observed by other studies, in which the decrease has been related with pavement age (Razzaghmanesh and Beecham, 2018) or with the number of cycles of clogging assays (Kia et al. 2018).

Despite this significant reduction of permeability, it remained above the simulated rainfall intensity (80 mm/h) even after the maximum surface sediment dosing, when sediments UDC-4, UPV and BEN were used. Concretely it remained at 583±567, 286±56 and 860±527 mm/h for UDC-4, UPV and BEN respectively. This may be the reason why no runoff was generated in the experiments with UPV and BEN sediments, as explained in the next section.

Focusing on the experiments performed to assess in detail the effect of particle size distribution (UDC-1, UDC-2 and UDC-3), a different behaviour was obtained for the granulometries tested, with the finest granulometry (UDC-1) being the one that least clogged the slabs, while the real granulometry (UDC-3) was the most unfavourable for a cumulative sediment load of 1 kg/m^2. We can also observe that finer sediment (UDC-1) was much less harmful to the pavement than the coarser

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[1] Material suplementario del Anexo 1.

one (UDC-2) and the realistic one (UDC-3), as the former can restore permeability to almost 100% of the original (Figure III.3). The fine material was able to pass through the asphalt slab, percolating with the rainwater, while the larger grain size material was trapped, causing a greater loss of permeability. Nevertheless, not only sediment diameter affects to clogging process of PP.

The tests also shown the importance of using graded sediments instead of uniform particle size distribution. Thus, uniform UDC-2 distribution has a d_{50} of 391 microns while graded UDC-3 sediments of about 282 microns, but the percentage of clogging is much higher for the realistic sediment (78% vs. 53%). It is possible that the latter material had a grain size similar to that of pore size of the porous asphalt, resulting in a higher potential for clogging. A literature review concluded that findings from clogging studies are not always consistent with each other, since differences in the clogging material used, pore structure of the pavement, exposure conditions and other variables can influence the results (Kia et al. 2017). Neupert et al. (2021), highlighted that using small diameter sediments (d_{50}~63 μm) to analyse permeable pavement performance as in some German standardised procedures, may lead to underestimation of the actual road sediment deposits load. In our work it is shown that the reduction in permeability is also underestimated.

The effect of organic matter can be observed by comparing the experiments performed with UDC-3 and UDC-4. It can be observed that UDC-4 caused a larger loss of permeability, which could be related to the higher content of organic matter (UDC-4).

After different sediment loading steps, the porous asphalt was vacuum-cleaned, and the recovery of permeability was checked (Figure III.3). The experimental batteries with UDC-1 and UDC-2 recovered the most permeability after vacuum cleaning, followed by UDC-4 and BEN, while the battery with UDC-3 recovered the least permeability, both in absolute and relative terms. UDC-1 and UDC-2 were subjected to four rainfall events, UDC-4 and BEN to six and UDC-3 to eleven (Table III.2). From these results, one can deduce that, for similar sediment loads, the number of rainfall events has a negative influence on the potential permeability recovery. Therefore, the frequency of rainfall events should also be considered when establishing maintenance protocols.

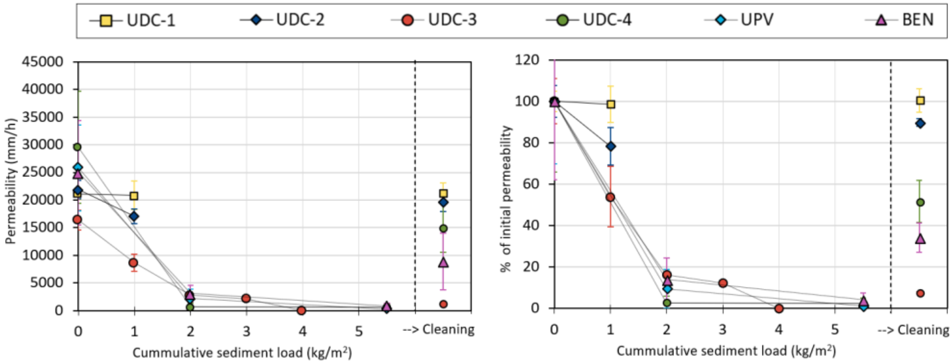

Figure III.3. Reduction of permeability observed for different sediment loading steps over the porous asphalt for each sediment class tested. The results are presented in mm/h (left) and in relative terms with respect to the initial permeability (right).

III.3.2 Flow rates drained

The hydraulic efficiency, measured as the percentage of rainfall volume that is infiltrated through the porous asphalt, was very high for loading steps up to 1 or 4 kg/m^2 when sediments UDC-1, UDC-2 and UDC-3 were used, with a negligible runoff flow (Figure III.4). It was 100% for all the sediment loads when UPV and BEN sediments were used. The filtration flow rate was very similar among the different experiments for sediment loadings below 4 kg/m^2, almost equal to the applied rainfall (80 mm/h), despite the loss of permeability shown in the previous section. This can be explained by the fact that the permeability, despite the reduction, was still higher than the applied rainfall intensity, as well as the possible existence of unclogged areas and the occurrence of preferential flows through them.

UDC-3 total clogged for 5.0 kg/m^2 as seen in Figure III.4. The effect of clogging was noted from a cumulative load of 4.5 kg/m^2, when rainwater can no longer be drained completely through the slabs and generates runoff. The runoff generated was collected, increasing runoff discharge and decreasing filtered discharge. Initial measured runoff showed in Figure III.4 was due to splashing of raindrops on the lateral runoff collection funnel, so the runoff caused by clogging for 4.5 kg/m^2 was 0.0027 L/s, which was increased up to 0.0039 L/s for 5.0 kg/m^2 of cumulative load as more percentage of the surface slab becomes clogged. However, looking at the third test (UDC-3), where the realistic granulometry was distributed, we observed a reduction of the filtered flow and an increase of runoff at roughly 3.5 kg/m^2 of accumulated load. This indicates that some parts of the slabs are starting to clog at a sediment load between 3.5 and 4.0 kg/m^2.

The tests performed with UDC-4, which is the same sediment as UDC-3 but not calcined, presented a filtration rate lower than those performed with UDC-3. This decrease of infiltration rate, as in the case of loss of permeability, could be related to the presence of organic matter, which confers cohesivity to the sediment. The runoff generated at a cumulative load of 2 kg/m^2 is very similar in both cases, varying between 1 and 2 mm/h, and total volumes between 0.10 L/m^2 (UDC-3) and 0.32 L/m^2 (UDC-4) (3% of the rainfall depth). At the top sediment load tested (5.5 kg/m^2), the runoff flow was significantly higher (54 mm/h for UDC-4) as well as its volume (24.4 L/m^2; 61% of the rainfall depth applied).

In contrast, UPV and BEN sediments did not generate runoff for any of the sediment loading steps. These sediments have a less proportion of fine material, so they hardly led to physical clogging. Instead, UPV and BEN have a higher potential to induce clogging due to biofilm growth, also known as bioclogging (Perujo et al. 2019), as they have a larger content of organic matter and nutrients, or even, chemical clogging, as they have more substances able to react and precipitate with others. Probably, a longer period would have been necessary to detect this clogging mechanism.

As shown in Figure III.4, the vacuuming of the pavement surface produces a moderate recovery (25%) of the filtration capacity for the realistic granulometry (UDC-3), which is in line with the low recovery of permeability for this sediment and within the range reported in literature (Kia et al. 2017). These authors concluded that the recovery rate depends on several factors, such as porosity, pore size and connectivity of the porous pavement, and on the properties of the sediments that clog the pavement, mainly on its grain size.

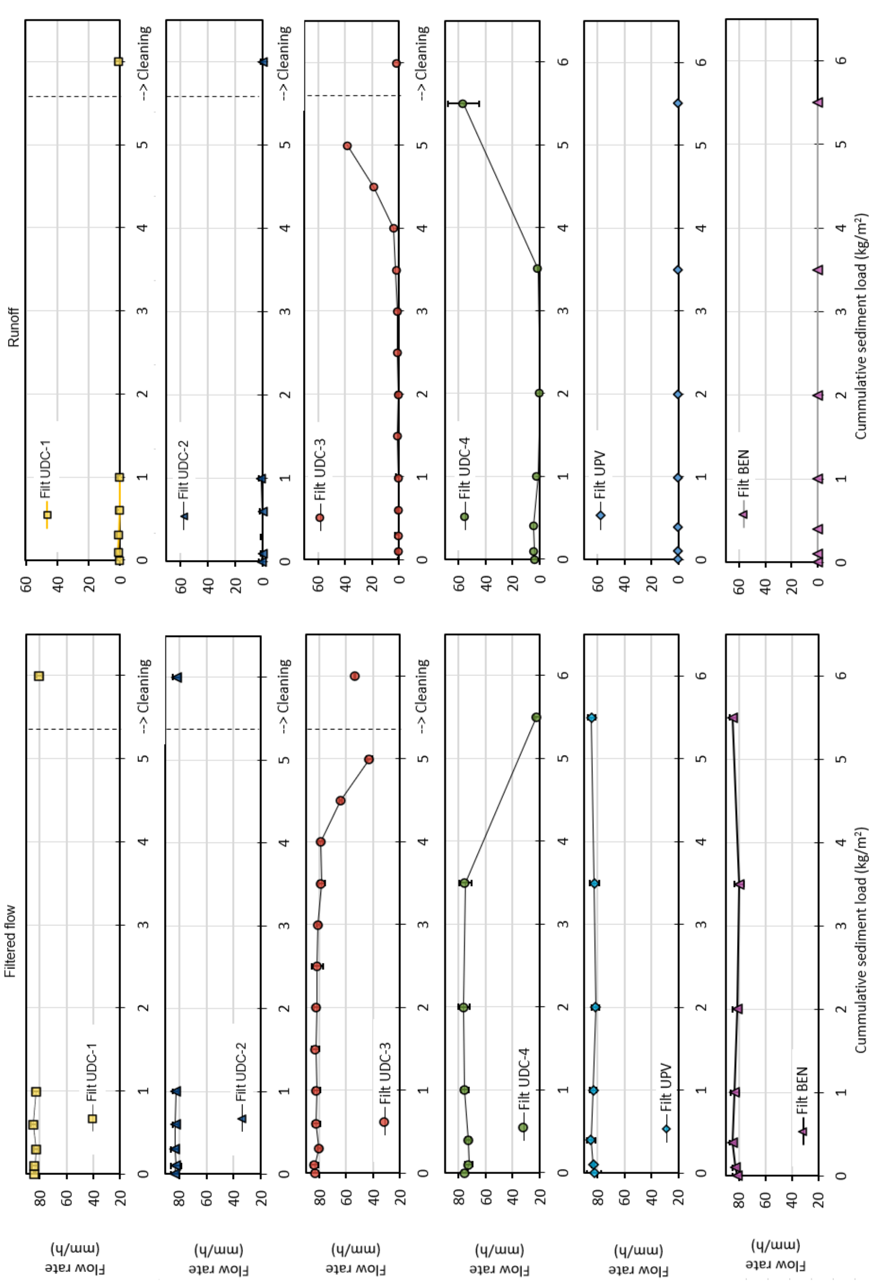

Figure III.4. Mean of the filtered (left column graphs) and runoff (right column graphs) flow rates drained for each sediment class and different grades of clogging when the hydrograph reached stationary condition between 900 and 1500 s from the beginning of the experiment. Standard deviation represented with error bars.

III.3.3 Water quality of filtrate and surface runoff flows

Water quality (WQ) of the filtrate and runoff flows was analysed for the experiments using real sediments (UDC-4, UPV and BEN) (Figure III.5). In general, all the WQ variables increased as the cumulative sediment load increased. For all variables except TSS, UDC-4 was the sediment that contributed the least pollutant load to the filtered water, followed by UPV; BEN was the sediment that leached more nutrients and organic matter. These results are related to the higher content of organic matter and nutrients of BEN sediments (Table III.1).

However, UDC-4 added more TSS to the filtered water, because of its higher proportion of fine material (Table III.1). After 1 kg/m^2 of cumulative sediment load, COD, TSS and TP reached concentrations higher than the discharge limits for treated wastewater (Directive 91/271/CEE, 1991) for at least one kind of sediment. Other WQ indicators to consider are those included in the regulation on the protection of groundwater against pollution and deterioration (Directive 2006/118/EC, 2006), which establishes quality standards for nitrates and pesticides, and call upon the European Union Member States to establish threshold values for additional WQ variables. Among all these variables, the ones analysed in the present study and their indicator value are nitrates (11.3 mg N/L), ammonium (1.91 mg N/L) and phosphates (0.52 mg P/L) (CHJ, 2022).

The concentration of filtered water is below the nitrate standard and the ammonium threshold for any of the sediment classes and their cumulative loads, even total nitrogen is below the standard. Although a low risk of nitrate pollution can be considered, measures such as water detention inside the PP are recommended to favour denitrification, and thus, to reduce pollution risk (Drake et al. 2014). However, phosphates exceed the threshold from a cumulative sediment load of 1 kg/m^2.

When the sediment characteristics are similar to those used in this study and considering all these indicator values, a maximum allowable sediment load on permeable pavements of 1 kg/m^2 could be established to avoid negative impacts on the receiving waters. According to previous studies (Fernández-Gonzalvo et al. (2021); Hernández-Crespo et al. (2019)), this could be equivalent to a period of around six months of pollutant build-up in urban road surfaces. Therefore, the obtained results are in line with the recommendations given in previous studies for establishing a monthly cleaning frequency for the routine maintenance tasks (Fernández-Gonzalvo et al. 2020), which is more frequent than maintenance usually recommended in other studies (1 to 4 times per year, (Kia et al. 2017)).

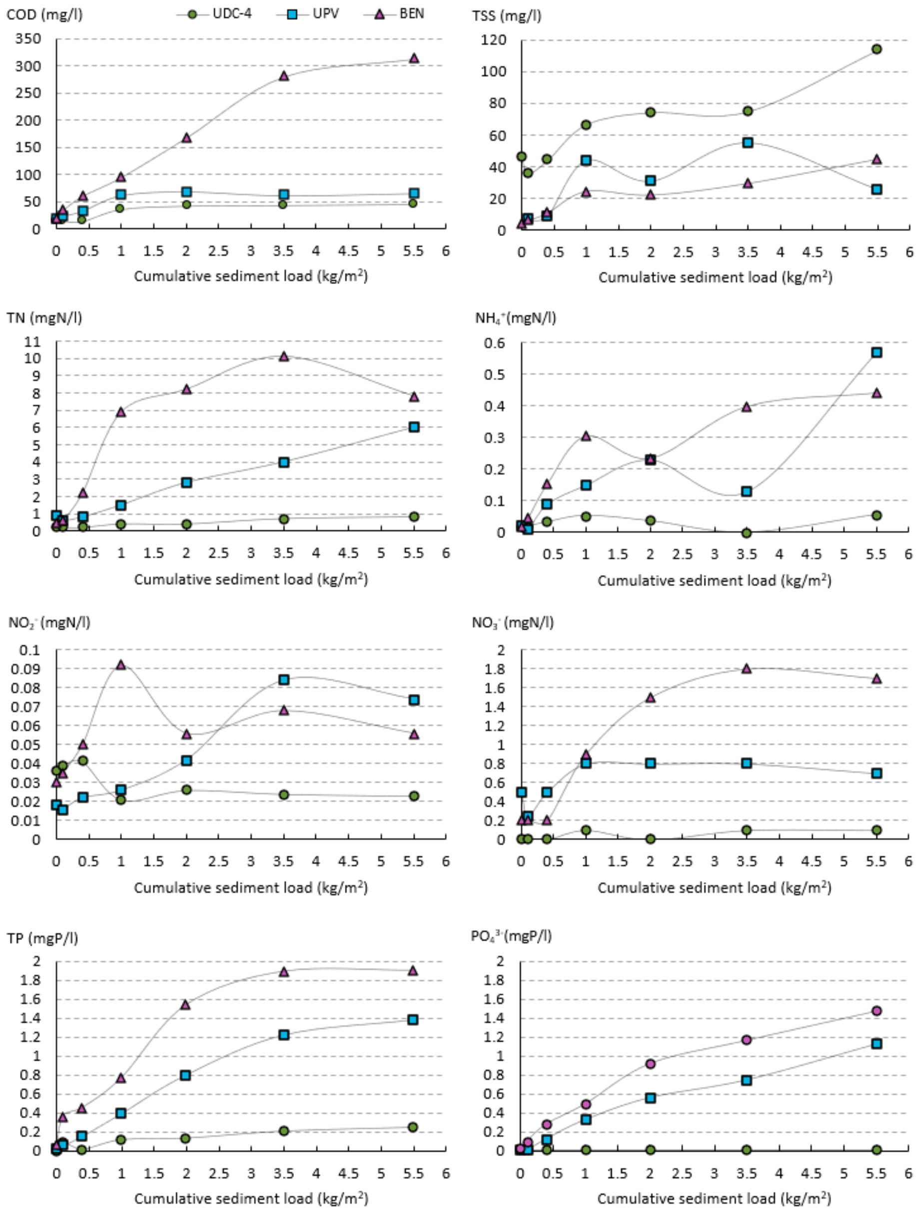

Figure III.5. Water quality results of filtrated water under increasing sediment load using different sediments (UDC-4, UPV and BEN).

If the total content of organic matter and nutrients in the sediments deposited on the pavement surface is considered, the relative release of these substances are, on average, 4% for COD (estimated from organic carbon in Table III.1.), 23% for TN and 21% for TP. This release percentage decreased as the sediment load increased, likely because rainwater is not able to mobilise all the pollutant mass accumulated on the pavement surface when the sediment load is large (Table III.3). Previous studies also pointed out this trend (Fernández-Gonzalvo et al. 2020). Complementary, the relative proportion retained on the surface or inside the porous asphalt may be considered as an indicator of the PP performance, which gives, on average, 96% for COD, 76% for TN and 79% for TP. The efficiency obtained is among the highest values reported in the literature. For instance, Liu et al. (2020), reported mean load reductions around 59% for TP and 43% for TN by permeable bricks and 43% (TP) and 52% (TN) for porous concretes. Kamali et al. (2017) and Mahmoud et al. (2020), obtained removal performances of 100% and 77% respectively for TSS, and Braswell (Braswell et al. 2018) found load reductions of 95% for TSS and TP, and 70% for TN.

Table III.3. Organic matter and nutrients released from the sediment deposited on the surface of porous asphalt to the filtrated water, expressed as percentage (%) relative to the accumulated mass on the surface, and leaching capacity expressed as mg per kg of sediment and L of rainwater applied (mg/kg/L). Note: (*) indicates nutrients released by the surface runoff; NA: not available.

Sediment class	Sediment loading (kg/m²)	COD (% released)	COD (mg/kg/L)	TN (% released)	TN (mg/kg/L)	TP (% released)	TP (mg/kg/L)
UDC-4	0.1	7.6%	439.9	58%	13.0	65%	3.1
	0.4	2.0%	113.2	22%	4.9	19%	0.2
	1.0	2.3%	130.7	15%	3.4	16%	0.4
	2.0	1.3%	73.7	11%	2.4	13%	0.2
	3.5	0.8%	44.1	9%	2.1	12%	0.2
	5.5	0.2%	9.6	7%	1.5	8%	0.1
	5.5 (*)	NA	NA	4%	1.0	11%	0.6
UPV	0.1	14.1%	893.4	64%	58.2	18%	2.4
	0.4	5.1%	322.4	25%	22.5	12%	1.6
	1.0	3.8%	243.6	16%	15.0	13%	1.6
	2.0	2.1%	132.7	14%	12.9	14%	1.6
	3.5	1.1%	67.1	13%	11.8	15%	1.4
	5.5	0.7%	46.6	13%	11.8	15%	1.0
BEN	0.1	9.7%	1264.9	32%	42.8	53%	14.4
	0.4	4.4%	570.4	24%	32.0	27%	4.5
	1.0	2.8%	371.7	30%	40.1	21%	3.1
	2.0	2.4%	313.6	26%	35.5	19%	2.9
	3.5	2.3%	297.4	23%	31.0	18%	2.0
	5.5	1.6%	213.1	19%	25.0	15%	1.3

The leaching capacity of organic matter and nutrients increased with sediment concentrations. Concretely, BEN sediments leached more organic matter and nutrients than UPV and UDC-4 sediments (Table III.3). It is also remarkable that leachability decreases with the cumulative sediment mass deposited on the surface, as commented previously. The values obtained in this study are in the same order of magnitude that those obtained in previous studies (Naves et al. 2020a). These results are useful to assess the pollution potential of each sediment class. It is important to emphasize that physical characteristics of PP such as roughness and porosity allow pollutant retention so that they can be easily removed later, and do not reach the environment. By contrast, accumulated pollution on impervious surfaces, with a low void-ratio, is likely to be washed during rain events. In consequence, less quantity of contaminants can be removed, and end up affecting the environment.

III.3.4 Fate of sediments at the end of the tests

Finally, the mass balance shows how much and what type of sediment has been retained for each test in the surface, dragged to the runoff tank or filtered through the asphalt slab (Table III.4). Overall, a 98% of the sediments remains accumulated over the surface and inside the porous asphalt, meanwhile just roughly a 2% is mobilized by surface runoff or filtrated water. This result demonstrates that physical interception is a major mechanism for solid removal, which coincides with previous studies (Hernández-Crespo et al. (2019); Li et al. (2017)). The sediment with finer granulometry (UDC-1) was mainly retained inside the porous asphalt, while coarser sediments (UPV and BEN) remained mainly on the surface. Sediment UDC-2, which is slightly coarser than sediment UDC-1, was retained on the surface to a greater extent than sediment UDC-1. Sediment UDC-2 clogged the upper pores of the asphalt largely and therefore did not allow more sediment to pass through it. This result is consistent with the fact that sediment caused a greater loss of permeability of the asphalt slab (Figure III.3) and with the conclusions reached by other studies (Kia et al. (2018); Zhang et al. (2018)).

Sediment UDC-4 was retained on the surface in higher proportion than UDC-3. This fact that can be explained by the higher organic matter content of UDC-4, which could have become more cohesive on the surface, trapping more fine particles. Additionally, UDC-4 received less rain events than UDC-3, thus having less probability of penetrating inside the porous asphalt.

Figure III.6 shows the particle size distribution of the sediments collected from the surface, from the runoff or filtered through the pavement at the end of the tests for sediment class UDC-3, which is the one with a realistic inorganic granulometry. Comparing initially distributed granulometry and particle size distribution of sediment present at filtered flow, it can be seen that only the finest material was able to pass through the slab (approximately d_{50} 75 μm), with coarsest sediments (approximately d_{50} 300-400 μm) being retained on the pavement surface. It can also be seen that sediment washed into the runoff tank, either by saltation by raindrops or when runoff is generated, is similar to that on the surface. This is in line with and reinforces the conclusions drawn from the mass balance and stated previously.

Table III.4. Fate of sediments at the end the tests, for each battery of experiments. Sediment applied on the surface, in runoff, filtered and surface are measured data. The sediment load retained in the asphalt slab is estimated through a mass balance, from the total mass distributed over the pavement and the previous values.

Sediment class	Sediment mass (%)			
	Surface	**Runoff**	**Retained**	**Filtered**
UDC-1	0.1	1.6	97.8	0.5
UDC-2	20.7	0.8	75.9	2.6
UDC-3	12.8	2.3	84.7	0.2
UDC-4	31.6	0.5	67.5	0.3
UPV	80.7	0.0	19.0	0.3
BEN	92.9	0.0	7.0	0.1

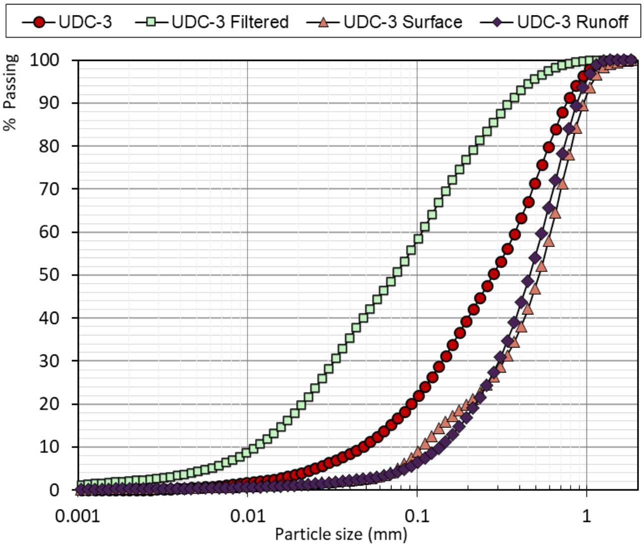

Figure III.6. Particle size distribution of sediment collected at the end of the experiments in the different parts of the rainfall simulator compared to the sediment initially distributed.

III.4 Conclusions

Porous asphalt is one feasible solution for continuous surfaces of permeable pavements. Although it has been widely used, there is still a lack of knowledge on mechanisms influencing the clogging process and how this problem affects the water quality of filtrated water. This research developed in two different laboratories an experimental strategy to analyse the influence of sediment particle size distribution on the clogging of the permeable pavement and, to evaluate in detail the behaviour of the porous asphalt in terms of pollutant reduction for different degrees of clogging. From the tests carried out and the results obtained, the following conclusions can be drawn:

The use of two different facilities managed by two independent teams demonstrates the transferability of the methodology proposed in this study, the comparability of the results obtained and the possibility to obtain complementary results. Testing different sediment materials provide valuable information to evaluate the clogging process, the water quality of filtrated water and, consequently, establish recommendations for PP cleaning maintenance protocols. Therefore, when a PP is designed, it is highly recommended to characterize the potential for sediment production within the catchment and to propose cleaning and maintenance frequencies adapted to local conditions. In addition, the quality of filtrated water should be analysed whenever possible, as it can determine the frequency of sediments cleaning needed to avoid negative impacts on the receiving waters. Fine sediments with a maximum diameter lower than 125 μm cause a lower permeability loss than sediments with a wider minimum-maximum diameter range (250-500 or 0-1000 μm), so standardized methods for assessing clogging potential should consider this fact. The number of rainfall events (or clogging cycles) influences negatively on permeability recovery by vacuum cleaning, thus the rainfall frequency is an important variable to consider when cleaning methods are going to be tested and proposed. The porous asphalt tested in this study has shown an elevated hydraulic efficiency and high capacity to retain sediments and pollutants, thus installing this kind of infrastructures in urban areas makes a significant contribution to the environment and the sustainability of urban drainage. It must be considered that the sediments used in the experiments were collected from parking lots and residential sites. Nevertheless, a wider range of land uses can be identified within the urban environment, such as commercial or industrial among others. According to the site and the urban activities that take place, pollutant composition and concentration can vary significantly. For this reason, it is suggested to widen consider additional types of sediments generated at more diverse sites to complete this experience. It might be suggested that future research lines focus on the development of site-based maintenance and cleaning procedures of permeable pavements, according to the direct influence of the sediment characteristics and the rainfall conditions on the clogging process.

Capítulo IV

Los SUDS como solución para el control de microplásticos

El agua de escorrentía pluvial urbana está considerada como una de las fuentes más importantes de contaminación por microplásticos. En este capítulo se realiza un exhaustivo proceso de revisión y análisis de los estudios que, hasta el momento, han evaluado el papel de los sistemas urbanos de drenaje sostenible para hacer frente a este problema mundial. Múltiples factores de diferente índole, como la climatología, el planeamiento urbanístico, o las características de los propios, influyen en la capacidad de gestión de microplásticos. Los sistemas basados en los procesos de sedimentación (humedales o estanques) y de filtración (celdas y jardines de biorretención, o pavimentos permeables), atrapan eficientemente un número significativo de microplásticos. Generalmente, los microplásticos tienden a concentrarse en los sedimentos y medios filtrantes próximos a las estructuras de entrada, ocupando las capas menos profundas. Polímeros como el polipropileno, el tereftalato de polietileno, el polietileno y el poliestireno, son los más frecuentes y abundantes que se han encontrado en la escorrentía urbana. Destacan principalmente por su complicada gestión, las partículas más pequeñas y de tipo fibra. La gran variabilidad de métodos empleados para la detección de microplásticos, así como la representación de los resultados publicados, dificulta la extracción de conclusiones globales. En última instancia, se proponen medidas para complementar el diseño actual de los SUDS con el objetivo de reducir la contaminación por microplásticos, y se sugieren futuras líneas de investigación.

García-Haba, E., Hernández-Crespo, C., Martín, M., & Andrés-Doménech, I. (2023). The role of different sustainable urban drainage systems in removing microplastics from urban runoff: A review. Journal of Cleaner Production, 411, 137197. https://doi.org/10.1016/J.JCLEPRO.2023.137197

IV.1 Introduction

Scientific literature defines microplastics (MPs) as plastic particles whose longest dimension is below 5 mm (Malankowska et al. 2021). In the first International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris, MPs origin was defined according to primary and secondary sources. Primary MPs consists of manufactured particles for a specific use or purpose, whereas secondary MPs are plastics which have suffered breakdown processes in the environment (Arthur et al. 2008).

Widely present in the environment, MPs cause threats to the environment and humans, and contribute significantly of the deterioration of natural resources and wildlife (Grbić et al. 2020; Müller et al. 2020; Sun et al. 2019 and Zhang, 2017). There are several modes of harm, depending on the size of plastic specks (Lim, 2021). When plastics are small enough (nanoplastics), they can enter cells or tissues, which might cause irritation or inflammation of lung tissue and lead to cancer, or deposit in the airways and lungs, provoking respiratory damages, among others. Larger microplastics are more likely to cause negative effects due to chemical toxicity, because they may contain plasticizers, stabilizers and pigments, many of which are hazardous. They can also adsorb toxic substances and act as carriers or cause malnutrition and starvation through satiation by ingesting particles with no nutritional value (Lim, 2021).

These small particles can be found in the atmosphere, soil, sediment, freshwater bodies and oceans (Ziajahromi et al. 2020). Focusing on freshwater, the main sources and paths of MPs to reach these water bodies come from the urban environment. Human's activities related to industry, household laundry, construction, tire wear, street furniture wear, leakages from urban waste collection systems, among others lead to wastewater treatment plant (WWTP) effluents and stormwater runoff contamination (Koutnik et al. 2021 and Qiu et al. 2020).

Great proportion of the MPs removed at WWTPs are transferred into the sludge, whereas others are released to the environment (Liu et al. 2021). This poses an environmental risk because sewage sludge is frequently applied in croplands and hence represents a major input to the environment (Hernández-Arenas et al. 2021). The efficiency of big WWTPs at MP removal is thus a cutting-edge research topic. Many studies on the different techniques used for collecting MPs, their pre-treatment and characterization methods, have been issued (Sun et al. 2019). Further, in recent years, it has been noticed a major concern on studying WWTPs in small communities. These treatment plants are often based on or complemented with constructed wetlands that provide tertiary treatment (Wang, Q. et al. 2020).

In wet weather, stormwater runoff and combined sewage overflows (CSOs), transport important loads of pollutants, reaching water bodies without previous treatment (Piñon-Colin et al. 2020). Indeed, some studies have found a higher MP abundance in rainy seasons or after a rain event, in river, estuarine or seawater

(Cheung et al. 2019; Jiang et al. 2022). Cheung et al. (2019) showed that plastic abundance dropped over ten times (14.0 to 1.3 pieces/m^3) within two hours after a rainfall event in Lam Tsuen River. Zheng et al. (2020) measured a significantly higher quantity of MPs in Bohai Sea zooplankton community in the rainy season than that in dry season. These findings suggest that diffuse pollution during rainfall events may be a major MP pollution pathway. Nonetheless, there is a limited number of studies focused on the removal of MPs from urban stormwater runoff.

MP pollution control requires a combination of multiple and varied actions, including legislation to regulate the production of single use plastics or banning the addition of microbeads in personal care products, improving policies of plastic waste management, strengthen the recycling and utilization of plastic waste (Zhong and Li, 2020; Directive (EU) 2019/904), developing technologies to prevent and collect marine plastic pollution, such as laundry balls or water filters on laundry machines or stormwater and wastewater filters (Schmaltz et al. 2020). Even if waste management was improved significantly, there are many plastic-made elements in urban areas that can release MPs in rain events (street furniture, pipes, car pieces, etc.). For preventing the discharge of MPs from urban runoff, sustainable urban drainage systems (SUDS) can be part of the solution.

SUDS are engineered nature-based solutions for sustainable urban stormwater management, that provide water quality improvement and prevent from diffuse pollution. SUDS aim at mimicking and restoring hydrological processes existing prior to urban development (infiltration, filtration, storage, evapotranspiration, etc.), by integrating runoff management devices into the urban landscape (Andrés-Doménech et al. 2021). There is a wide variety of SUDS, including permeable pavements, filter strips, vegetated swales, infiltration trenches, soakaways, rain gardens, detention and retention basins, detention and retention ponds, and constructed wetlands, among others (Woods-Ballard et al. 2015).

This review aims to compile and analyse the results obtained in previous studies in which the capacity of various types of SUDS to retain and remove MPs from urban runoff has been evaluated. The distribution of the MPs within the systems, and the influence of their size, shape or composition is also analysed. The ultimate goal is to identify possibilities for design improvements, as well as aspects that remain to be studied.

IV.2 Methodology

IV.2.1 Literature search

An exhaustive searching process of a wide variety of keywords, using different scientific and academic engines, has been carried out (Table IV.1). The databases were accessed on 6th September 2021 for the first time and reviewed every two weeks since then. No time limit of publication date was defined. A first search roughly checked existing studies related to microplastics in stormwater runoff, combining keywords such as "stormwater", "runoff", "urban", "surface", "microplastics" and "retention", obtaining a large number of results.

From the analysis of these results, a second search (A) used the combination of the terms "microplastics" as term 1, and "stormwater runoff" or "runoff" or "surface runoff" or "urban runoff" as terms 2. It was noticed that the papers found according to this search, were closer to the interest of this investigation.

Then, to slightly narrow the search and to select proper papers, a more refined search was done (B), incorporating a complementary term. Term 3 aims at encompassing terminology that describes MP retention techniques, as it varies according to its location of application. For example, the term SUDS is used in the UK; Water Sensitive Urban Design (WSUD) in Australia; Best Management Practices (BMPs) in North America; Low Impact Development (LID) in North America and New Zealand, and Sponge Cities in China. Other recent globally adopted terms, are Green Infrastructure (GI) and Nature-Based Solutions (NBS) (Qi et al. 2020). Additionally, to strengthen the literature search, citations to the papers selected from search B and its own bibliography, were tracked.

Table IV.1. Summary of searches, terms and results from the considered search engines.

							Results	
Search id	Term 1	Boolean operator	Term 2	Boolean operator	Term 3	Web of Science	Science Direct	Google Scholar
A	Microplastics	AND OR	Runoff Stormwater runoff Urban runoff Surface runoff	-	-	252	2041	8770
B	Microplastics	AND OR	Runoff Stormwater runoff Urban runoff Surface runoff	AND OR	NBS	10	104	1120
					SUDS	10	42	278
					Sponge cities	10	35	267
					LID	10	36	277
					BMPs			
					GI			
					WSUD			

IV.2.2 Selection criteria and results of the search

Eligible studies focus on whether stormwater runoff and microplastics have been managed by any SUDS technique, and provide relevant information, such as treatment capacity efficiency, or microplastic identification methods used, among others. Only articles and review articles published in the English language were examined, excluding index documents.

As a result, a total of 23 studies met the requirements and were selected for this review. The studies were geographically located in Europe (n=10), North America (n=6), Oceania (n=6) and Asia (n=1). It is important to emphasise the significantly reduced number of publications on this research line.

IV.3 SUDS experiences for MP management

Covering available literature, fewer SUDS techniques for MP management have been identified, in comparison to all available solutions. Specifically, five different SUDS types have been studied under diverse land use conditions. A brief description of these SUDS is included in the Supplementary Information[2]. These techniques consist of urban wetlands (in 4 studies), including urban park water bodies (UPWB, in 1 paper); stormwater detention ponds and basins (SWP, in 7 papers); bioretention structures (BS, in 7 papers), that comprise rain gardens, biofilters, bioretention cells and bioretention basins; sand filter (SF, in 4 papers); and permeable pavements (in 1 paper).

The research developed by Su et al. (2019) within the Greater Melbourne Area in Australia, monitored microplastic presence in nine urban stormwater wetlands, that intercept and treat stormwater from intensive commercial and industrial activities. Townsend et al. (2019) examined microplastic pollution in 20 urban wetlands, also in the Greater Melbourne Region. These water bodies receive water from stormwater runoff, produced at commercial, industrial, open space (undeveloped), residential, road/rail, rural, semi-rural and urban growth land uses. Also in Melbourne, Pramanik et al. (2020) collected stormwater road runoff samples from a constructed wetland. A research developed by Ziajahromi et al. (2020), aims to measure concentrations of MPs at inlet and outlet of a stormwater floating treatment wetland, located at the Gold Coast, Australia. Yu et al. (2021), investigated MP pollution in 12 UPWB in Xi’an (China), according to different specific locations and land uses, such as industrial, tourism, commercial and residential. Although the UPWB were not specifically implemented to manage urban runoff, they have been considered in this review as they receive stormwater runoff. More recently in Gdansk (Poland), a multistage constructed wetland system was preliminary studied by Jakubowicz et al. (2022) to detect and remove

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[2] Material suplementario del Anexo 1.

pollutants from a stormwater collector, in a highly urbanised catchment of 1,740 hectares (Vahvaselkä et al. 2022).

Besides, Coalition Clean Baltic (2017) summarizes the study carried out by Jönsson (2016). In this case, MPs are managed by two stormwater ponds in Sweden. Klöckner et al. (2019) studied a determination method of tire and road wear particles (TRWP) and obtained concentrations of these particles in two road and highway runoff treatment facilities in Halensee and Leipzig, Germany. The treatment systems consisted of a sedimentation basin (SB) and a soil retention filter (SRF) and two consecutive settling ponds (SP). Liu et al. (2019a, b) analysed MP concentrations in both water and sediment matrix of seven retention ponds in Denmark, from residential, industrial, commercial and highway landscapes. A study carried out by Olesen et al. (2019), analyses the presence of MPs in a stormwater retention pond located in the Danish city of Viborg. A total area of 166 ha (70 ha impervious) drains to the stormwater pond, which surface area is 6690 m^2 and approximately 7500 m^3 its total volume. The catchment land use is defined as light industry, including production industries, retailers, building supply stores, parking lots, and roads with semi-heavy traffic. Pramanik et al. (2020) studied road dust as a potential source of MPs in a stormwater pond. Laplaca and van den Hurk (2022) characterized MP abundance found in aquatic biota from 3 stormwater ponds and 4 adjacent tidal creeks in South Carolina (USA). These SWPs receive stormwater from drainage areas with different land uses, such as residential, commercial, highway and golf course.

Recently, Lange et al. (2023) investigated the abundance and distribution of microplastics in nine 7-12 year-old BS, looking at different depths of the filter media and distance from the inlet. The BS were located adjacent to roads or parking lots in urban areas classified as industrial, commercial, downtown ultra-urban, or mixed residential and commercial, which catchment areas to the BS ranged from 50 m^2 to 318500 m^2. Koutnik et al. (2022a, b) focused their investigations on filtration-based BS. In the first study, the authors analysed atmospheric deposition of MPs, together with spatial distributions above and below ground of 14 structures in Los Angeles, USA. These BS manage stormwater from driveways and parking lots, residential and commercial areas with low and medium traffic streets, high traffic areas, and a natural area. Within the second study, 2 biofilter models (sand-based and soil-based) at laboratory scale were simulated, and evaluated the remobilization effect of loaded MPs, after subjecting the biofilters to dry-wet or freeze-thaw cycles. Mbachu et al. (2022) studied MPs and meso-plastics accumulation in 20 BS in suburban residential areas. Werbowski et al. (2021) support the study conducted by Gilbreath et al. (2019), which aims at assessing the efficiency of a rain garden for pollutant removal, including MPs. The BS is filled with engineered soil mix and manages a drainage area of 4080 m^2 in California, USA. The catchment, mostly impervious, includes medium-density residential, commercial and road land uses. A more recent study, characterizes and quantifies MPs in urban stormwater runoff through a bioretention cell (Smyth et al. 2021). In this case, the study site located in Ontario (Canada), receives stormwater runoff from an impervious parking lot with a 265 m^2 drainage area. Boni et al. (2022), determined MP presence in a bioretention basin that receives stormwater from an adjacent parking lot, road, and academic buildings in New Jersey, USA.

Lange et al. (2021 and 2022) studied a stormwater treatment train located in Sundsvall, Sweden. The treatment train is composed of a gross pollutant trap (GPT) connected to either a subsequent vertical flow BS or a non-vegetated SF system. The system manages runoff from a total impervious catchment of 4.7 ha including motorway use. Another SF system was studied by Pankkonen (2020) to compare two fine filtration media (sand and biochar) for stormwater filtration in Helsinki, Finland. The SF system is placed in a separate stormwater sewer, to manage runoff generated in a 53 ha catchment with intense traffic, before entering a seawater bay.

The study developed by Rasmussen et al. (2023) concerned the analysis of sediment dust accumulated on seven permeable pavement roads and parking lots, used for residential, industrial, and commercial purposes. The sampling sites were located on the peninsula of Jutland and the island of Funen in Denmark.

IV.4 Microplastic detection techniques

IV.4.1 Sample matrix

The sample matrix represents the medium where samples are taken and needs to be defined according to the objectives of the research. Three different matrices have been detected from the considered studies: water, sediment and fauna.

Water and sediment are the most sampled mediums. Boni et al. (2022); Coalition Clean Baltic (2017); Gilbreath et al. (2019); Jakubowicz et al. (2022), Lange et al. (2021 and 2022); Liu et al. (2019a); Pankkonen (2020), Pramanik et al. (2020) and Smyth et al. (2021), exclusively focused their analysis on this matrix. Concretely, samples were taken from inlets (IN) and outlets (OUT), and/or inside the water column (IWC).

In relation to the sediment, Lange et al. (2023), Rasmussen et al. (2023), Koutnik et al. (2022a, b), Mbachu et al. (2022), Liu et al. (2019b), Klöckner et al. (2019) and Townsend et al. (2019) analysed this medium, while Yu et al. (2021) and Ziajahromi et al. (2020) studied both water and sediment matrices.

Fauna is the least studied matrix within the revised studies. Su et al. (2019) monitored MPs in fish and amphibian species from stormwater wetlands, whereas Laplaca and van den Hurk (2022), studied the presence of MPs in fish and invertebrates. Only the study developed by Olesen et al. (2019) addressed the identification of MPs in the three matrices, showing the importance of this holistic approach. When the three matrices are evaluated, it is possible to know whether there is an accumulation of MPs in any of them, in comparison to the others.

IV.4.2 Sample collection

The sample collection process can be conducted in different ways. Parameters such as number and volume of samples, or mesh sizes, widely varies depending on the authors, even when the same sampling matrix is considered.

Meteorological conditions and available resources, determine the number and volume of samples to process. Depending on the medium where MPs are analysed, samples are measured as volume (at water and sediment matrices), mass (at sediment matrix), and as a number in fauna. According to the sample matrix, Tables IV.2, IV.3 and IV.4 show and describe characteristics and particularities of the samples taken according to the literature for the different matrices.

From the consulted references, a total of 21 different sieve sizes have been identified. Table IV.5 shows references which provide mesh size information, and fraction limits defined by the authors. Whenever possible, it is recommendable to use 10 or 20 µm as minimum size because of the high abundance of particles ranging in size from 10 or 20 to 100 microns, according to the reviewed studies, and as discussed later in section 5.3.

At this stage, it is noteworthy that a proper sampling of urban runoff should cover as much rainfall events as possible, in order to estimate the total quantity of pollutant that enters and leaves the SUDS structure. At least the first flush, when pollutants are usually more concentrated, should be covered. This task is commonly addressed by using autosamplers programmed according to the typical rain pattern of the area to be characterised (Andrés-Doménech et al. 2018; Perales-Momparler et al. 2014 and Sansalone and Cristina, 2004).

Table IV.2. Detailed information of samples characteristics in water, including number of samples taken, sampled volumes and a short description of the procedure.

Reference	No. of samples	Total sampled volume	Additional information
Boni et al. (2021)	3	15 litres	Samples taken from 3 separate events, considering 1 to 18 antecedent dry days. Every sample (5 litres) consists of the composition of 1 litre collected 20 to 40 minutes apart during the storm.
Coalition Clean Baltic, (2017)	Non-defined	Non-defined	Non-defined
Gilbreath et al. (2019)	6	20 to 40 litres	Samples taken from 3 storm events and collected at inlet and outlet points.
Jakubowicz et al. (2022)	4	Non-defined	Two samples taken before treatment, and 2 samples after the treatment process.
Lange et al. (2021, 2022)	48	1.8 to 20 litres	Composed water samples were taken during 9 rain events, at 5 points (inflow, GPT outflow, filter inflow, bioretention cell outflow and sand filter outflow). 3 additional samples were taken from the surface water (0–5 cm) of the sedimentation compartment from 3 specific events.
Liu et al. (2019a)	21	6,742 litres	The sampling campaign consisted of 3 rounds during dry weather, with a minimum of 2 weeks between samplings.
Olesen et al. (2019)	5	50 litres	Water sampled 5 times during dry weather. At least 14 days between samplings. Every sample consisted of 10 litres of pond water.
Pankkonen (2020)	6	Non-defined	Influent and effluent water samples taken from 3 rain events.
Pramanik et al. (2020)	Non-defined	Non-defined	Samples taken during rain events from different points in the stormwater pond inlet; and from inlet and outlet of the constructed wetland.
Smyth et al. (2021)	19	9.5 to 38 litres (0.5 to 2 litres per sample)	A total of 19 runoff events were sampled at inlet and outlet points.
Yu et al. (2021)	36	360 litres	3 different samples collected from different points in each water body. Each sample was a composite of multiple parallel sub-samples.
Ziajahromi et al. (2020)	6	Non-defined	Samples collected at inlet and outlet points with 2 replicates, after a heavy rain event (34 mm/d).

Table IV.3. Detailed information of samples characteristics in sediment, including number of samples taken, sampled volumes or mass, and a short description of the procedure.

Reference	No. of samples	Total sampled volume or mass	Additional information
Lange et al. (2023)	33	Non-defined	Samples from 9 BS located at 1 and 3 meters from the inlet (locations 1 and 2). At location 1, 2 samples were taken at 0-5 cm and 10-15 cm depth of the filter media. At location 2, samples were taken at 0-5 cm of the filter media.
Liu et al. (2019b)	>7	≥ 21 litres (≥ 3 litres of sediment from each pond)	Sediments sampled during dry weather with antecedent dry weather period of more than 2 days. Samples were taken at 1 m water depth, collecting the top 5 cm of the sediment. For each pond, samples were collected the same day from three randomly locations and were combined as one sample.
Mbachu et al. (2022)	60	Non-defined	The sampling period took place for 3 months. Soil samples were taken from 0 to 400 mm depth at each system. Three sampling locations were selected for each site (inlet, middle and outlet).
Klöckner et al. (2019)	5	5 g (1 g of sediment from each environmental samples)	Particulate samples from 2 road/highway runoff treatment facilities. 1 sample was conducted at the SB, and 2 samples at the SRF. Other 2 samples were taken from the 2 SPs.
Koutnik et al. (2022a)	140	Non-defined	Soil samples collected after a two months dry period, and at 10 cm depth.
Koutnik et al. (2022b)	26	26 g	A total of 14 and 12 samples of the filter media for sand-based BS and soil-based BS respectively. Half of the samples correspond to dry-wet and freeze-thaw cycles.
Olesen et al. (2019)	1	1 to 2 kg	Sediments were collected approximately midways between the inlet and outlet of the pond, from the top 5–8 cm of sediment layer.
Rasmussen et al. (2023)	Non-defined	750 kg	Road dust was collected from seven sites. Total sampled road area was 5300 m^2 and approximately 100 kg of particulate material was sampled per site.
Townsend et al. (2019)	20	10 litres	Composed sample of 500 ml of superficial sediment, taken from inlet, middle and outlet of every wetland.
Yu et al. (2021)	36	60 kg	A total of 5 kg of surface sediment (0 – 6 cm) was collected at the same sampling points and sites of the water samples.
Ziajahromi et al. (2020)	6	6 kg (1 kg wet weight from each sampling point)	Samples taken from the top 5 cm of the bottom sediment at the inlet and outlet, considering 2 replicates.

Table IV.4. Detailed information of samples characteristics in fauna, including number of samples taken, sampled species, and a short description of the procedure.

Reference	No. of samples	Specie(s)	Additional information
Laplaca and van den Hurk (2022)	118	*Micropterus salmoides,* *Gambusia holbrooki,* *Menidia menidia,* *Lepomis spp.*	Information referred only to the stormwater ponds.
Olesen et al. (2019)	Non-defined	*Gasterosteus aculeatus* *Triturus vulgaris*	Fish and newts were sampled in quantities suitable for further analysis. The fish caught were 2 to 6 cm long (average of 4.8 cm and 6.38 g of wet weight). The newts were 5 to 7 cm long with an (average of 5.9 cm and 4.61 g of wet weight.
Su et al. (2019)	180	*Gambusia holbrooki*	Fish individuals caught from nine wetlands, and collected from an approximate depth of 200-500 mm.

Table IV.5. Sieves used in revised literature.

Reference	Sieve
Boni et al. (2022)	250 µm – 500 µm – 2 mm
Coalition Clean Baltic, (2017)	20 µm – 300 µm
Gilbreath et al. (2019)	125 µm – 355 µm – 500 µm – 1 mm
Klöckner et al. (2019)	500 µm
Koutnik et al. (2022a)	2 mm
Lange et al. (2021)	100 µm – 300 µm
Lange et al. (2022)	20 µm – 100 µm
Lange et al. (2023)	40 µm – 5000 µm
Laplaca and van den Hurk (2022)	53 µm – 500 µm
Liu et al. (2019a, b)	10 µm – 500 µm – 2 mm
Mbachu et al. (2022)	300 µm – 4 mm
Olesen et al. (2019)	10 µm – 80 µm – 500 µm
Pankkonen (2020)	90 µm – 300 µm – 1 mm
Smyth et al. (2021)	106 µm – 300 µm – 500 µm – 1 mm
Townsend et al. (2019)	35 µm – 1 mm
Yu et al. (2021)	75 µm for water samples
Ziajahromi et al. (2020)	25 µm – 100 µm – 190 µm – 500 µm

IV.4.3 Sample processing method

Once the sample is sieved and particles are recovered, it is highly desirable to process it in order to facilitate identification and characterization of MPs. Shruti et al. (2021) produced a very illustrative diagram concerning the stages for sample conditioning. A first step is the digestion of the material recovered from the sieves to remove organic matter and open up the matrix. Several digestion procedures have been used in the reviewed studies: H_2O_2 (9 studies), Fenton's reagent (4 studies), enzymatic (1 study), combination of enzymatic and Fenton digestion (4 studies), microwave assisted nitric acid digestion (1 study which used Zn as marker), Sodium Dodecyl Sulfate (1 study), KOH (2 studies), NaOH (1 study) or none (6 studies). In general, H_2O_2, Fenton's and enzymatic digestions, and combinations thereof, are used for water and sediment samples, while alkaline solutions are employed for fauna.

A second step is density separation, in which salt concentrated solutions are used for this purpose. The solutions, and their density, utilized in the reviewed studies were: $ZnCl_2$ (1.5-1.97 g/mL, 5 studies), $CaCl_2$ (1.4 g/mL, 2 studies), NaI (1.59-1.85 g/mL, 2 studies), NaCl (1.2 g/mL, 1 study), mixed salt solution (unknown, 1 study), sodium polytungstate (1.9 g/mL, 1 study), and KI solution (1.68 g/mL, 2 studies). Shruti et al. (2021) recommended the following workflow: sieving – digestion (H_2O_2, 60ºC) – density separation (NaI or $ZnCl_2$) – Fenton's/Enzymatic digestion – filtration. The higher density of $ZnCl_2$ provided better recovery results than NaCl, especially for acrylic, Polyvinyl Chloride and Polyethylene terephthalate (Townsend et al. 2019). However, these recommended denser solutions are discarded by some authors for reasons of toxicity or price, as they are more expensive than common salt or calcium chloride. An alternative to enhance the performance of NaCl or $CaCl_2$ is the addition of $NaHCO_3$, heating and stirring the solution, to facilitate the release of CO_2 bubbles and promote the flotation of denser MPs (Hernández-Arenas et al. 2021).

IV.4.4 Microplastic identification methods

Microplastics identification represent a difficult task in their analysis due to the existence of a wide variety of sizes, shapes, and polymers. Therefore, the MP identification process commonly combines different analytical techniques, based on physical characterization (for example visual identification or microscopy), and chemical characterization, such as spectroscopy (Shim et al. 2017).

Looking at chemical identification procedures, Fourier transform infrared (FTIR) spectroscopy is the most used method (14 studies). It has been noticed that FTIR method is complemented with additional modes when small or irregular microplastics need to be detected. In these cases, authors use both micro-FTIR (μFTIR) to perform microscopic observation of MPs; and attenuated total reflectance (ATR-FTIR) to produce stable spectra from irregular microplastic surfaces. Also, semi-automatic mapping techniques are usually applied to FTIR method. The focal plane array (FPA)-based reflectance imaging method identifies microplastics on larger surface areas and allows reduction of manual effort in the FTIR process (Shim et al. 2017). In some cases, different methods are combined with the objective to cover wider microplastic size ranges and origins in the identification process. Raman spectroscopy is also used (3 studies), particularly convenient for small particles (< 1μm), as it shows better spatial resolution (Sun et al. 2019).

Only 3 studies considered the use of stereo or dissecting microscope for MP identification. Other less common techniques are the selection and quantification of markers. For instance, Klöckner et al. (2019) developed a procedure based on Zn determination after density separation, or thermal extraction desorption gas chromatography-mass spectrometry (TED-GC-MS) (Eisentraut et al. 2018). The methodology is considered a fast process that simultaneously can analyse thermoplastics and tire wear particles, although it cannot provide particle information (number, size, or shape). Koutnik et al. (2022a, b) used an UV–Vis spectrophotometer after colouring MPs with Nile Red in chloroform solution. This method has limitations, as it does not differentiate between types of polymers, and tire particles might not be detected if they do not absorb Nile Red. Another technique to be mentioned, despite it is not used in the reviewed papers, is the scanning electron microscope (SEM), which allows to characterise particles surface and to detect signs of degradation (Chen et al. 2021), so it could evaluate whether physicochemical and biological degradation processes are affecting to retained MPs in SUDS infrastructures.

Some authors have faced the challenge of evaluating tire wear particle content. Despite meeting the International Organization for Standardization's (ISO) description of plastic, elastomers are not considered plastics in ISO's definition because of their reversible elastic deformation (Hüffer et al. 2019). Nevertheless, as they represent a major pollution problem, representing around 60% of MP emissions when considered as MPs, and have synthetic polymers in their composition (Eisentraut et al. 2018), it is desirable to assess them when characterizing urban runoff. However, the identification of tire wear particles is a challenging task. Carbon black, used as a reinforcing filler in tires, absorbs light throughout the infrared region, thus hindering the acquisition of transmission or reflection spectra by FTIR (Liu et al. 2019a, b). For this reason, these authors could not identify car tire rubber in water or sediments. Other identified issues for spectroscopy methods (Raman, FTIR) are the emission of fluorescence, particle burning, uninterpretable spectra, or variability in tire composition, which can include natural rubbers and a host of fillers and property enhancing agents (Eisentraut et al. 2018; Smyth et al. 2021; Werbowski et al. 2021). Smyth et al. 2021 used μFTIR after applying a baseline correction to spectra, as needed. Even so, they could not confirm the chemical composition of rubbery particles. Laplaca and van den Hurk (2022) classified as suspected tire wear particles, those that met certain criteria of colour, shape, texture, flexibility and state of cleanliness.

However, some authors could identify tire and road wear particles (TRWP) using Raman or FTIR techniques (Lange et al. 2023; Grbić et al. 2020; Moruzzi et al. 2020). Two particles were identified as Vine Black or carbon with Raman, and others as Ethylene Propylene Diene Monomer rubber (EPDM rubber) and Ethylene-Vinyl Acetate (EVA) rubber using µFTIR and ATR-FTIR (Grbić et al. 2020; Lange et al. 2023). They assumed that non-identifiable particles came from tires based on their rubber-like texture and elongated shape. Klöckner et al. (2019) developed a method based on the selection of Zn as a marker element of TRWP, consisting of density separation and Zn determination, suitable for samples from high traffic density environments. Eisentraut et al. (2018) simultaneously measured microparticles derived from thermoplastics and tire wear using thermal extraction desorption gas chromatography-mass spectrometry (TED-GC-MS) and selecting decomposition compounds as markers.

IV.4.5 Quality assurance and quality control methods

Quality assurance and quality control usually include measures to minimize and quantify potential contamination, replication of samples and recovery assays to check the performance of the methods used. The main actions to prevent artificial contamination consist of thoroughly rinsing of all materials and equipment, avoiding plastic as much as possible, using cotton lab coats and nitrile gloves, cover filters and samples with aluminium foil and avoid air flows (Shruti et al. 2021). Commonly implemented measures to assess background contamination include the processing of a given volume of deionised water as if it were a sample, covering all steps of both sampling and laboratory treatment (usually referred to as field blanks). Some authors run a second type of blanks including only the steps carried out in laboratory (lab blanks) (Lange et al. 2021). Additionally, it is also advisable to expose wet filters to air during microscopic examination of samples (Lange et al. 2021). The analysis of particles scraped from the equipment used for sampling, or from the SUDS infrastructures, is useful to assess contamination from these potential sources (Ziajahromi et al. 2019; Lange et al. 2021). Finally, recovery assays consist of spiking some clean samples, or samples of known concentration, and analyse them to assess what percentage of the spiked particles is detected. It is advisable to include a variety of polymers, sizes and shapes to be as representative as possible (Townsend et al. 2019; Olesen et al. 2019; Smyth et al. 2021).

IV.5 Occurrence and fate of MPs in SUDS

IV.5.1 Background contamination

Data concerning the background contamination shows high variability, both in the procedure and in the way the results of blanks are reported, as well as in the magnitude of the values measured by the different authors. Several studies reported the blank results in terms of concentration (Olesen et al. 2019; Liu et al. 2019a, b; Smyth et al. 2021; Lange et al. 2022; Boni et al. 2022).

For water, the values varied between 0 and 89 items/L. The minimum value of no particles was found by Boni et al. (2022), who highlighted that it could be related to the fact that they did not target either fibers, particles of size lower than 250 μm, nor non-buoyant MPs because they used NaCl 1.2 g/mL. Ziajahromi et al. (2020) and Werbowski et al. (2021) reported the values in terms of items, obtaining 7 and 13 items in field blanks and 4 and 2 items in laboratory blanks, respectively. Others do not give information about background contamination. Ziajahromi et al. (2020) checked the composition of blank items by FTIR, concluding that they were not plastic. Smyth et al. (2021) did not confirm the lab blank particles as plastic either. In general, fibers accounted for a significant part of blanks items: around 60% (Werbowski et al. 2021), 95% (Smyth et al. 2021) or 25% (Liu et al. 2019a; Olesen et al. 2019).

For sediments, only Liu et al. (2019b) and Olesen et al. (2019) reported blank contamination, obtaining largely different values, 108 and 5000 items/kg respectively (Figure IV.2).

For fauna, Su et al. (2019) obtained a mean level of background concentration of 0.033 items/g or 0.067 items/ind. and a detection rate of 6.67%. Laplaca and van den Hurk (2022) considered 10 procedural blanks, containing an average of 1.1 ± 0.6 MP per blank. In these 2 studies all the results were corrected by subtracting this mean value. In contrast, Olesen et al. (2019) found a concentration several orders of magnitude larger, $5 \cdot 10^4$ item/kg.

Most studies did not correct the sample results, i.e., they did not subtract the values obtained in the blanks. The main reason is the uncertainty on whether all samples were equally contaminated. Blank concentration can be considered as limit of detection instead (Smyth et al. 2021; Miller et al. 2021). In general, none or small contamination from the sampling instrumental was found (Liu et al. 2019a; Lange et al. 2021). Contamination presumably came from the equipment and surrounding air and not from the water used (Liu et al. 2019a). Indeed, atmospheric deposition is a significant source of MPs in urban areas (Koutnik et al. 2022a).

IV.5.2 Microplastics abundance in SUDS

The information gathered from the reviewed studies is shown in Figure IV.1 (water matrix) and Figure IV.2 (sediment matrix). The box-and-whisker plot in Figure IV.1, indicates a high variability of microplastic concentration in water, ranging from less than 1 to 4250 items/L in the inlet of SUDS, and between 0.16 and 335.48 items/L in the outlet or inside the system. Most descriptive statistics (min, mean, median, Q3, max and outliers) decrease from the inlet to the outlet, so it is right to conclude that SUDS develop a significant role in MP pollution control. Indeed, outlet or inside system values, were in the same order of magnitude as background concentration. Studies related to stormwater ponds or wetlands did not analyse inlet and outlet sites, apart from Ziajahromi et al. (2020) and Coalition Clean Baltic (2017). The former, who sampled after a heavy rain event (34 mm/d), found higher concentration (4.0±2.4 items/L) in the outflow than in the inflow (0.9±0.3 items/L), while the latter obtained a decrease in concentration from the inlet (1000-4250 items/L) to the outlet (100-50 items/L) in two stormwater ponds. Higher concentrations in outflows than in inflows, could be related to the first flush effect, as the authors discussed, highlighting the risk of mobilization of MPs previously settled in pond sediments. Nevertheless, it is worth noting that actual pond efficiency should be calculated in terms of load reduction, as in general, these stormwater management systems dampen down both the flow rate and the concentration. In case of BS, abundance of MPs shows a clear decrease from inlet to outlet (Figure. IV.1). Lange et al. (2022) obtained a reduction in particle concentrations from 230 items/L (median particle concentration in stormwater inlet) to 26.5 items/L (median particle concentration in bioretention cell effluent).

It can be considered that inlet concentrations found in the revised literature (less than 1 to 4250 items/L), are representative for urban stormwater if compared with studies focused on stormwater (Järlskog et al. 2020; Shruti et al. 2021; and Zhu et al. 2021). In comparison to treated wastewater concentrations, which vary from 0 to 447 items/L (Sun et al. 2019), MP abundance inside or at the outlet of SUDS, cannot be neglected. Hence, there is room for improvement in the SUDS design to optimise MP retention and to discharge cleaner effluents into downstream environments. Nonetheless, we should recall that outlet or inside samples are at levels similar to blanks concentrations. Some design suggestions are set out in section 7.

Results from Jakubowicz et al. (2022) are not included in Figure IV.1 because they are presented in other units (μg/m^3). They found a significant reduction of MPs from the inlet (0.56 – 104.77 μg/m^3, depending on the polymer) to the outlet (0 – 23.61 μg/m^3) of a multistage constructed wetland.

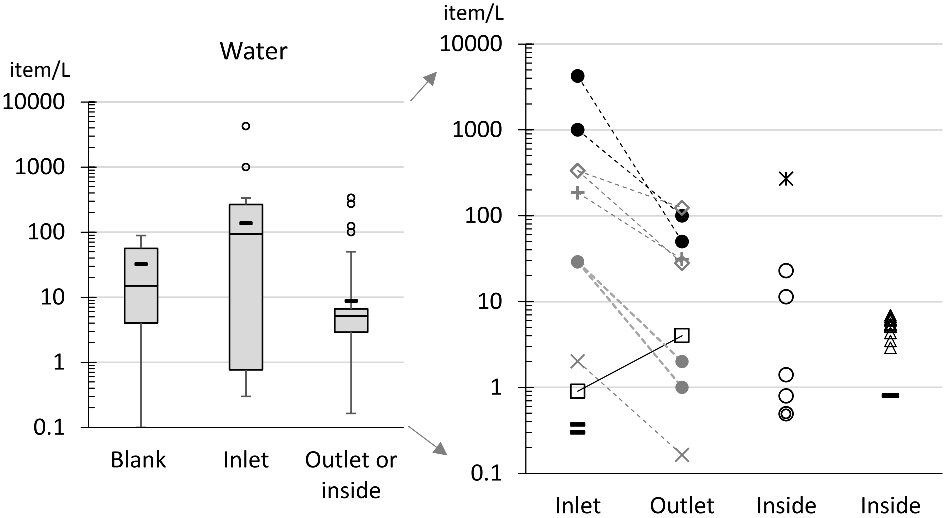

Figure IV.1. Left: box-and-whisker plot of all stormwater data gathered in the review; dots above the boxes are outliers. Right: disaggregated data indicating inlet and outlet, when available, or inside the SUDS systems. Ponds are in black colour, bioretention cells or filtration systems are in grey colour. Different symbols are used for each study: ● Coalition Clean Baltic (2017); ■ Liu et al. (2019b); × Gilbreath et al. (2019); ∗Olesen et al. (2019); •Pankkonen, 2020; □ Ziajahromi et al. (2020); —Boni et al. (2022); ◇ Lange et al. (2021, 2022); + Smyth et al. (2021)[1]; △ Yu et al. (2021). [1]Data consider plastic and non-plastic microparticles.

In sediments or filter media, concentrations also show wide variability and data from different studies tend to be grouped. For instance, sediments sampled by Townsend et al. (2019) and Mbachu et al. (2022), were in the lower range of concentrations (2-180 items/kg), Yu et al. (2021) in the middle; and Liu et al. (2019b), Lange et al. (2023), Rasmussen et al. (2023) and Olesen et al. (2019) reported larger concentrations. Koutnik et al. (2022a) found a wide range of variation (0-$2.8 \cdot 10^6$ items/kg), reporting the highest value among the reviewed studies. The fact that Rasmussen et al. (2023) have all their results in the upper range is because they sampled road dust deposited on the surface of permeable pavements, while the others are sediments inside urban wetlands or bioretention structures, where the road dust washed-off by the runoff is deposited on the bed of these SUDS. Thus, the samples taken from the latter are a mixture of the dust and dirty entering the SUDS with the original clean sediment.

According to spatial distribution of MPs, several authors have addressed the fate of MPs in the studied SUDS (Ziajahromi et al. 2020; Koutnik et al. 2022a; Mbachu et al. 2022; Lange et al. 2023). In general, these studies found that MP concentration was significantly higher in the top layers of sediments or filter media (0-2 or 0-5 cm), and their concentration exponentially decreased with depth (Koutnik et al. 2022a; Lange et al. 2023). Normally, MP and overall plastic concentration decreased from the inlet from the inlet to the outlet (Ziajahromi et al. 2020; Mbachu et al. 2022) although in other cases the distance from the inlet was not significantly influential (Lange et al. 2023). In spite of these findings, the actual fate of MPs cannot be fully determined because of their potential fragmentation into particles smaller than the detection size, as discussed by Lange et al. (2023).

Results from Klöckner et al. (2019) and Eisentraut et al. (2018) are not included in Figure IV.2 as MP or TRWP abundance was expressed in terms of mass (mg/g). The former reported a concentration in a SB of 130 mg/g, which was somewhat higher in the site close to the inlet of a subsequent SRF (150 mg/g). The results significantly decreased along the SRF, reaching 16 mg/g at 35 m to the discharge point. A significant decrease in concentration was also noted at two consecutive SP, from 2.0 to 0.38 mg/g respectively. Important differences in concentration between the two infrastructures are due to different traffic conditions and the surrounding environment. Eisentraut et al. (2018) monitored the same SB as Klöckner et al. (2019) obtaining lower concentrations (less than 1 mg/g and around 9.5 mg/g, depending on the polymer), likely due to the use of different methodology. These concentrations are higher than those reported by Liu et al. (2019b) or Olesen et al. (2019), who estimated the concentration in terms of mass from particles abundance and their density. A possible reason could be that the latter did not identify tire particles and consequently they were not accounted in mass estimation. Rasmussen et al. reported concentration varying between 8.1 and 122.3 mg/kg for MP and between 0 and 2868 mg/kg for tyre wear particles. As counting and spectrometry methods (Raman or FTIR) cannot completely confirm the presence of tyre wear particles, which are abundant in urban runoff, it would be of interest to combine spectrometric and thermal degradation methods.

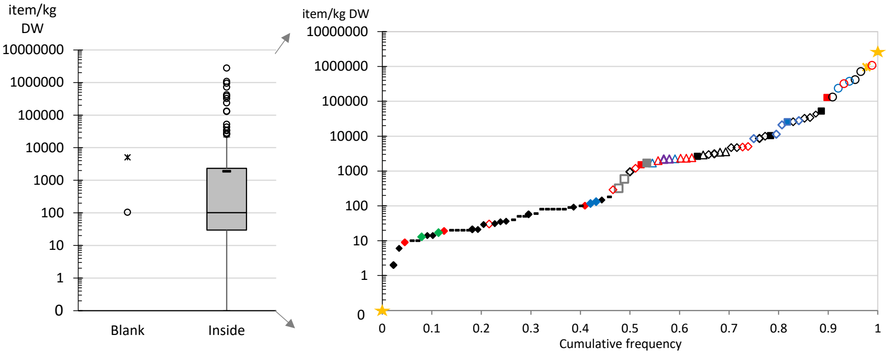

Figure IV.2. Left: box-and-whisker plot of all sediments or filter media data gathered in the review; dots above the box are outliers. Right: disaggregated and sorted data; colours indicate different land uses: residential–black, industrial–red, commercial–blue, highway–grey, open space–green, tourism areas–purple, varied or no specified–yellow. Different symbols are used for each study: ■ Liu et al. (2019b); ✱Olesen et al. (2019); ♦ Townsend et al. (2019, for this study the main land use in each wetland has been indicated in colours); ☐ Ziajahromi et al. (2020); △ Yu et al. (2021); ✶Koutnik et al. (2022a; only min and max are shown); - Mbachu et al. (2022); ◊ Lange et al. (2023); ○ Rasmussen et al. (2023).

Several factors can lead to such large differences in the abundance of MPs: methodological aspects, land use, quantity and quality of inflows, meteorological conditions (rainfall intensity and depth, antecedent dry days, etc.), frequency in urban cleansing, catchment area to SUDS area ratio, age of the SUDS or time elapsed since last dredging or replacement of filter media, wetland hydromorphology (area, depth, hydraulic retention time, etc.), sediment resuspension, or the presence of gross pollutant traps or forebays, among others. Considering all these factors, the only one that can be harmonised across studies is the methodology, which highlights the need for an internationally agreed procedure.

Some authors found a relation between MP concentration in water or sediment/filter media and land uses. However, there is no clear trend when all the data are represented together (Fig. 2). Townsend et al. (2019) reported a negative correlation between proportion of open space and MP concentration in sediments, whilst the correlation with the proportion of industrial area and the dwelling density were positive. These both correlations were confirmed by Werbowski et al (2021), who also showed positive significant correlation between imperviousness and stormwater concentration. Other correlations tested by Townsend et al (2019), such as size or population density, other land uses, and catchment size were non-significant. Yu et al. (2021) obtained the maximum water concentration in a wetland park located in an industrial area. MP concentration declined through three wetland parks connected by a river, suggesting that wetlands effectively removed MPs from water. These authors analysed sediments as well, finding a higher concentration of MPs respect to water. In sediments, the highest concentration was found in a residential area, maybe because these water bodies were closed without external disturbance, thus facilitating sedimentation process. Conversely, water parks connected to rivers or with ornamental fish had less MPs in sediments, indicating a poorer sedimentation process in these cases (Yu et al. 2021). Liu et al. (2019a, b) found a significant correlation between MP concentration in water samples and land use, whereas this correlation did not exist in sediments.

The influence of further variables on MP concentration in water and sediments was evaluated. MP abundance in sediments was positively correlated with hydraulic loading (Liu et al. 2019b). The influence of maximum rainfall intensity was statistically significant if fibers were excluded from the concentration in urban runoff, and antecedent dry days (ADD) also had a positive correlation with runoff microparticle concentration, though it was not statistically significant (Smyth et al. 2021). Other climatic variables analysed by Smyth et al. (2021), such as mean rain intensity, rain duration, rainfall depth, runoff flow rate and volume, were not significantly correlated with microparticle concentration in urban runoff. In contrast, precipitation depth was found to correlate positively with MP load in urban runoff (Piñon-Colin et al. 2020). Werbowski et al. (2021) supported the positive trend between maximum-2h storm intensity and concentration, and the non-dependence on total storm rainfall, contrariwise the correlation with ADD was too weak.

Finally, the influence of SUDS age and the presence of forebays (FB) or gross pollutants traps (GPT) on MP concentration in sediments or filter media has been addressed by some authors (Mbachu et al. 2022; Lange et al. 2023). Lange et al. (2023) found a moderate negative correlation between MP concentration in surface layer of filter media and age, while no correlation was found by Mbachu et al. (2022). Analysing together data from different studies a general positive trend can be observed but with a weak correlation ($r_{Pearson} = 0.23$, $p>0.05$) (Fig. IV.S1). Data from Liu et al. (2019b) present a positive correlation although non-statistically significant ($r_{Pearson} = 0.67$, $p>0.05$). Regarding the presence of FB or GPT, Mbachu et al. (2022) found a strong negative correlation, i.e. the MP concentration in sediments from BRS with GPT were in general lower (Fig. IV.S2). The concentrations measured in sediments from the FB were in general higher than in the filter media, although not significantly different (Lange et al. 2023).

In fauna, Olesen et al. (2019) took samples of three-spined sticklebacks (*Gasterosteus aculeatus*) and young newts (*Triturus vulgaris*) and detected a high concentration of MPs ($3.4 \cdot 10^5$ items/kg; 65 items/ind.). The authors highlighted that sediment and fauna samples were concentrated by several orders of magnitude with respect to the water matrix. Su et al. (2019) sampled *Gambusia holbrooki* from nine stormwater wetlands and analysed head and body separately because the fish size was too small to extract gills and guts. They found that the abundance in the body (0.60 ± 1.33 items/ind.) was significantly higher than in head (0.11 ± 0.44 items/ind.) in terms of items/ind., whereas non-significant differences were found in terms of items/g (1.94 ± 3.82 and 3.10 ± 10.13 items/g respectively). This finding led the authors to conclude that the occurrence of MPs in gills was more random, whereas ingestion could be considered a primary pathway of MP uptake. Moreover, they assessed the influence of gender, size, and weight of fish. The abundance of MPs in body was significantly correlated with size and total weight. Female individuals had more and more diverse MPs in their body than male individuals, which contained almost only fibers. The main explanations given by the authors were that female individuals caught were generally more prominent than male counterparts and that they have different feeding behaviour. Females tend to feed in deeper waters, close to sediments, which are believed to be a final sink of MPs because of settling processes (Su et al. 2019, and Olesen et al. 2019). In the SWPs studied by Laplaca and van den Hurk (2022), an average of 9 items/ind. and 7.9 suspected tire wear particles per individual were accounted.

IV.5.3 Microplastics properties in SUDS

IV.5.3.1 Shapes

The analysis of microplastic particle morphology was conducted in only 13 of the 23 revised studies. Considering the water matrix, fibers were the most dominant shape (Figure IV.3). Generally, when the presence of MPs is analysed in the sediment, fragments are detected in the greatest quantity. This could be explained by the existence of a direct correlation between shapes, materials, size particles, and its ease of being affected by land uses, hydrodynamics, and meteorology, such as wind and rain (Chen et al. 2020). A wider variety of shapes were identified in fauna, which consisted of fibers, fragments, films, pellets and suspected tire wear particles. Only the studies developed by Rasmussen et al. (2023), Jakubowicz et al. (2022), Koutnik et al. (2022a, b), Lange et al. (2022), Pankkonen (2020), Liu et al. (2019b) and Coalition Clean Baltic (2017) did not analyse shape distribution, meanwhile Lange et al. (2023) and Boni et al. (2022) did not quantify MP morphologies detected in their experiments.

Fibers represent a major fraction of MPs, especially in water inlet and outlet (Figure IV.3).

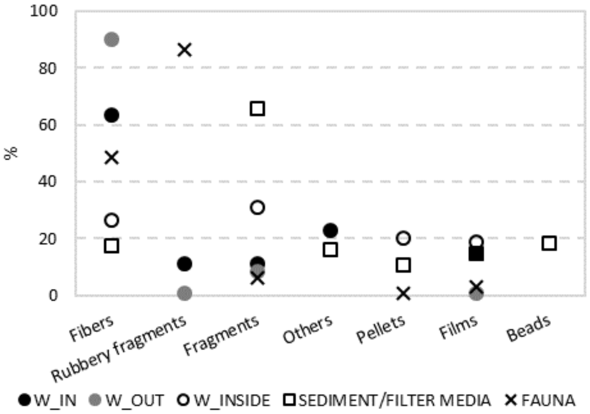

Figure IV.3. Abundance of microplastic shapes found in water inlet (W_IN), inside (W_INSIDE) and outlet (W_OUT), sediment/filter media and fauna samples. Data represent the number of shaped particles, in percent average, from the reviewed studies.

This finding can be related with the generally lower settling velocity of fibers (0.39-6.5 cm/s, Waldschläger and Schüttrumpf, 2019; 0.1-0.55 mm/s, Nguyen et al. 2022), compared to fragments or spheres (0.5-11.2 cm/s and 1.6-18.4 cm/s respectively, Waldschläger and Schüttrumpf, 2019). Furthermore, some factors, such as length, orientation or bending, affect the magnitude of settling velocity for fibers with length between 2 and 6 mm, whereas settling velocity do not significantly depend on their orientation or curliness for short fibers (≤ 1 mm) (Nguyen et al. 2022). These authors found that curliness of fibers longer than 2 mm can hinder settling up to 1.75 times due to an increase in drag force (Nguyen et al. 2022). It is remarkable that these studies focused on fibers longer than 1 mm, so the behaviour of smaller fibers is a research field to cover.

IV.5.3.2 Polymers

In relation to MP composition, all the revised studies considered polymer identification, except Koutnik et al. (2022a, b) and Laplaca and van den Hurk (2022). Petroleum-based plastics, concretely, polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS), polypropylene (PP) and polyvinyl chloride (PVC) were present in a major number of the considered studies. The fact that these polymers were the most abundant, might be because these are the most demanded plastics for human's activities and products, such as food packaging, automotive parts, floor and wall covering, bottles, bags or synthetic textile among others, and thus, degraded and deposited in the environment (Plastics Europe, 2020).

In the water matrix, inlet and inside samples had major presence of PP particles than in outlet samples, in which PE, PET and PP showed similar quantities (Figure IV.4). It is noteworthy that PET is present in outlet samples, even though its density is higher than that of water (Prata et al. 2019). This might be because PET could be in form of fibers, which have a settling velocity lower than fragments or spheres, as explained in the previous section.

Looking at the sediment or filter media matrix, particles of PP were found in major quantities than other polymers. This finding contrasts with the fact that PP is less dense than water (Prata et al. 2019), and therefore tends to float rather than sinking. In this case, physical and biological processes like degradation or biofilm formation on PP particles, may increase particle density and therefore, encourage sedimentation. However, in the case study of Mbachu et al. (2022), low density PE was the most common polymer (50%), followed by PP (34%).

Interestingly, Lange et al. (2022, 2023) found that EVA and EDPM rubber were also frequently observed in highway stormwater, sediment and filter media, which may differ from other studies that did not report results on black particles, possibly due to interferences and difficulties in identifying TWRP, as discussed in section IV.4.4.

According to polymers found in fauna samples, PET was the most frequent. It must be noticed that feeding behaviours of fauna, play an important role in finding different types of MPs. For instance, pelagic fauna would have access to buoyant MPs, mainly PET fibres, while benthic fauna would be exposed to different types of MPs settled in debris (Su et al. 2019).

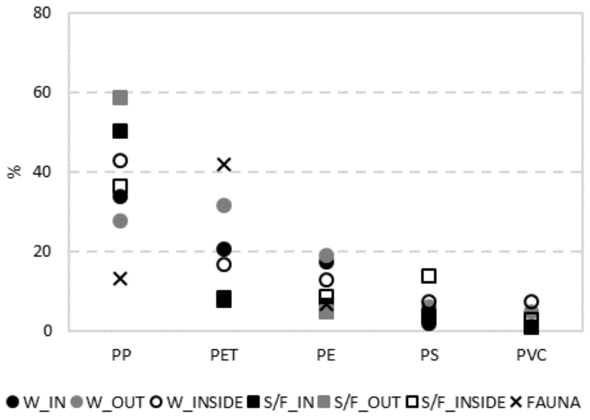

Figure IV.4. Abundance of the five most common polymers found in water inlet (W_IN), inside (W_INSIDE) and outlet (W_OUT), sediment or filter media inlet (S/F_IN), sediment or filter media inside (S/F_INSIDE) and sediment or filter media outlet (S/F_OUT), and fauna samples. Data represent the number of polymer particles in percent average, from the reviewed studies.

IV.5.3.3 Size relation

Distribution of particles by size presents a wide variability according to the fractions considered in the investigations. Going through the selected studies, frequent size sections used to differentiate between smaller and bigger particles were 10 - 500 µm and 500 - 2000 µm respectively. Regarding the sampling matrix, information provided by authors is diverse and not homogeneous enough between studies.

In the water matrix, Coalition Clean Baltic (2017), Jakubowicz et al. (2022) and Lange et al. (2021 and 2022) found that most of the plastic particles were detected in the small size fraction, probably because of a proper sedimentation process of large particles. Lange et al. (2022) also highlight the variability of MP concentration in the small size fraction due to the influence of rain events characteristics. Greatest MP concentrations were captured when high peak flows produced by severe rain events took place. Other authors relate size particle with shapes and polymers. According to Liu et al. (2019a) findings, larger particles were mostly of PP and shaped as fragments, films, fibers, and pellets, whilst smaller particles were predominantly plump ellipsoids. In contrast, Yu et al. (2021), observed that these small plastics were fragments and fibers. Based on the sampling point, Ziajahromi et al. (2020) found that smaller MPs were detected in outlet water samples, while larger particles in the inlet water samples. However, Smyth et al. (2021) and Werbowski et al. (2021) obtained that the most common particles found at both water inlet and outlet of the BS, correspond to small size.

Smaller particles are easier to transport than bigger ones and escape more easily from the retention system.

As it occurs on the water matrix, small plastic particles were predominant in sediment and fauna samples. In case of sediment or filter media, Mbachu et al. (2022) and Liu et al. (2019b) found that small size particles concentration decreased as particle size increased. According to the sampling point, Mbachu et al. detected larger particles in the inlet, than those from the middle and outlet sampling locations. This fact suggests that bigger particles can settle faster, accumulating in the inlet sediment. Additionally, Yu et al. (2021), observed that most of the small particles were fragments and fibers.

In relation to fauna, Laplaca and van den Hurk (2022) and Su et al. (2019) detected that small size particles were prevalent in biota. Looking at Olesen et al. (2019), who sampled the three matrices (water, sediment, and fauna), it was found that particles size in water and its fauna was rather similar, while significantly smaller than in the sediments. This fact can be explained by a fast sedimentation of bigger particles, together with feeding of aquatic fauna of small suspended or buoyant particles.

IV.6 Microplastic retention efficiency of SUDS

According to the analysed literature, it can be strongly believed that SUDS are an effective solution for MP management, in terms of particle reduction from stormwater runoff. Only studies focused on BS, SWP, SF and UPWB provide efficiencies from the experiments, demonstrating very similar high performances in MP reduction.

Gilbreath et al. (2019) estimated a reduction of 91% in average between inlet and outlet of the BS. Further, MP removal efficiencies by particle size were obtained as 100% for MPs >500 µm, 81% for MPs between 355 - 500 µm, and 55% for MPs between 125 – 355 µm.

Over the two-year study period carried out by Smyth et al. (2021), high reductions of microparticle (plastic and non-plastic) load were provided by the BS, ranging from 92% to 100%, considering all sizes together. Sorted by sizes, median microparticle concentrations were reduced by 76% for the 300 – 500 µm size fraction and > 95% for the other three size ranges.

MP tend to accumulate on the surface layers of bioretention filter media (Lange et al. 2023). As part of the stormwater treatment train, the BS studied by Lange et al. (2021 and 2022) showed a removal efficiency of 88%. Comparing performances between the vegetated BS and the other SUDS element of the treatment train, the bioretention area worked significantly better than the SF at particle retention, which efficiency obtained was of 47%. Vegetation probably has positive influence in the MP removal efficiency, but additionally, it also offers multiple benefits such as: carbon fixation, enhanced biodiversity, landscape integration, greater and more varied surface area for biofilm formation (important for biodegradation of organic compounds, and hence greater probability for MP biodegradation), and oxygen supply among others. Very high removal efficiency in SF was obtained by Pankkonen (2020), ranging from 95% (for 90 – 300 µm), 97% (for 300 µm - 1 mm) and 100% (for > 1 mm).

Two studies quantified the performance of SWP for MP retention. Olesen et al. (2019) provided a rough first estimation of the retention efficiency. Despite of an assumed uncertainty in the calculations addressed, the results showed an efficiency of 85%, which is rather similar to particular matter performance in SWP. Hence, it is quite evident that this SUDS technique acts as an important sink of MPs from urban areas. Coalition Clean Baltic, (2017) concluded that SWP could suppose efficient barriers to tackle MP pollution. Efficiencies obtained in MP retention were >90% for 20-300 µm and >73% for >300 µm size fractions.

In the constructed wetland studied by Jakubowicz et al. (2022), the reduction efficiencies ranged from 77.16 to 100% depending on the polymer type. These results contrast to the low efficiency (28%) of the constructed wetland studied by Pramanik et al. (2020). Despite the lack of data to quantify effectiveness of UPWBs to function as sink of MPs, it can certainly be affirmed that sedimentation processes that occur in this SUDS type, provide fundamental basis for MP retention. The presence of these pollutants in the sediment, demonstrates that UPWBs can protect the receiving environments from MP pollution (Townsend et al. 2019; Yu et al. 2021 and Ziajahromi et al. 2020).

IV.7 Future perspectives

Several research fields, addressed so far by one or few studies, have been identified and should be further investigated in the future for better understanding:

- The role of vegetation in MP sequestration.
- The fate of MPs in the vertical and horizontal profiles of sediment or filter material, which can provide information on how incoming pollutant loads have been retained in the system, as well as signs of biodegradation.
- The evaluation of MP concentration in different matrices (water, sediments or filter media, fauna at different levels of the trophic web) to assess potential accumulation and biomagnification processes.
- To expand research on other SUDS techniques such as PPs, vegetated swales or engineered tree pits, among others.

Based on the current state of knowledge, a collection of suggestions to reduce the presence of MPs in the environment are described and encompassed in the following aspects:

IV.7.1 Implementation of smart urban services

The intensification of street cleaning tasks in areas that receive high pollution loads, or the placement of flip-top lids on litter bins to avoid waste blowing. It would be of interest to complement these actions with public awareness campaigns and the regulation of single-use products.

IV.7.2 The study of other SUDS techniques for microplastic retention

Bioretention areas, ponds, or wetlands are the SUDS solutions more deeply studied for MP retention purposes. These SUDS structures provide effective management of first-flush (Andrés-Doménech et al. 2021). However, these events can lead into resuspension of contaminated sediment that reach the structure, with an increase in pollutant load at outflow point (Ziajahromi et al. 2020). An interesting alternative to complement the previous techniques, are vegetated swales. These naturalised channels may provide runoff storage, conveyance, infiltration, and particle settling, based on retention and interception processes (Andrés-Doménech et al. 2021).

Scientific sources reveal that SUDS contribute to remove total suspended solids (TSS) among other pollutants (O Nnadi et al. 2019). This contaminant can be used as an indicator of possible presence of MPs, due to a significant linear correlation found by between these two pollutants (Wang, Q. et al. 2020). Filtration-based SUDS trap pollutants within the aggregate or on geotextile layers, and avoid sediment loads discharges to receiving environment. For example, filter drains could effectively retain MPs from stormwater, as they can reduce TSS by 76% (Andrés-Valeri et al. 2014; Lucke et al. 2014).

Further, multiple studies have verified the effectiveness of permeable pavements (PPs) in TSS removal. According to Kamali et al. (2017), PPs performance can vary between 72% and 100%. Hernández-Crespo et al. (2019) and Fernández-Gonzalvo et al. (2021) demonstrated very high efficiencies up to 99% for TSS retention, even under high degree of pollution build up and intense rainfall. Just one research has put interest in the role that PPs could play as possible sink for MP. In this regard, despite the lack of knowledge in how PPs function and how efficient are, Rasmussen et al. (2023) suggest that the porous structure of PPs could retain a significant fraction of MPs generated on roads.

IV.7.3 Design improvement suggestions

Although the studied SUDS techniques have shown high efficiency in terms of MP reduction, there is still further work to investigate the behaviour and enhancement of these nature-based solutions.

With the aim of reducing floating particles in SWPs and UPWBs, it would be of interest to incorporate vegetation in the design of these structures. For example, consideration of floating macrophytes as complement, following the same line as Ziajahromi et al. (2020). The roots of the plants provide entrapping/filtration of suspended particles and creates laminar flow conditions between the root mat and the bottom and encourage sedimentation processes (Oliveira et al. 2021).

Another suggestion is to implement vegetated or non-vegetated filtration structures at the end of the treatment system, which may retain higher number of floating particles (Townsend et al. 2019). Ziajahromi et al. (2020) propose to investigate the sustainability of construction materials to avoid MP release to the environment, although they did not found evidence of MP pollution derived from the floating plastic structure.

Also, the installation of baffles near the outlet may help to prevent the discharge of buoyant MPs into the receiving environment. Another option to improve efficiency of wetlands or ponds, would be to retrofit them into a treatment train, through the incorporation of an additional SUDS downstream, based on filtration process (bioretention areas, infiltration basins, rain gardens, etc.). In the design phase, the settling velocity of MP fibers should be considered for sizing of sedimentation-based SUDS, provided that space is available.

In relation to improvements on BS, future thoughts might consider the effects of filtering material on clogging, an optimal ponding volume/depth ratio, and even the type of vegetation to incorporate at the bioretention structure, as Smyth et al. (2021) and Lange et al. (2022) suggest. Finally, some authors have observed an insufficient removal of small plastic particles (<100 μm) in GPT and its possible remobilization during rain events (Lange et al. 2022). This may arise in re-thinking the GPT concept, for example, through the incorporation of superficial filtering baffles to trap remobilized particles.

IV.8 Conclusions

Urban runoff is considered an important source of MP pollution. Several types of SUDS have been evaluated in the literature as part of the measures to tackle this worldwide problem. Sedimentation-based systems, such as wetlands or ponds, and filtration-based systems, such as bioretention cells or gardens, have been shown to effectively retain a significant number of MPs.

Indeed, outlet or inside system concentrations are at similar levels to blank concentrations. Nevertheless, it is considered that efficiencies could be enhanced if the retention of MPs was considered as one of the main objectives at the design stage.

Some design improvements are proposed in this paper. Future studies should carry out integrated event samplings to estimate event mean concentrations and total MP loads entering and leaving the systems. PP, PE, PET and PS are the most frequent and abundant polymers in urban runoff, due to high consumption in a wide variety of urban products and activities. Fibers and smaller particles are the most challenging fraction, as their retention efficiency is lower. Maximum rainfall intensity, antecedent dry days, rainfall depth, land use, dwelling density, imperviousness, hydraulic loading, SUDS age, and the presence of forebays or gross pollutant traps have been influential variables on the abundance of MPs in some of the studies, although not always statistically significant.

The assessment of the fate of MPs by some studies indicates that they are more concentrated in the sediment or filter media near the inlet, as well as in the shallower layers, thus indicating that sedimentation and filtration are important retention mechanisms. This, together with the existence of a correlation between total suspended solids and MP concentration, makes TSS a potential indicator of MP pollution. A wide variability in methods and reporting data format has been found. This makes it difficult to process the data together, and draw conclusions about the performance of SUDS systems, or the influence of certain variables. Therefore, there is a need to develop an internationally agreed methodology for MP sampling and analysis in urban runoff and SUDS.

Capítulo V

Control de microplásticos mediante pavimentos permeables

La creciente presencia de microplásticos (MP) en los entornos urbanos ha suscitado especial preocupación por sus efectos negativos en los ecosistemas naturales y en la salud humana. Las escorrentías pluviales, así como el sedimento acumulado en las superficies urbanas, actúan como principales vectores de contaminación por microplásticos de las masas de agua naturales. Conscientes del potencial de los pavimentos permeables en la retención de partículas contaminantes, se evalúa, a escala de laboratorio, el comportamiento de estas estructuras para el control de microplásticos. Las altas eficiencias de retención obtenidas (entre el 89 y el 99.6%), indican que los pavimentos permeables son una potente herramienta para capturar microplásticos. El análisis de la distribución de los microplásticos en las capas de los pavimentos permeables, resalta el papel fundamental que representan tanto la superficie como el geotextil en la retención de este contaminante. Se observa que estas capas son especialmente eficaces al capturar una mayor cantidad de partículas, lo que subraya su relevancia en la gestión de la contaminación por microplásticos. Los fragmentos de tamaño inferior a 0.1 mm fueron los microplásticos más comunes que se detectaron en los efluentes de los pavimentos permeables. Este trabajo pretende avanzar en el conocimiento sobre los complejos mecanismos de movilización de los microplásticos en los entornos urbanos.

García-Haba, E., Benito-Kaesbach, A., Hernández-Crespo, C., Sanz-Lazaro, C., Martín, M. and Andrés-Doménech, I. (2024). Removal and fate of microplastics in permeable pavements: An experimental layer-by-layer analysis. Science of The Total Environment. Volume 929, 172627, ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2024.172627

V.1 Introduction

Microplastics are becoming of increasing concern due to their environmental and human threats. These tiny plastic particles, which can measure up to 5 mm in their longest dimension, have negative impact on the physiology of both humans and marine organisms, causing genetic alteration or behavioural changes (Sharma et al. 2023; Prata et al. 2021; Thompson et al. 2004).

Urban areas constitute an important diffuse source of microplastics as consequence of anthropogenic activities, including wear processes, landfills or sewage treatment among others (Österlund et al. 2023; Qiu et al. 2020). The substantial growth of cities, coupled with the expansion of impervious surfaces, lead to significant alteration of urban catchments and hydrology (Walsh et al. 2012). During rain events, stormwater runoff can mobilise the accumulated microplastic particles (i.e. plastic fragments and fibres, and tire wear particles among others), into receiving ecosystems (Cho et al. 2023; Werbowski et al. 2021), acting as the main driver of this pollutant to water bodies, including rivers ending up in the oceans (Sugiura et al. 2021; Bilkovic et al. 2019; Andrés-Doménech et al. 2018; Pal et al. 2014). Tire wear particles, classified as a subset of microplastics due to their physical and chemical properties, are the result of tread abrasion against the road surface, and represent a major contributor of microplastic emissions to the environment (Knight et al. 2020).

Microplastic removal from stormwater is crucial to mitigate the associated environmental and human impacts (Stang et al. 2022). Conventional drainage systems collect and transport microplastics via storm and combined sewers to the wastewater treatment plant (WWTP). Although microplastics are efficiently captured at this stage, they are transferred into sewage sludge and reach the natural environment via agricultural applications (Calzadilla et al. 2023; van den Berg et al. 2020). In some cases, when the amount of runoff exceeds the capacity of the drainage system, combined sewer overflows (CSOs) occur, and microplastics can be discharged into water bodies without treatment (Zhou et al. 2023; Piñon-Colin et al. 2020).

To reduce these negative impacts, stormwater should be treated before it reaches the aquatic ecosystem (Walsh et al. 2012). Sustainable urban drainage systems (SUDS) are engineered nature-based solutions for sustainable urban stormwater management that deliver multiple benefits, such as water quality improvement, or prevention from urban diffuse pollution among others, promoting several processes such as infiltration, filtration, retention/detention and treatment (García-Haba et al. 2022; Andrés-Doménech et al. 2021). SUDS comprise a wide variety of structures, e.g. permeable pavements, vegetated swales, bioretention structures or constructed wetlands, etc. (Woods-Ballard et al. 2015). Some of them have been studied for their capacity to capture microplastics (Bodus et al. 2024). Sedimentation-based systems, such as wetlands or ponds, and filtration-based systems, including bioretention cells or gardens, have been shown to effectively retain a significant number of MPs within the sediment and the filter media. However, there is still lack of knowledge in the application of SUDS to tackle the problem of microplastics (García-Haba et al. 2023b).

Permeable pavements allow water to soak into its layered structure, where it is temporarily held before it infiltrates into the ground, enters the drainage network, or is harvested for a possible later use (Woods-Ballard et al. 2015). It is widely demonstrated that permeable pavements significantly improve water quality through filtration processes (Hernández-Crespo et al. 2019a; Fernández-Gonzalvo et al. 2021; Razzaghmanesh and Borst, 2019). Despite the limited research to date, these structures seem a promising solution for microplastic retention (Kong et al. 2024; Mitchell and Jayakaran, 2023; Rasmussen et al. 2023). The incorporation of adsorbent materials within the structure of a permeable pavement could help in the retention of microplastics due to their immobilisation capacity in the aqueous phase (Chen, Z. et al. 2022). However, uncertainty remains about the fate of microplastics in the inner layers of permeable pavements, and about the effectiveness of this technology compared to other solutions. Additionally, the underlying migrating processes within the permeable structure are not fully understood (Österlund et al. 2023).

By means of a laboratory approach, this investigation aims to evaluate the efficiency of permeable pavements for the control of microplastic and tire wear particles. The novelty of this study lies in the layer-by-layer analysis of retained microplastics, providing new insights into the mechanistic understanding of micropollutant retention by permeable pavements. This was achieved by simulating synthetic rainfall and percolation processes of surface-accumulated dust and sediment, and the application of real runoff. The incorporation of adsorbent material within a permeable pavement was tested to analyse its influence on the retention of microplastics. Drinking water treatment sludge, combined with granular filter media, was used with the objective of laying the basis for future research.

V.2 Materials and methods

Two experiments (E1 and E2) were accomplished in this research. Information regarding the setup and the specific objectives pursued in each experiment is summarised in Table V.1 below. The details of each experimental configurations are explained within the next subsection.

Table V.1. Summary of characteristics and objectives of experiments E1 and E2.

	Device tested	Permeable pavement configuration	Water management system	Microplastic input source	Rainfall input	Direct runoff input	OBJECTIVES
E1	Infiltrometer 1 Infiltrometer 2 Infiltrometer 3	Configuration 1 Configuration 2 Configuration 3	Infiltration	Dry road dust and sediment	Yes	No	To study the influence of the type of surface pavement layer, and an adsorbent material (DWTS) on microplastic retention.
E2	Storage tank	Configuration 1	Harvesting	Real urban runoff	Yes	Yes	To study the influence of the microplastic input source, and the structural configuration on microplastic retention.

V.2.1 Materials

V.2.1.1 Infiltrometer 1, 2 and 3 setups (experiment E1)

Each infiltrometer was composed of three main parts: input setup, permeable pavement structure, and output setup (Figure V.1). The input setup comprises a rainfall simulator (Rodriguez-Hernandez et al. 2016), composed of a water supply tank, two peristaltic pumps (LLG-uniPERISTALTICPUMP 3), and a grid of drip irrigation pipes with a plastic mesh to break rainfall drops (Naves et al. 2020).

The permeable pavement structure (50 cm wide and 50 cm long) is placed 40 cm below the rain simulator and is assembled inside a 0.25 m^2 bottomless plastic chamber. The cross section was defined according to Woods-Ballard et al. (2015): surface, base, and sub-base. Three different surface configurations were tested. Configuration 1 consists of permeable interlocking concrete pavement (PICP) using fine gravel (3-6 mm) as joint filler; configuration 2 consists of PICP but considering a mixture of 80% fine gravel and 20% drinking water treatment sludge (DWTS) in the joint filler, hereafter PICP-DWTS (García-Haba et al. 2021a); and configuration 3 consists of porous concrete pavement (PCP).

Each permeable pavement structure had the same base and sub-base layers, consisted of fine washed gravel (2-4 mm), and coarse washed gravel (25-40 mm) respectively. The permeable pavement structure is supported on a 52 mm thick drain cell and includes nonwoven polypropylene-based geotextile (thickness of 0.15 mm, opening size of 0.09 mm, and vertical permeability of 90 mm/s) between base and sub-base, and between sub-base and drain cells for separation/retention purposes (Figure V.1).

For the output setup, infiltrated water is collected through a receiving stainless-steel hopper, and a precision balance (611-2299 VWR) is placed below each infiltrometer to measure the infiltrated water volume. Distance between hopper and sampling glass was approximately 20 cm.

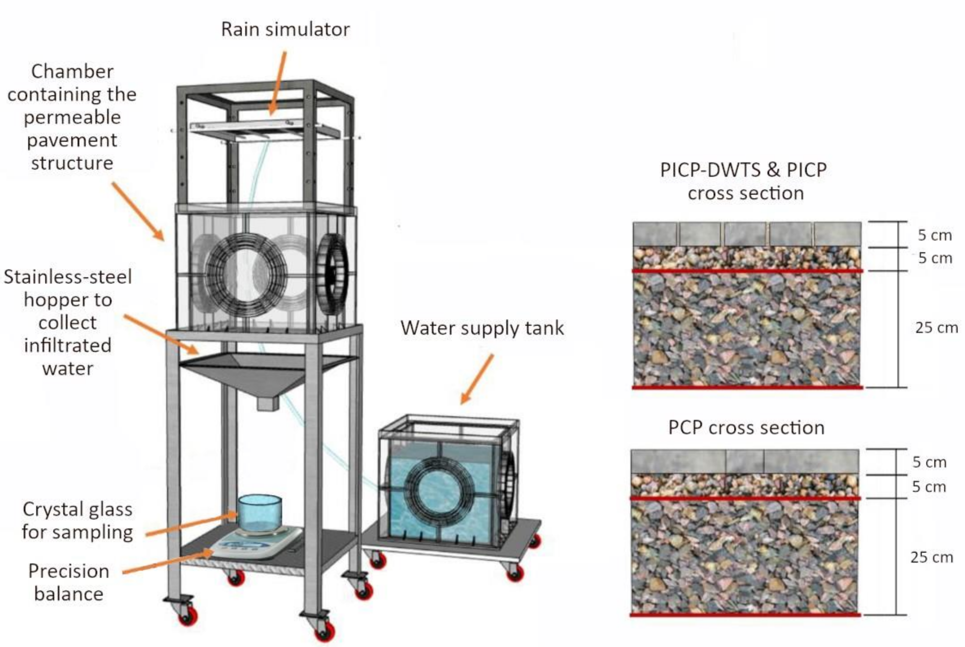

Figure V.1. Scheme of permeable pavement infiltrometer setup (input setup, permeable pavement structure and output setup) and cross sections. Geotextiles are represented as horizontal red lines (adapted from Fernández-Gonzalvo et al. 2021).

V.2.1.2 Storage tank setup (experiment E2)

The experimental setup of the storage tank follows the same pattern as configuration 2 in experiment E1, except that only 1 geotextile was placed between fine gravel and coarse gravel layers, as no free infiltration was allowed (Woods-Ballard et al. 2015). A drainpipe was included at the bottom of the system to allow water extraction and level regulation inside the storage tank (García-Haba et al. 2021b).

Figure V.2. Details of the storage tank setup and cross section. Geotextile is represented as horizontal red line. Own elaboration.

V.2.1.3 Road dust and sediment (experiment E1)

To simulate street pollution build-up in E1, real dry dust and sediment was collected from an intense traffic road within the campus of the Polytechnic University of Valencia (UPV) (Fernández-Gonzalvo et al. 2021; Andrés-Doménech et al. 2018). Samples were collected by mechanical vacuum-sweepers (Yang et al. 2022) and sieved to a size of 5 mm.

V.2.1.4 Rainwater (experiments E1 and E2) and stormwater runoff (experiment E2)

To simulate rainwater in experiments E1 and E2, deionised water was used (10 µS/cm and pH of 7.1), given its analogous properties to the analysed rainwater in the Valencian region (Perales-Momparler et al. 2017). Regarding runoff, real samples from rain events were collected by an automatic sampler (ISCO3270), equipped with a liquid detector and a set of 24 1-litre bottles from a small impervious urban catchment (Andrés-Doménech et al. 2018). This runoff was a direct surface input in experiment E2.

V.2.2 Methods

V.2.2.1 Rainfall simulation (experiments E1 and E2) and pollution build-up (experiments E1)

A long-term simulation period encompassing progressive pollution build-up in the permeable pavements under dry-rain conditions was conducted (Fernández-Gonzalvo et al. 2021). The simulated rainfall reproduced the average regime of Valencia (Spain): events with a rainfall volume of 16 mm and 30 min duration (32 mm/h) (Andrés-Doménech et al. 2010), whereas pollution build-up was simulated by means of manual dispersion of dry dust and sediment on the pavement surface. A visually uniform and homogeneous layer of sediment was formed, so that the sediment percolation was as regular as possible. A deposition rate of 5 g/m^2/d was selected according to Hernández-Crespo et al. (2019). The simulation process consisted of the application of dust on each permeable pavement and later the rainfall simulation. This process was carried out every 2 weeks for a 2-year period for PICP-DWTS and PICP infiltrometers, and a 5.5-year period for PCP. After each simulation process, the stainless-steel hopper was thoroughly rinsed with deionised water to ensure that any potential adhering microplastics were included in the infiltrated water.

V.2.2.2 Operation of the storage tank (experiment E2)

During a four-month period, the operation procedure consisted of two main processes: filling of the storage tank with direct rainwater and real runoff, and water extractions from inside the storage tank (Figure V.S4 of the Supplementary Material[3]). The filling process took place when a rain event occurred. The methodology consisted of gradually application of runoff and rainwater volumes onto the pavement bricks. A glass vessel was used to ensure uniform distribution, thus mitigating the risk of excessive washing of sediment accumulated on surface during previous filling processes. Entered rainfall and runoff volumes corresponded to those monitored within the campus catchment (Andrés-Doménech et al. 2018). Water extractions represented filtered effluents through the permeable pavement structure. Water extractions simulated a fictitious regular and cumulative demand for irrigation water, alongside potential overflows that may occur as consequence of a complete filling of the tank. Water abstractions for irrigation were carried out every 2 weeks, and represented the accumulated water volume demand for irrigation over the two-week interval. The irrigation volumes were estimated as function of rainfall records and the potential evapotranspiration rate recorded at a nearby meteorological station. Occasionally, overflows occurred when the water level exceeded the surface layer after the filling of the tank. The excess water was then withdrawn through the drainpipe until it equilibrated with the uppermost level of the surface layer (see Figure V.S4). The water extractions were carried out by gravity through the drainpipe, by simulating small discharge flows to avoid the dragging of solids that could enter a hypothetical pipe network, and consequently, cause blockages.

V.2.2.3 Sample collection

The microplastic sampling campaign for E1 started in January 2022 which means 1 year after the start of the experiment for PICP-DWTS and PICP infiltrometers, and 5 years after for PCP. Samples of infiltrated water were immediately taken after a simulation process, using 2 litre glass beakers for collection. In total, 6 effluent samples were taken from PICP-DWTS and PICP configurations, and 9 from PCP. Volumes of sampled effluents ranged between 300 and 700 ml.

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[3] Material suplementario del Anexo 1.

In relation to E2, a total of 11 water extractions took place. Therefore, 11 samples were taken. It is important to notice that only 2 of them corresponded to overflows. The small number of overflow samples represent a limitation of the study. A 1 litre sample from every water extraction was taken and analysed. A metal bucket was used for water collection. Samples of water extractions were immediately taken after the discharge process.

At the end of the experiments, the permeable pavement structures were disassembled, layer by layer. Retained dust and sediment on the surface was collected with a vacuum cleaner and processed as solid matrix. To mitigate the risk of cross-contamination between samples, the vacuum cleaner was rinsed with ultrapure water following each sampling to ensure that any adhering microplastic was included in the samples. MPs retained in granular layers were washed-off using deionised water. Washing water was then filtered through a 40-µm sieve. If the solid content intercepted in the sieve was abundant, it was processed as solid matrix. Otherwise, the sieve was washed with deionised water and the sample was processed as liquid matrix. Geotextile layers were wrapped in aluminium foil for subsequent visual inspection.

V.2.2.4 Sample processing and analysis

V.2.2.4.1 MP extraction

Liquid samples (stormwater runoff and, infiltrated and extracted water) were filtered through glass fibre filters with a nominal pore size of 1.2 µm and diameter 47 mm. For solid matrices, a pre-treatment was applied to remove organic matter, while minimizing alteration of MPs. The pre-treatment consisted in two digestions. For the first digestion, 150 ml of an acidic oxidant solution (H_2SO_4 1:1 H_2O_2), that do not alter the chemical structure of microplastics (Hernández-Arenas et al. 2021), was slowly added to sediment subsamples (5-10 g). To prevent the sample from burning due to the exothermic reaction produced when the solution contacts organic matter, it was added in 10 ml fractions every 30 minutes. Once all the reagent was added, it was left to react for 72 hours in a gas chamber. Then, the solution was filtered, and a second digestion was performed with Fenton reagent, which produces an advanced oxidation process using H_2O_2 in the presence of a catalyst (Fe^{2+}). The Fenton reagent does not produce chemical or morphological changes in different polymers (Pfohl et al. 2021), being a suitable reagent for the extraction of microplastics from a solid matrix. During the addition of the reagent, an ice bath was used to keep temperature below 40 °C (Hurley et al. 2018). Once the Fenton was added, the samples were mixed at 100 rpm for 5 days to ensure that all the organic matter of the sample was in contact with the reagent. Subsequently, they were left in the oven at 45 °C for 4 days.

Afterwards, MPs were extracted by density separation using NaCl at saturation. The selected salt was NaCl, (with a concentration of 322 g/L and a density of 1.2

g/cm^3) due to its low cost and lack toxicity (Bellasi et al. 2021). This method allows settlement of the sediment to the bottom of the beaker and promotes microplastic flotation. Once the saturated solution was added to the previously digested sample, the mixture was stirred with a stirring rod to ensure a homogeneous distribution of microplastics. After that, the sample was left to settle for 24 hours to ensure that separation between inorganic matter and MPs occurred. Then, the upper part of the water column was filtered ensuring their extraction, following the liquid matrix process. The extraction process was repeated four times. To improve the recovery rate of MPs of high dense particles in every sample, sodium bicarbonate was added only in the fourth extraction, promoting flotation of microplastics via CO_2 bubbles release (Hernández-Arenas et al. 2021). This method was validated in previous works, with a recovery percentage of 87 ± 2% (mean ± SE) (Hernández-Arenas et al. 2021), being efficient in the extraction of microparticles of Polypropylene (PP), Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE), and Polyethylene Terephthalate (PET), which are the most commonly used plastics worldwide (Plastics Europe, 2022) and expected to be found in this study.

V.2.2.4.2 Polymer identification and size estimation

All filters (from both liquid and solid matrices) were visually analysed using a stereomicroscope (MOTIC SMZ 143 N2GG, Wetzlar, Germany) coupled to an integrated camera to select potential microplastics. This combined equipment achieves a maximum resolution of 10-20 µm. Identified particles counted as possible microplastic were analysed with Raman spectroscopy. The laser excitation frequency and intensity used were 784.79 nm and 11.8 mW, respectively. Raman spectra were recorded with a charge-coupled device camera (UV-NIR range, 1024 × 255 pixels) electrically cooled to -70°C. Raman spectra were obtained in the range 162 - 1886 cm^{-1} with a spectral resolution of 2.47 cm^{-1}.

To determine whether the material of identified particles was plastic, polymer spectra obtained from the Raman spectrometer (NRS-5100, Jasco) and from the Open Specy 55 spectral library were compared (Cowger et al. 2021). Special attention was paid to tire wear particles due to its high presence in the samples. To ensure the correct identification of this type of microplastic, samples from different tires and different levels of wear were previously analysed by means of Raman spectroscopy and added to the library used for polymer identification. Two factors were considered to perform the classification: the similarity degree between the two spectra, expressed as the coincidence factor R (Huppertsberg and Knepper. 2018), and the coincidence between the main bands of both spectra. The closer the value of R is to 1, the closer the spectrum of the analysed particle resembles the spectrum of a plastic type in the database. When $R > 0.7$ the correlation between the two spectra is considered as high. However, it might occur that although the R value is low (< 0.7), the particle is made of the plastic material of the reference spectrum in the database. Microplastics in the environment suffer weathering which results in the modification of their original spectrum, which is used as their fingerprint by spectroscopic equipment such as Raman to identify its polymeric composition. Additionally, some materials may be made of a composition of several types of plastic. In these cases, the assignment of the tentative particles to virgin (non-weathered) plastics is hindered. To overcome this issue, SLoPP and SLoPP-E databases, which contain spectra of degraded polymers (Munno et al. 2020), were used. Spectra of all microplastic particles detected in the study are available upon demand.

To estimate the size of all the particles analysed, a Java-based public domain image processing software developed by the U.S. National Institutes of Health (ImageJ) was used (Rosal, 2021). Size ranges of < 0.1 mm; 0.1 - 0.5 mm; 0.5 - 1 mm and 1 - 5 mm were considered for microplastic identification. The smallest identified microplastics measured 10 µm in size.

Microplastic identification from geotextile samples was visually performed using a stereomicroscope with augmentations ranging from x20 to x40 (SZ30, Olympus, Japan). Only the morphology of the particles detected was estimated. It is worth noting that the microparticles detected in the geotextiles were not confirmed as microplastics through spectroscopy, unlike those detected in other layers of the permeable pavement. Instead, "The Hot Needle Test" was used as an alternative identification method (De Witte et al. 2014).

V.2.3 Quality assurance and quality control

Quality control management was carried out during the whole experiments. Cross-contamination of samples was minimised by using aluminium and glass material that had been cleaned with ultrapure water, cotton laboratory coats and, whenever possible, clothes that were made of natural fibres. Additionally, containers holding the samples were covered to prevent airborne contamination of microplastics (Krüger et al. 2020). The NaCl solution was always previously filtered to remove any possible microplastics in the salt. Blanks from the laboratory environment and from component materials of permeable pavements were analysed (Table S6). However, they have not been considered to correct the sample results due to uncertainty regarding whether all samples were equally contaminated. Samples of plastic materials involved in the experiments, including the geotextile, were analysed with Raman and spectra were added to the database in order to detect contamination generated by them. No particles from these materials were found.

V.2.4 Statistics

Statistical analyses were performed using STATGRAPHICS Centurion 19 (version 19.1.2). The effects of the permeable pavement configuration (PICP-

DWTS, PICP and PCP) on microplastic levels at infiltrated water was studied. ANOVA test was used if normality was satisfied whereas Kruskal-Wallis was used for non-normal distributions.

Furthermore, the assessment of the impact of permeable pavement layers on the internal accumulation of MPs was accomplished by comparing microplastic retention percentages within each layer, considering that vertical profiles were related samples. In this case, t-student test was used if normality was met and Wilcoxon model otherwise. Statistical significance was indicated by a probability of a type I error of 5% or less ($p \leq 0.05$).

No comparison was undertaken between storage tank and other setups due to dissimilarities in their operational procedures. To measure the relationship between accumulated sediment on the pavement surface and microplastic levels in infiltrated water, linear correlations between variables were obtained using either Pearson correlation coefficient (for normal distribution variables) or Spearman correlation coefficient (for non-normal distribution variables). It was assumed that correlation coefficients were statistically significant with a probability of a type I error of less than 5% ($p \leq 0.05$).

V.3 Results and discusión

V.3.1 Levels and characterisation of MPs in road dust and sediment

Average level of microplastics in road dust and sediment was 4762 ± 974 MP/kg (n=3). Similar results were reported by other studies that also studied microplastics in road dust: 2279 ± 914 MP/kg, n=3 (Patchaiyappan et al. 2021); and from 2777 ± 333 to 20167 ± 333 MP/kg (Dehghani et al. 2017).

Polymers found were PET, Polymethylstyrene (PMS), Polyester, PP, Polyvynyl Chloride (PVC) and Polyvinyl alcohol (PVOH), where PP (75%) was the most prevalent (Figure V.3). This is consistent with the polymers demanded by markets, mainly for household and industrial purposes (Plastics Europe, 2022; Monira et al. 2021).

In relation to morphology, fragments were the most common shape (90%). This finding is also in line with Patchaiyappan et al. (2021) (92.5%) and Dehghani et al. (2017) (65.9%). Fragment type microplastics usually originate from the decomposition plastic waste, or from the wear and tear of plastic products (Grbić et al. 2020). Looking at size levels, most of the particles were classified in the smallest size fraction (86%).

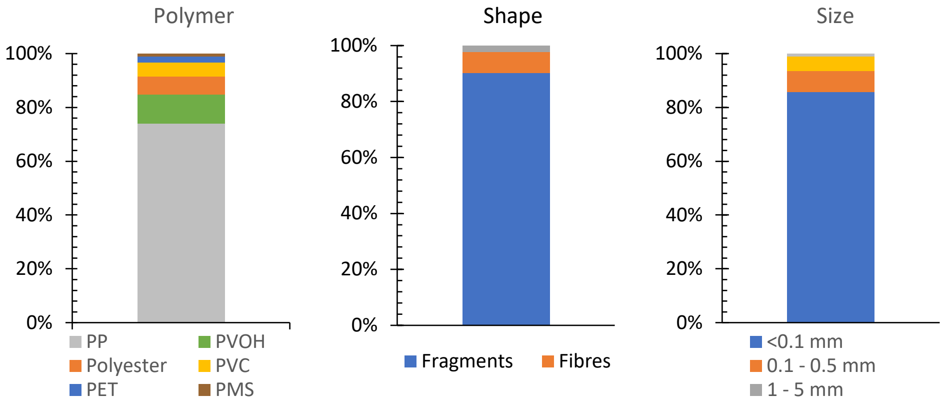

Figure V.3. Microplastic distribution in road dust and sediment, according to polymer, shape and size in average percentage. Total sampled dry weight= 19.35 g (n=3).

V.3.2 Levels and characterisation of MPs in stormwater runoff

Microplastic levels in the stormwater runoff samples greatly varied from 2.00 to 110.59 MP/L (Table V.S4). Previous studies that also investigated the presence of microplastics in stormwater runoff, show a significant variation in microplastic levels, ranging from less than 1.00 to 8550 MP/L, due to differences in catchment land uses, rainfall intensities and duration, and methodological procedures, making comparison difficult (Wang, C. et al. 2022).

In average, runoff MPs level was estimated at 23.90 ± 17.40 MP/L (n=6), which is similar to that determined by Ross et al. (2023), who obtained a mean of 31.90 ± 34.00 MP/L (n=7), in the analysis of stormwater runoff samples from different types of urban catchments.

Polymers detected were PP (62%), PVOH (23%), PVC (6%), Polyester (4%), PMS (2%), HDPE (2%), PET (1%) and Acrylonitrile Butadiene Styrene (ABS) (0.1%) (Figure V.4). With respect to morphology, fragments represented the highest fraction (84.7%). Other authors such as Chen et al. (2022) and Sang et al. (2021) also detected fragments as the most common shape in road runoff. Regarding to size, most of the particles were within the 0.1 – 0.5 mm range (61.3%).

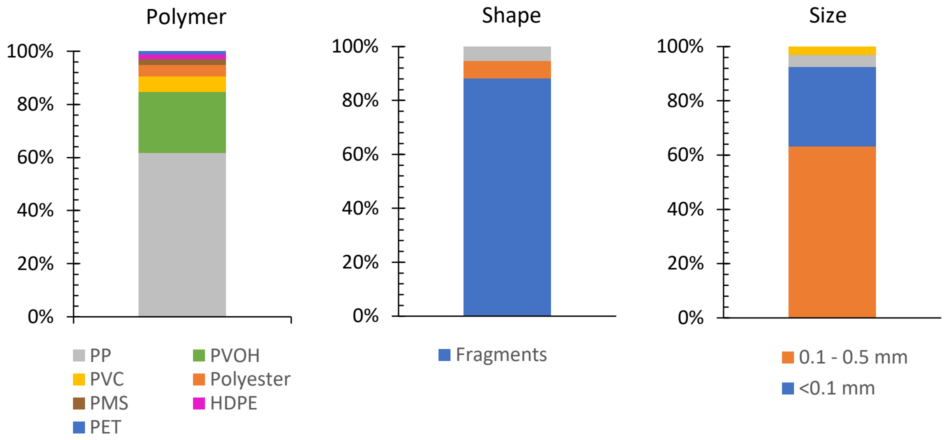

Figure V.4. Microplastic distribution in stormwater runoff according to polymer, shape, and size in average percentage. Total sampled runoff= 153 litres (n=6).

V.3.3 Levels and characterisation of MPs in infiltrated water

V.3.3.1 Infiltrometers (experiment E1)

Estimated average microplastic levels in the infiltrated water through PICP-DWTS, PICP and PCP were 2.22 ± 1.03 MP/L (n=6), 2.99 ± 1.00 MP/L (n=6) and 5.17 ± 1.05 MP/L (n=9) respectively. No significant differences in output microplastic levels between infiltrometers were detected ($p>0.05$), and no correlation between surface dust and sediment accumulation and microplastic abundance in the effluent of every infiltrometer was found: PICP-DWTS ($r=0.10$; $p>0.05$); PICP ($r=-0.19$; $p>0.05$); PCP ($r=0.44$; $p>0.05$).

Similar percentages of fibres, films and fragments were released from PICP-DWTS (39.3%, 35.7% and 25%) (Table V.1). In PICP, fragments and fibres were prevalent (46.4 and 44.3%). In case of PCP samples, the highest microplastic shape proportion corresponded to fragments (89%). Regarding to size, most of the particles released in PICP and PCP effluents were below 0.1 mm (55.7 and 81.4% respectively), while 0.5 – 1 mm particles were prevalent in PICP-DWTS (64.3%). The higher proportion of intermediate-sized particles escaping from PICP-DWTS, mostly represented by fibres, can be attributed to their perpendicular alignment with the filtering matrix, enabling passage through the layers due to their smaller diameter compared to their length (Choi et al. 2021).

From the results, it seems that permeable pavement structures present difficulties at retaining the smallest size fraction and fragment shaped particles (Table V.2). This is particularly noticeable in PCP configurations. This fact suggests that the permeable surface configuration could influence on retained particle characteristics. For example, PCP are much better than PICP at stormwater treatment as consequence of a smaller porous structure (Kuruppu et al. 2019 and Lucke and Beecham, 2013).

Comparable microplastic levels at PICP-DWTS and PICP effluents might suggest that DWTS does not have influence in microplastic capture. This result is surprising since recent studies reported that reactive porous media have positive influence on the removal and immobility of microplastics (Abuwatfa et al. 2021). Retention efficiencies higher than 95% were obtained for Polystyrene (PS) spheres (1 – 10 μm), Polyethylene (PE) cylindrical fragments (2 - 3 mm) and fleece fibres, using biochar with pore sizes ranging from < 2 to 50 nm (Wang, J. et al. 2021; Siipola et al. 2020; Wang, Z. et al. 2020). It is plausible that the proportion of DWTS used was insufficient to capture significant amount of particles.

Table V.2. Microplastic proportions and levels according to polymer, shape and size identified in permeable pavement effluents (percentage and mean concentration ± standard error). Percentage refers to sampled effluent volumes. Empty cells represent that no MPs were detected.

	PICP (n=6) Experiment E1, config. 1		PICP-DWTS (n=6) Experiment E1, config. 2		PCP (n=9) Experiment E1, config. 3	
Polymer	MPs proportion (%)	MP level [MP/L]	MPs proportion (%)	MP level [MP/L]	MPs proportion (%)	MP level [MP/L]
ABS	9.3	0.27 ± 0.30			3.5	0.18 ± 0.18
LDPE			12.5	0.27 ± 0.27		
PET	9.3	0.27 ± 0.30	12.5	0.27 ± 0.27	3.6	0.18 ± 0.18
Polyester	9.3	0.27 ± 0.30	26.8	0.59 ± 0.37	3.5	0.18 ± 0.18
PMS	9.3	0.27 ± 0.30			10.7	0.55 ± 0.39
Polyphenylsulfone			12.5	0.27 ± 0.27		
PP	27.9	0.83 ± 0.62	35.7	0.79 ± 0.55	54.3	2.80 ± 0.67
PVC	9.3	0.27 ± 0.30				
PVC+PP	16.4	0.49 ± 0.53				
PVOH	9.3	0.27 ± 0.30			24.3	1.25 ± 0.91
Shape						
Films			35.7	0.79 ± 0.55		
Fibres	44.4	1.32±0.69	39.4	0.87 ± 0.39	11.4	0.5 9± 0.29
Fragments	46.5	1.38±0.56	24.9	0.55 ± 0.35	88.6	4.58 ± 1.08
Pellets	9.1	0.27±0.30				
Size						
< 0.1 mm	55.7	1.66 ± 0.66			81.4	4.21 ± 1.05
0.1 - 0.5 mm	9.3	0.27 ± 0.30	35.7	0.79 ± 0.55	3.6	0.18 ± 0.18
0.5 - 1 mm	9.3	0.27 ± 0.30	64.3	1.42 ± 0.79	11.5	0.59 ± 0.29
1 - 5 mm	25.7	0.76 ± 0.56			3.6	0.18 ± 0.18

V.3.3.2 Storage tank (experiment E2)

Average MPs level in water extractions for irrigation was estimated at 2.00 ± 0.73 MP/L (n=9). PP particles represented once again the highest fraction (44%) (Figure V.5). Fragments represented 61.6% of the particles, followed by fibres (31%) and films (7.3%). In relation to size, small MPs (< 0.1 mm) were predominant (55.2%). Similar percentages were estimated between the size ranges 0.1 – 0.5 mm (13.7%), 0.5 – 1 mm (10.1%) and 1 – 5 mm (21%). In case of water overflows, average MPs level was estimated at 3.08 ± 0.42 MP/L (n=2). Polyester was the most frequent polymer (38%), followed by PP (27%). Only fragments and fibres were present in the overflows (51% and 49%), and predominant sizes were < 0.1 mm (43%) and 1 – 5 mm (41%).

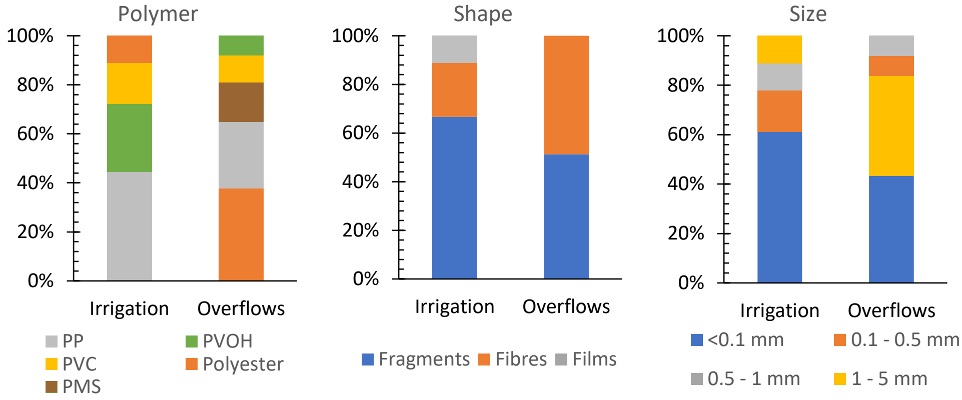

Figure V.5. Microplastic distribution in water extractions from the storage tank for irrigation (n=9) and in storage tank overflows (n=2) according to polymer, shape, and size in average percentage.

V.3.4 Microplastic retention efficiency, accumulation and fate of MPs retained within the permeable pavement layers

V.3.4.1 Infiltrometers (experiment E1)

A total of 4345 microplastic particles were estimated as input in both PICP-DWTS and PICP infiltrometers, and 11030 MPs in PCP. No significant differences were detected in the quantity of MPs retained within all permeable pavement infiltrometers (p>0.05). The number of MPs in the permeable pavement outputs were estimated at 145 (PICP-DWTS), 186 (PICP) and 1240 (PCP). Hence, estimated retention efficiencies of the permeable pavements were 96.7% (PICP-DWTS), 95.7% (PICP), and 88.8% (PCP). The lack of similar studies to compare these results with other authors findings, suggests looking at similar indicators such as TSS, which have a strong correlation with MPs (Wang, Q. et al. 2020). TSS retention efficiencies in permeable pavements have been reported from 91 to 96% (Zheng et al. 2022); 70 to 80% (Liu W. et al. 2020); up to 99% (Hernández-Crespo et al. 2019a); and 100% (Kamali et al. (2017).

Significant amount of MPs was accumulated on permeable pavement surfaces over the other layers (Figure V.6.). This finding is directly related to sediment accumulation, as consequence of the formation of an impermeable matrix or "crust", which is generally limited to the upper few centimetres of the surface structure (Brown et al. 2009; James, 2004; James and Gerrits, 2003; Pratt et al. 1995; Baladès et al. 1995). Therefore, surface sediment accumulation might be considered as an integral component of the permeable pavement system's retention efficiency as it can be effectively removed by cleaning services.

Although this study did not characterise the porosity of the permeable joint in the PICP or the porous surface of the PCP, it is thought that the pore size of the latter is generally smaller than in the permeable joint (Figure IV.S3). This fact suggests that PCP can be more easily clogged by small particles and contributes more than PICP to the formation of the "crust" previously commented. This hypothesis is plausible since fine sediments are prone to cause permeability loss in porous asphalt (García-Haba et al. 2023a).

In this study, identified microplastic sizes are grouped in the mentioned size ranges, and consequently, might contribute to the clogging process of PCP (Rasmussen et al. 2023). The high proportions of fragments observed in the accumulated dust and sediment (89.7% in PICP-DWTS; 91.4% in PICP; and 81.4% in PCP) could be attributed to the morphology itself. Fragments, which are generally angular shaped, might be susceptible to get trapped by other particles contained in the sediment, resulting in a barrier effect on MPs to enter the system.

In the inner structure, geotextiles play a major role in microplastic retention compared to other layers, more specifically for fibres capture. Upper geotextiles captured 38.1% (PICP-DWTS), 35.3% (PICP), and 14.7% (PCP), whereas lower geotextiles retained 13.7% (PICP-DWTS), 19.1% (PICP), and 5.2% (PCP). Fibres were the most frequent shape retained in the geotextiles installed in PICP based infiltrometers, while fibres and fragments were found in equal proportions in PCP. This result agrees with previous studies wherein geotextiles improved TSS removal efficiency in permeable pavements by about 30% (Kamali et al. 2017; Rowe et al. 2009).

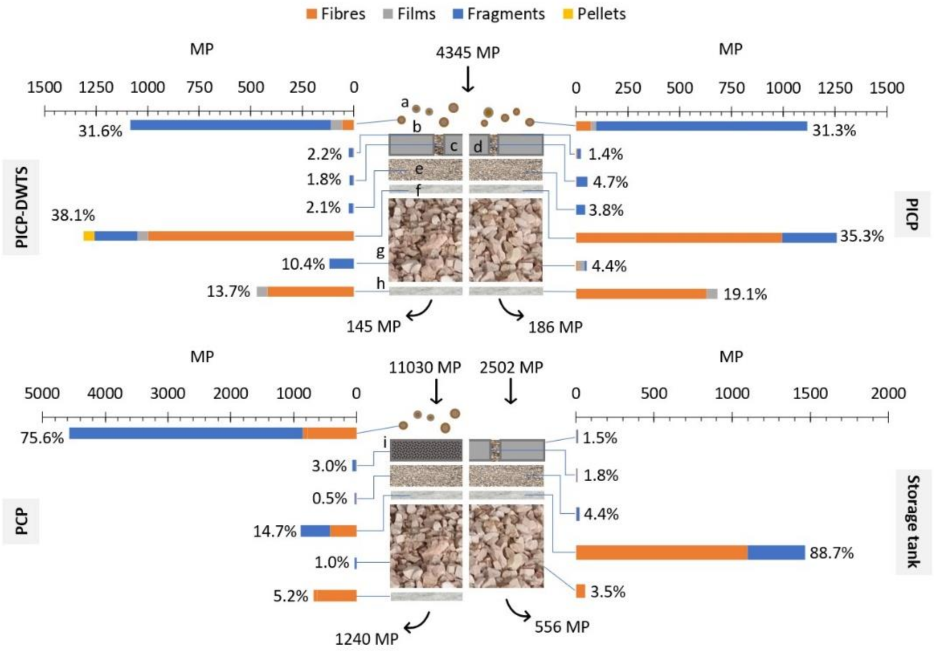

Figure V.6. Total MPs estimated at input and output of the permeable pavements, MPs fate (%) and shape distribution and accumulation within the permeable pavement layers (a. Dust and sediment accumulated on surface; b. Concrete brick; c. Filler+DWTS; d. Filler; e. Fine gravel; f. Upper geotextile; g. Coarse gravel; h. Lower geotextile; i. Porous concrete brick). Microplastics found in geotextiles lack spectroscopic confirmation, unlike those identified in other layers which have been spectroscopically confirmed.

Caution should be exercised regarding the obtained results, as the particles suspected to be microplastics were not verified by spectroscopy, but The Hot Needle Test, which may be less precise than the former. This fact could potentially affect the reported particle quantities. Looking at other permeable pavement layers above the upper geotextile (filler and fine gravel) and below (coarse gravel), they had very little influence on retaining microplastic particles (Figure V.6).

A high variability in the retention capacity of the rest of the layers was observed in the three infiltrometers, being fragments and sizes from less than 0.1 mm up to 0.5 mm the most common particles retained. Likely, fibres can fit and adapt to void spaces of the granular layers, being susceptible to be washed off.

Recovery percentages, estimated as the relation between MPs collected, encompassing particles recovered from the permeable pavement layers and contained in effluent, and the total amount of input MPs applied via dust and sediment were 82%, 86% and 66% for PICP-DWTS, PICP and PCP infiltrometers. These recovery percentages are within the range reported in other studies assessing the vertical fate of MPs (Wang, Q. et al. 2021), except for PCP. An important fraction of particles might have been retained within the inner pores of this type of pavement, rendering them inaccessible for analysis.

V.3.4.2 Storage tank (experiment E2)

At the end of the experiment E2, a total of 2503 microplastic particles were estimated as input and 556 MPs as output. This results in a retention efficiency of 77.8% (Figure V.6), which is within the range of other studies that reported TSS retention efficiencies of 54% (Ghisi et al. (2020) and 98.8% Winston et al. (2020). The smaller retention efficiency of the storage tank in comparison to the other infiltrometers, might be supported by the presence of only one geotextile. These findings provide evidence that the retention of MPs can be effectively achieved in permeable pavements when more than one geotextile is incorporated into their structure.

Microplastic distribution in the storage tank layers follows a similar pattern than in the infiltrometers. As an exception, no sediment was accumulated on the surface. This fact can be explained as the total sediment mass contained in stormwater runoff samples was 25 times lower than the total dust and sediment used in E1. Another reason that could explain this situation would be the way in which the runoff was applied to the permeable pavement surface. Particles accumulated on the surface could have been washed-off by the runoff flow, entering the system through the joints between bricks. According to the results, approximately 30% more microplastics entered the system via runoff. Geotextile is once again revealing itself as the main microplastic trapping layer (88.7%), mainly fibres, followed by fine gravel (4.4%), coarse gravel (3.5%), filler (1.8%), and concrete brick (1.5%). In the layers above the geotextile, fragments (75% concrete brick; 43% filler) and films (43% filler) represented the major retained fraction, whereas only films were found in the coarse gravel layer. The particle recovery percentage was estimated at 88%.

V.3.5 Tire wear particles

V.3.5.1 Levels and characterisation of TWP in road dust and sediment, and stormwater runoff

Tire wear particles constituted a significant fraction of the total microplastics accounted in this study (51% in road dust and sediment, and 40% in stormwater runoff). This finding confirms that TWP make substantial contribution to microplastics accumulated on urban surfaces, susceptible to being washed-off (Österlund et al. 2023), and that stormwater runoff represents a major source of TWP, contributing to microplastic pollution, as they are estimated to account for 5-10% of the total plastic entering the global ocean (Jan Kole et al. 2017). All the particles detected in road and runoff samples measured less than 0.5 mm, with 80 µm being the smallest size identified.

Calculated mean level of TWP in road dust and sediment was 4935 ± 1040 TWP/kg (19.35 g of total sampled dry weight; n=3), which is in the range of other reported TWP levels: 340 ± 45.5 TWP/kg dw, n=3 (Worek et al. 2022); 3600 - 9100 TWP/kg dw, (Järlskog et al. 2020); and 854832 ± 1 071 314 TWP/kg dw, n=3 (Järlskog et al. 2021). Wide variation in TWP levels in road dust and sediment is influenced by various factors, including maintenance practices, weather conditions and traffic level (Wagner et al. 2018; Jan Kole et al. 2017). Most of previous studies reported TWP levels in units of particle mass/wet sediment volume and/or particle mass/dry sediment mass (e.g., Rasmussen et al. 2023; Knight et al. 2020; Klöckner et al. 2019), making it difficult to compare between results. This study provides more reliable data as they are reported in number of particles per dry weight, which is a more comparable unit of measurement.

In stormwater runoff samples, TWP average level was estimated at 7.95 ± 1.75 TWP/L (total sampled runoff= 153 litres, n=4), which falls within the range of other TWP levels reported by previous studies: 20.40 ± 5.70 TWP/L, n=23 (Mahjoub et al. 2023); 31.62 ± 29.41 TWP/L, n=13, (Smyth et al. 2021); 219 ± 129 TWP/L, n=6 (Järslkog et al. 2021); 0.064 TWP/L, n=3 (Gilbreath et al. 2019). Several factors such as traffic load, catchment features, and rainfall conditions can be attributed to have significant influence on large variations of the TWP levels reported (Järlskog et al. 2020; Liu et al. 2019a).

V.3.5.2 Levels and characterisation of TWP in infiltrated and extracted water

No significant differences in output TWP levels between infiltrometers were detected ($p>0.05$). However, significant correlation between surface dust and sediment accumulation and TWP abundance in the effluent of PICP-DWTS ($r=0.9$; $p<0.05$) and PICP ($r=0.65$; $p<0.05$) was found. Similar average levels of TWP compared to those obtained in the analysis of MPs: 0.28±0.28 TWP/L (PICP-DWTS; n=6), 2.71 ± 0.82 TWP/L (PICP; n=6)), 3.30 ± 0.89 TWP/L (PCP; n=9), 2.67 ± 0.65 TWP (Irrigation water extracted from the storage tank; n=9) and 4.67 ± 3.33 TWP/L (Storage tank overflows; n=2). Identical pattern of the TWP size distribution to that of MPs was detected: prevalent sizes corresponded to 0.1 – 0.5 mm fraction in PICP-DWTS (100%), and <0.1 mm in PICP (56%), PCP (65%), and Storage tank (69%). The substantial difference in TWP levels between PICP-DWTS and PICP, coupled with the absence of particles smaller than 0.1 mm, might suggest that DWTS has an influential role on the removal mechanisms of these particles (Abuwatfa et al. 2021).

V.3.5.3 TWP retention efficiency of the permeable pavement

Input TWP applied on PICP-DWTS and PICP infiltrometers was 4503 particles, and 11430 on PCP. Regarding to the infiltrated water, a total of 18, 169 and 791 TWP were estimated at PICP-DWTS, PICP and PCP effluents. Consequently, the experiment yielded remarkably high retention efficiencies of 99.6%, 96.3% and 93.1%. The results obtained demonstrate the good performance of permeable pavements in the capture of TWP, preventing their access to natural ecosystems. A recent study also tested PCP structures and showed a TWP retention of over 96% in terms of mass, which corroborates its high retention efficiency (Mitchell and Jayakaran, 2023). Regarding the storage tank, a total of 1035 TWP were applied as input, while 775 TWP were accounted in all water extractions. Therefore, the TWP retention capacity of the storage tank was 25%. The observed reduction in efficiency, when compared to estimations from other infiltrometers, could be attributed to the relatively smaller number TWP inputs in comparison to number of MPs. Furthermore, apart from only one geotextile layer was considered, all particle sizes were less than 0.5 mm, which are the most likely to escape from the system.

V.4 Conclusions

This study represents the first attempt of a complete estimation of the efficacy of permeable pavements in retaining microplastics, on a layer-by-layer focus. Moreover, it offers a comprehensive analysis of the characteristics, fate, and distribution of these microparticles present in road dust and sediment, stormwater runoff, and within the structure of a permeable pavement. The investigation demonstrates that permeable pavements represent a feasible and effective solution for retaining MPs from urban stormwater runoff, including tire wear particles, thereby reducing their discharge into the natural environment. However, fragments and small particles (< 0.1 mm) represent a challenge, as these are the most common particles capable of eluding permeable pavements.

In general, when large dust and sediment contributions reach the permeable pavement surface, MPs tend to accumulate on the permeable pavement surface (generally fragments) and in geotextile layers (mostly fibres). Despite clogging of permeable pavements is not desirable, the surface layer itself acts as a potential barrier for MPs, which can be easily collected through appropriate mechanical maintenance tasks. In particular, PCP surface configurations captured more MPs than PICP and geotextiles due to a smaller porous structure, which is more susceptible to clogging.

Geotextiles play a significant role in microplastic interception. Permeable pavement structures that comprise 2 geotextiles show higher microplastic and TWP retention efficiencies than permeable pavements with 1 geotextile layer.

Optimal design of a permeable pavement should incorporate a minimum of two geotextile layers. In scenarios where infiltration is not feasible or when permeable pavements are designed for water storage and reuse, the drainpipe should be wrapped with geotextile to ensure particle retention, whenever high permeability is guaranteed.

It is important to highlight that after the whole testing period, no particles dislodged from the geotextiles, nor from other plastic parts of the experimental setups were observed in the effluents of the permeable pavements tested. Nonetheless, further research and implementation of non-polymeric materials such as natural fibres are recommended to potentially substitute this layer in order to reduce plastic use.

Further research should investigate the effect of rain intensity and duration, as well as the porosity of the materials, on microplastic mobilisation and fate under severe weather conditions. Additionally, although adsorbent materials have started to be studied for microplastic retention, it would be interesting to investigate on the incorporation of this material in permeable pavement structures to deliver additional and efficient retention capacity, particularly concerning particles smaller than 0.1 mm. Special efforts should be put on TWP to assess its fate and accumulation within filtration layers. This crucial step will enable the enhancement of permeable pavement design to prevent this widespread pollutant reach natural environments.

Capítulo VI

Discusión

En este capítulo se interpretan y analizan los resultados obtenidos en los 4 capítulos anteriores: "Pavimentos permeables: estado actual y retos futuros", "Influencia de la colmatación a largo plazo", "los SUDS como herramienta de control de microplásticos" y "control de microplásticos mediante pavimentos permeables".

VI.1 Pavimentos permeables: estado actual y retos futuros

Las guías y manuales de diseño de Sistemas Urbanos de Drenaje Sostenible constituyen las principales referencias para el diseño de estructuras de pavimento permeable.

Para comprender la situación en la que se encuentra esta tecnología, y los desafíos a los que se enfrenta, se han analizado los criterios de diseño que proponen las actuales guías y manuales disponibles en España, y que son objeto de esta Tesis Doctoral, sin dejar de lado los aspectos relativos a su mantenimiento. Estos criterios abarcan los aspectos hidrológicos e hidráulicos, y medioambientales.

Respecto a los criterios de diseño hidrológico e hidráulico

Destaca positivamente que el parámetro que define el volumen de agua de lluvia a gestionar por el pavimento permeable "volumen de gestión", se adapta a la precipitación de la zona. Esto es especialmente interesante para optimizar el diseño y la gestión del agua de lluvia. Por ejemplo, el complemento de los pavimentos permeables con estructuras de tipo aljibe o depósito de almacenamiento, podrían gestionar parte del agua de lluvia, dejando libre un cierto volumen para recibir posibles eventos sucesivos. Un caso de éxito de este tipo de aplicación se llevó a cabo en el proyecto *CerSUDS* (Life CerSUDS, s.f.) bajo condiciones de climatología mediterránea. Aunque algunas guías sugieren la adopción de un factor de seguridad para anticipar su posible colmatación por las partículas en suspensión arrastradas por el agua de lluvia, es fundamental realizar un estudio previo de los posibles aportes de sedimentos que pueden generarse en la cuenca. En el caso de que los aportes puedan ser significativos, tanto por la cantidad como por sus características físicas y químicas, es posible que incluso sea necesario replantearse su instalación, o incorporar medidas de captura de sedimentos previas a la entrada del pavimento, como drenes filtrantes.

Respecto a los criterios de diseño medioambientales

Es prácticamente inexistente la información que puede encontrarse en las guías con respecto a estos criterios. Solamente se recomienda la instalación de geomembranas envolviendo al sistema para proteger el suelo subyacente y las aguas subterráneas de posibles efluentes con elevada carga de contaminantes. En este sentido, es fundamental el soporte de los trabajos de investigación que vienen desarrollándose para potenciar la funcionalidad de los sistemas de pavimento permeable desde el punto de vista de tratamiento y remoción de distintos contaminantes. Por ejemplo, Naves et al. (2021) y Goya et al. (2022) determinaron una capacidad de retención de sedimentos superior al 95% tras el análisis de dos tipos de pavimento permeable (continuo poroso y adoquines porosos) sometidos a varios ciclos de acumulación-precipitación. También se está estudiando la integración de barreras reactivas en el sistema de pavimento permeable mediante el empleo de biochar, utilizando materiales residuales o subproductos como el fango deshidratado de ETAP, para potenciar la biodegradación de contaminantes orgánicos (García-Haba et al. 2021b; Qi et al. 2021). Otras actuaciones, encaminadas a la eliminación de nitratos, podrían consistir en la retención temporal del agua almacenada mediante reglas de operación, que permitan el proceso biológico de desnitrificación, y reduzcan el riesgo de contaminación de las aguas subterráneas por este contaminante (Brown y Borst, 2015). Además, esta medida favorecería la biodegradación de contaminantes orgánicos y fecales (Hernández-Crespo et al. 2019b; García-Haba et al. 2021a), fomentando la posibilidad de reutilización del agua almacenada en el propio sistema de pavimento permeable, o en aljibes conectados al mismo.

Investigaciones recientes indican que el hormigón poroso puede alcalinizar el agua del efluente, empeorando significativamente la calidad del agua en el medio receptor durante los primeros meses de funcionamiento (Hernández-Crespo et al. 2019a). No obstante, se observó que este fenómeno disminuía con el lavado del material (Fernández-Gonzalvo et al. 2021). Por tanto, con el objetivo de minimizar el impacto ambiental, podría considerarse un lavado controlado del material previo a su instalación. Una posible alternativa, quizá más viable, sería emplear materiales que no causen estos efectos, como los adoquines con junta permeable (García-Haba et al. 2021b).

Respecto al mantenimiento

El tipo de superficie permeable determina el empleo de la técnica de barrido o de aspirado. En el caso de pavimentos de tipo adoquín con junta permeable, es recomendable emplear la técnica de barrido manual (escoba) o mecánico (mediante soplador) para evitar la pérdida del material granular contenido en las juntas. Por el contrario, para pavimentos porosos, se recomienda la técnica de aspirado mediante vehículo de limpieza. Con respecto a la frecuencia de las tareas de mantenimiento, estudios recientes recomiendan que se realicen con una periodicidad mensual para evitar la generación de escorrentía y la dispersión de contaminantes acumulados en la superficie, especialmente ante la llegada de eventos de lluvia de alta intensidad (Fernández-Gonzalvo et al. 2020).

VI.2 Influencia de la colmatación a largo plazo

Respecto a la permeabilidad y capacidad de infiltración del pavimento de asfalto poroso

En general, tanto la permeabilidad como la capacidad de infiltración del pavimento se reducen exponencialmente con la carga de sedimento acumulado en superficie, independientemente de las características físicas y químicas del material. Este hecho se intensifica particularmente para sedimentos de granulometría no uniforme. En superficies de asfalto poroso, una acumulación de este tipo de sedimento de 1 kg/m^2, equivalente a la acumulación estimada durante un periodo de 6 meses[4] sin limpieza ni mantenimiento, puede provocar una reducción de más del 50% en la permeabilidad inicial. Sin embargo, esta disminución en la permeabilidad no compromete la capacidad de infiltración de la estructura. En los experimentos ensayados, se observó una permeabilidad inicial muy alta ($k \approx 20000$ mm/h), incluso tras su reducción ($k \approx 9000$ mm/h). Esto permitió mantener una eficiencia hidráulica completa de la superficie permeable, demostrando ser capaz de filtrar todo el volumen de lluvia precipitado sobre ella. Esto se debe a que la permeabilidad de la superficie era considerablemente superior a la intensidad de lluvia simulada en los experimentos (80 mm/h).

A partir de una tasa de acumulación de 2 kg/m^2 (12 meses[4]), la permeabilidad del asfalto poroso se reduce, en términos relativos, entre el 88 y el 98% de la permeabilidad inicial. En términos absolutos, se determinaron valores de permeabilidad por encima de los 700 mm/h, siendo todavía muy superiores a la intensidad de lluvia simulada. Este hecho permitió que la capacidad de infiltración se mantuviese prácticamente igual a la inicial. Llama especialmente la atención que una reducción tan importante de la permeabilidad de la superficie porosa apenas modifique la capacidad de infiltración. En este sentido, se planteó la

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[4] Estimado a partir de la determinación experimental de una tasa de deposición de sedimentos lineal equivalente a 5 g/m^2 día (Hernández-Crespo et al. 2019a).

hipótesis de la posible existencia de flujos preferenciales en la estructura heterogénea de la superficie permeable que pudieran favorecer el paso del agua (Preti et al. 2018). Los primeros síntomas de colmatación de la superficie porosa aparecieron con tasas de acumulación de sedimentos entre 3.5-4.0 kg/m^2 (21-24 meses[4]), apreciándose una tímida disminución de la capacidad de infiltración. Finalmente, se produjo escorrentía superficial a partir de 4 kg/m^2. En esta situación, la permeabilidad del pavimento poroso era prácticamente nula, y la capacidad de infiltración disminuyó a una velocidad de 40 mm/h por kg/m^2 de sedimento acumulado.

En el caso de sedimentos de granulometría uniforme, se observó que una acumulación superficial de sedimentos de hasta 1 kg/m^2, apenas afectó la permeabilidad inicial del pavimento. Tras la aplicación de sedimento de granulometría fina (63 - 150 µm), la permeabilidad se mantuvo prácticamente inalterada. Sin embargo, al aplicar sedimentos de granulometría más gruesa (250 - 500 µm), la permeabilidad se redujo aproximadamente en un 20%. Esto sugiere que, a priori, cuanto menor es el tamaño de los sedimentos, menor capacidad para colmatar presentan. Esta diferencia se puede explicar por el hecho de que un sedimento más fino posee mayor capacidad para percolar hacia los intersticios del pavimento, con respecto a un sedimento de mayor tamaño. La retención de sedimento en los primeros centímetros del pavimento puede provocar una disminución de la permeabilidad. Este fenómeno fue confirmado por Zhang et al. (2018) y Kia et al. (2018), quienes simularon una acumulación de 8 kg/m^2 de sedimentos.

Otro factor que afecta a la funcionalidad hidráulica de los pavimentos permeables, es la presencia de materia orgánica en el sedimento. Se ha observado que aquellos sedimentos con mayor concentración de materia orgánica, provocan una reducción más significativa de la permeabilidad, favoreciendo la colmatación, tal y como ya pusieron de manifiesto Davies et al. (2002) y Pratt et al. (1995). Al fenómeno de la colmatación producido por la materia orgánica, se le denomina *bioclogging* en la terminología anglosajona. La materia orgánica favorece la formación de una biopelícula sobre el material granular, ocupando la red de poros de la estructura, aportando cierta cohesión al sedimento percolado, y dificultando el paso del agua (Perujo et al. 2019).

La frecuencia de eventos de lluvia es otro de los aspectos que se relacionan con la pérdida de permeabilidad. Se observó que un mayor número de eventos simulados favorecía una mayor percolación del sedimento en la estructura. Este hecho complicaba su limpieza, afectando negativamente a la restitución de su permeabilidad original. Solamente se consiguió recuperar en torno a un 10% de la permeabilidad inicial. Por tanto, la frecuencia de eventos de precipitación es una variable a tener en cuenta a la hora de establecer protocolos de mantenimiento en pavimentos permeables., lo que complica su limpieza. Además, el efecto lavado puede arrastrar los contaminantes presentes en el sedimento hacia el medio natural.

Respecto a la calidad del agua infiltrada por el pavimento de asfalto poroso

Tal y como cabe esperar, la acumulación de sedimento en superficie tiene como consecuencia un incremento general en las concentraciones de los contaminantes en el agua infiltrada (DQO, SST, NT, NH_4^+, NO_2^-, NO_3^-, PT y PO_4^{3-}). Cuando la tasa de acumulación de sedimento urbano alcanza 1 kg/m^2, ciertos parámetros de calidad del efluente comienzan a ser preocupantes. En este sentido, es crucial prestar especial atención al destino final del efluente, o excedente, en el diseño del pavimento permeable. Si el objetivo es verter el efluente al medio natural, este podría presentar una calidad inferior en comparación con un agua residual urbana tratada. Los parámetros DQO, SST y PT podrían superar los valores límite que establece la Directiva 91/271/CEE para vertidos procedentes de instalaciones de tratamiento de aguas residuales urbanas. Cuando el objetivo del pavimento permeable es la infiltración al acuífero subyacente, las concentraciones de fosfatos (PO_4^{3-}) podrían superar los valores umbrales determinados por los organismos de cuenca, como el establecido en el Plan Hidrológico de la Demarcación Hidrográfica del Júcar (CHJ, 2022), tal y como insta la Directiva 2006/118/CE relativa a la protección de las aguas subterráneas contra la contaminación y el deterioro.

A pesar de que las concentraciones de nitrógeno en todos sus estados se encontraron por debajo de los umbrales, sería recomendable adoptar medidas para reducir todavía más el riesgo de contaminación. Por ejemplo, que el propio diseño del pavimento permeable permitiese el almacenamiento temporal de la escorrentía, previo a su evacuación, para favorecer el proceso de desnitrificación (Drake et al. 2014). Estos resultados podrían proporcionar información de gran utilidad para optimizar frecuencias de operación y mantenimiento de pavimentos permeables. En términos de eficiencia, se estimaron porcentajes de retención de contaminantes significativamente altos alcanzando el 96% para DQO, 76% para NT, 79% para el PT y 98% para SST. Estos valores se encuentran entre los más altos según los reportados por estudios similares. Por ejemplo, Liu et al. (2020) y Braswell et al. (2018) obtuvieron reducciones medias en torno al 59 y 95% de PT, así como del 43 y 70% de NT en pavimentos permeables de tipo adoquín con junta permeable, mientras que en pavimentos de hormigón poroso determinaron reducciones medias del 43% en PT y del 52% en NT. Con respecto a SST, los rendimientos de eliminación obtenidos por Mahmoud et al. (2020), Braswell et al. (2018) y Kamali et al. (2017) fueron del 77, 95 y 100% respectivamente en pavimentos permeables de tipo adoquín con junta permeable, y aproximadamente del 80% en pavimentos de hormigón poroso (Drake et al. 2014).

Respecto a la distribución del sedimento en el pavimento de asfalto poroso

Son las propiedades físicas del pavimento, tales como su rugosidad y porosidad, las que principalmente facilitan la retención de contaminantes por intercepción física.

Al final del experimento, el 98% de los sedimentos aplicados sobre la superficie permeable se encontraban retenidos sobre ella, así como en sus huecos internos. Solamente el 2% logró escapar, escurriendo por superficie, o bien, infiltrándose. Este mecanismo de intercepción demuestra ser altamente efectivo para la eliminación de sólidos, confirmando los resultados de Hernández-Crespo et al. (2019) y Li et al. (2017).

El alto porcentaje de sedimento retenido tanto en superficie como en la estructura interna del pavimento se debe fundamentalmente al tamaño de las partículas, además del contenido en materia orgánica. Tal y como demostraron los experimentos, las partículas de tamaño más fino pueden penetrar los primeros centímetros de la superficie permeable antes de quedar atrapadas en su interior. Por el contrario, las partículas más gruesas tienden a quedar retenidas sobre la misma superficie, siendo más abundantes aquellas partículas con mayor contenido en materia orgánica. Este fenómeno produce el bloqueo de las partículas, lo que impide la penetración de una mayor cantidad de sedimento. Esto implica una reducción de la permeabilidad de la superficie, confirmando los resultados derivados del estudio de la permeabilidad y la capacidad de infiltración, comentados anteriormente.

A partir de todo lo discutido, se puede deducir que aspectos como la meteorología, el uso del suelo y tipo de actividad de la cuenca que gestione el pavimento permeable, y la frecuencia de su limpieza, van a determinar su susceptibilidad a colmatarse. En consecuencia, un periodo sin mantenimiento superior a 6 meses, podría favorecer la dispersión de contaminantes, acarreando problemas ambientales, a pesar de que el funcionamiento hidráulico/hidrológico se mantendría en óptimas condiciones. En el caso de que la frecuencia de mantenimiento excediese de 1 año, el pavimento permeable podría generar problemas de cantidad de agua por producción de escorrentía superficial. Además, la dispersión de contaminantes persistiría, con la posibilidad de que los problemas ambientales se agravasen. Por tanto, la adopción de frecuencias de mantenimiento inferiores a 6 meses coincide con la propuesta de Fernández-Gonzalvo et al. (2020), quienes recomiendan reducir la frecuencia de las tareas de barrido y aspirado a 1 mes.

VI.3 Los SUDS como solución para el control de microplásticos

La gran capacidad de los SUDS para gestionar eficazmente la calidad de las escorrentías urbanas, presentan una oportunidad única para abordar el problema de los microplásticos. Cada vez más científicos de todo el mundo están comenzando a investigar el uso de SUDS para la gestión de los microplásticos presentes en la escorrentía urbana. A pesar de que la información disponible todavía es limitada, la creciente conciencia sobre la presencia de este contaminante tan abundante en los entornos urbanos, está impulsando la necesidad de profundizar en este tema.

Durante la realización de esta Tesis Doctoral, se identificaron únicamente 27 publicaciones científicas basadas en la gestión de microplásticos en escorrentía urbana mediante SUDS. La variedad de técnicas SUDS estudiadas hasta el momento es muy limitada, destacando aquellas basadas en procesos de sedimentación (como humedales y estanques) y filtración (como áreas o elementos de biorretención y filtros de arena). Es importante destacar que, durante la mayor parte del periodo de elaboración de esta Tesis, solo existía un estudio que evaluaba los pavimentos permeables como posible solución para la captura de microplásticos. Sin embargo, en la actualidad, el número de investigaciones centradas en esta solución se ha incrementado, contando con un total de 3 estudios, lo que demuestra el interés creciente por el potencial de los pavimentos permeables para el control de microplásticos.

La búsqueda de microplásticos en SUDS se centra generalmente en tres partes concretas: agua de escorrentía en la entrada, agua efluente en la salida, y sedimento acumulado entre la entrada y la salida. Según los estudios analizados, las concentraciones de microplásticos presentaban una notable variabilidad en la escorrentía de entrada (<1 – 4000 MP/L) (Boni et al. 2021 y Coalition Clean Baltic, 2017), así como en el efluente de salida (0.16 - 335 MP/L) medidos en un área de biorretención (Gilbreath et a. 2019) y en el elemento de pretratamiento de un área de biorretención (Lange et al. 2021), y en el sedimento acumulado (2.0 – 3600 MP/kg de sedimento seco) en humedales artificiales (Yu et al. 2019) y estanques (Liu et al. 2019b). Dos aspectos fundamentales influyen directamente en la cantidad de microplásticos identificados en las muestras recolectadas. Por una parte, factores locales específicos de cada caso, como el tamaño de la cuenca, uso del suelo, actividad humana, la meteorología (intensidad y volumen de precipitación, días secos precedentes), la calidad del flujo de entrada, la posible resuspensión de sedimentos, el diseño y antigüedad de los SUDS, y la frecuencia de mantenimiento de estos sistemas. Y, por otro lado, las diferentes metodologías de muestreo y de análisis empleadas por los autores.

A pesar de la notable variabilidad en las concentraciones de microplásticos entre las escorrentías de entrada y los efluentes de salida de los SUDS, los valores registrados en las salidas son consistentemente menores que en las entradas. Este resultado evidencia el papel fundamental que desempeñan los SUDS en el control de los microplásticos. Diversos estudios señalan que los SUDS poseen elevados porcentajes de retención de microplásticos, ya sea mediante procesos de sedimentación (> 85%) (Olesen et al. 2019; Coalition Clean Baltic, 2017), o de filtración (> 90%) (Gilbreath et al. 2019; Smyth et al. 2021; Lange et al. 2021, 2022).

El hecho de que los polímeros más comunes detectados en los estudios fueran tereftalato de polietileno (PET), polietileno (PE), poliestireno (PS), polipropileno (PP) y policloruro de vinilo (PVC), podría deberse a que son los plásticos más demandados para el desarrollo de actividades humanas y procesos de fabricación (PlasticsEurope, 2022). Según la morfología, los microplásticos más frecuentes que se encontraron en muestras de agua (en escorrentía de entrada y en efluente) eran de tipo fibras, mientras que en las muestras de sedimento, los fragmentos fueron los más comunes. Esta distinción se debe principalmente a que las fibras tienen una mayor dificultad para sedimentar que los fragmentos (Prata et al. 2019), aunque ciertos procesos como la formación de biopelícula en su superficie, o su propia degradación, podrían alterar esta dinámica. Es importante destacar que, en todos los estudios que incluían el análisis de microplásticos procedentes del desgaste de neumáticos, casi la mitad de las partículas detectadas pertenecían a esta categoría. Este hallazgo confirma que las partículas derivadas de neumáticos contribuyen de manera significativa a la producción de microplásticos (Österlund et al. 2023), representando entre el 5 y 10% del total del plástico que termina en los océanos (Jan Kole et al. 2017).

VI.4 Control de microplásticos mediante pavimentos permeables

Centrando la Tesis en los pavimentos permeables, se ha abordado el estudio experimental de estas estructuras como solución innovadora para el control de microplásticos, tratando de responder a las necesidades identificadas en la investigación. En términos generales, los pavimentos permeables han demostrado tener la capacidad de retener una cantidad significativa de microplásticos, lo que los convierte en una herramienta potencialmente válida para afrontar el problema de contaminación por estas partículas.

Las eficiencias de retención de los pavimentos permeables estudiados en esta Tesis Doctoral se estimaron entre el 78 y el 97%. Este rango demuestra que los pavimentos permeables son tan efectivos en la retención de microplásticos como las otras tipologías de SUDS analizadas en otros estudios, tal y como se describe en el epígrafe anterior. Además, estos resultados se alinean estrechamente con los obtenidos en la retención de SST, según Zheng et al. (2022), Liu et al. (2020) y Hernández-Crespo et al. (2019). Dada la limitada cantidad de investigaciones que abordan específicamente la problemática de los microplásticos mediante pavimentos permeables, se ha optado por comparar los resultados obtenidos con este parámetro, en base a la correlación existente entre ambos. Las diferencias observadas entre los porcentajes de retención estimados pueden atribuirse a la influencia de diversos factores, los cuales se describen a continuación.

Influencia del modo de captación de agua y entrada de microplásticos

La gestión de las aguas pluviales a través de los pavimentos permeables comienza con su capacidad de captura. Las superficies de estas estructuras reciben el agua de lluvia que cae directamente sobre ellas, pero también pueden captar la escorrentía que se origina en áreas adyacentes.

En el caso de un pavimento de tipo adoquín con juntas permeables que recibe aportes de escorrentía superficial, es más probable que se produzca una mayor penetración de microplásticos que cuando la entrada de agua se produce por precipitación directa. Los resultados mostraron un incremento aproximado del 30% en la cantidad de partículas que percolaron en la estructura cuando se simuló la entrada de escorrentía, con respecto a la precipitación directa únicamente. Este hecho podría atribuirse al lavado y movilización de las partículas localizadas sobre la superficie de los adoquines, las cuales son arrastradas hacia las juntas permeables.

Cuanto mayor es la cantidad de escorrentía movilizada, así como la pendiente sobre la que escurre, mayor es la energía con la que ésta se propaga. En tales circunstancias, las juntas que reciben el frente de escorrentía podrían tener mayor dificultad para absorberlo. En consecuencia, la escorrentía podría propagarse sobre un área más amplia, derivando en una mayor superficie de adoquín lavada. Sin embargo, con pendientes más suaves, las juntas podrían tener una mayor capacidad para absorber el frente de escorrentía que reciben. Como resultado, el efecto de lavado de superficie de adoquín se reduce. Debido a que la simulación de la entrada de agua, tanto de escorrentía como de precipitación directa, se realizó mediante una distribución manual, es probable que la energía con la que se vertió fuera comparable a la energía de propagación que resultaría en condiciones de pendiente alta, provocando el lavado de los adoquines. Hasta la fecha, se han realizado investigaciones sobre el efecto de la pendiente en la distribución espacial de la infiltración del agua de lluvia que cae directamente sobre el pavimento permeable (Hou et al. 2019; Lucke y Beecham, 2013). Sin embargo, estos estudios no consideran la captura de escorrentía procedente de áreas adyacentes.

Tal y como se detalla en el Capítulo II de la Tesis, las recomendaciones que exponen las guías y manuales de SUDS en relación con la pendiente del pavimento, solamente aluden a criterios hidráulicos. Sin embargo, la influencia de este parámetro hidráulico en la movilización de contaminantes debería replantear sus criterios de diseño. Por tanto, es necesario profundizar más en esta línea de investigación, con el fin de actualizar el rango de pendientes óptimo que garantice simultáneamente criterios de cantidad (hidráulicos) y de calidad (ambientales) del agua.

Influencia del tipo de superficie permeable

En el escenario de un pavimento permeable que solo recibe precipitación directa, la superficie constituye una de las barreras más importantes para la entrada de los microplásticos acumulados sobre ella, principalmente de fragmentos, con independencia de la tipología empleada (adoquín de hormigón con junta permeable, o continuo de hormigón poroso). La intrincada estructura de pequeños huecos a través de la cual infiltra el agua, junto con la morfología fragmentada de los microplásticos, podría favorecer la formación de costras en sus primeros centímetros (Brown et al. 2009; James, 2004; James and Gerrits, 2003; Pratt et al. 1995; Baladès et al. 1995), bloqueando la entrada de material contaminante, tal y como se discute en el epígrafe VI.1.

Este fenómeno podría ser más acentuado en pavimentos porosos. Los resultados obtenidos muestran que una superficie porosa continua posee mayor capacidad de retención que una superficie de adoquín con junta permeable (78,6% frente al 32,7%). Esta diferencia podría deberse a que, aparentemente, el tamaño medio de los huecos del hormigón poroso es inferior al del material de relleno de la junta de los adoquines. En este sentido, la propia acumulación en superficie podría considerarse como un proceso de tratamiento intrínseco al pavimento permeable. La transferencia de contaminantes por infiltración quedaría impedida, de modo que el material acumulado sería fácilmente recogido por los servicios de limpieza y mantenimiento.

Influencia de los geotextiles

Indudablemente, el geotextil es el componente fundamental para garantizar la captura de microplásticos, especialmente los catalogados como fibras. No obstante, se observan ciertas diferencias en su comportamiento, en función del número de capas de geotextil dispuestas, el tipo de superficie permeable empleada, y el modo de captación de agua del pavimento permeable.

Cuando la entrada de agua se producía por precipitación directa sobre sistemas de tipo adoquín con juntas, la capa de geotextil superior (Figura V.1) logró capturar alrededor del 35% de los microplásticos que ingresaron en la estructura, mientras que el geotextil inferior retuvo un 19%. En superficies de tipo poroso, los porcentajes de retención de los geotextiles superior e inferior fueron del 15% y el 5% respectivamente. Es decir, cuando se consideran 2 capas de geotextil, la capacidad de retención que proporciona este material es un 54% superior en sistemas de adoquín con junta permeable, y un 20% en sistemas de hormigón poroso continuo. Esta diferencia probablemente se debe al mayor número de partículas retenidas en la superficie porosa, tal y como se explica anteriormente.

El papel del geotextil adquirió mayor protagonismo cuando el método de captación de agua se produjo por escorrentía. En este caso, el geotextil superior capturó el 89% de los microplásticos que entraron en el sistema de adoquines con juntas permeables. Esta notable diferencia con respecto a la situación entrada de agua por precipitación directa, podría atribuirse a una mayor cantidad de microplásticos que penetraron en la infraestructura, tal y como se ha explicado anteriormente en este mismo epígrafe. A pesar de no haber simulado el escenario con una segunda capa de geotextil, cabe esperar que la capacidad de retención del conjunto podría superar el 90%, próximo a la retención total.

Es necesario recalcar dos aspectos acerca de los geotextiles. En primer lugar, es fundamental que el tamaño máximo del poro del geotextil sea lo más reducido posible, siempre y cuando no comprometa su permeabilidad. Las partículas de tamaño inferior al tamaño del poro del geotextil podrían atravesarlo, tal y como se ha evidenciado en este trabajo. Por otro lado, hay que destacar la calidad de la trama de hilos que conforman el geotextil. A pesar de tratarse de un material plástico (polipropileno), lo cual podría plantear preocupaciones sobre la generación de microplásticos procedentes del propio material, no se encontraron rastros de este componente tras cinco años de uso continuo del pavimento.

Influencia de la incorporación de material adsorbente

Hasta el momento, el empleo de materiales adsorbentes procedentes de carbón activado se ha estudiado en la formulación de asfaltos porosos para el control de contaminantes como el benceno, tolueno, etilbenceno y xileno, procedentes del tráfico de vehículos (Huang y Liang, 2018). Para la eliminación de los meteles peados y fosfatos presentes en la escorrentía urbana, Wang et al. (2021) emplearon con resultados muy satisfactorios, fango deshidratado procedente de planta potabilizadora mezclado con material granular, simulando procesos de filtración. Sin embargo, no se ha investigado la incorporación de estos materiales en pavimentos permeables para el tratamiento de microplásticos. El reciente estudio llevado a cabo por Abuwatfa et al. (2021), destaca el importante potencial de los procesos de adsorción en la retención de este contaminante. En el contexto de esta Tesis, el material adsorbente empleado (fango deshidratado procedente de planta potabilizadora), ejerció una influencia significativa exclusivamente en la retención de partículas de neumático. La concentración de estas partículas en el agua infiltrada a través de un pavimento permeable con el fango fue 10 veces menor que en un pavimento sin él. Además, solo el 11% de las partículas que lograron escapar del sistema procedían de neumáticos. Este resultado sugiere que el fango podría tener una capacidad de adsorción notable para atrapar ciertos componentes presentes en los neumáticos, como caucho o aditivos minerales, químicos y plásticos. Desde la perspectiva cualitativa, no se detectaron partículas de tamaño inferior a 0.1 mm en el efluente del pavimento con fango. Este hallazgo indica que el fango posee la capacidad para capturar partículas de tamaño reducido, lo que podría tener implicaciones significativas en la gestión de los microplásticos.

Capítulo VII

Conclusiones

VII.1 Consideraciones finales

A partir de la discusión de los resultados obtenidos en la presente Tesis Doctoral, se destacan las siguientes conclusiones.

Sobre el estado actual del diseño de los pavimentos permeables

- El diseño de los pavimentos permeables atiende fundamentalmente a tres criterios: hidrológicos/hidráulicos, ambientales, y estructurales.
- La existencia de una serie de obstáculos asociados principalmente a la funcionalidad hidráulica y ambiental de los pavimentos permeables, limitan la expansión de esta técnica.
- Se percibe cierta inseguridad acerca de la capacidad de gestión en términos volumétricos, y, por tanto, de la eficiencia hidráulica de los pavimentos permeables, debido a su susceptibilidad a colmatarse de sedimentos urbanos.
- Se observa una falta de información, lo suficientemente detallada, sobre los tipos de contaminantes que los pavimentos permeables pueden gestionar de forma eficiente, lo que dificulta implementar esta técnica con el objetivo de mejorar la calidad del agua de lluvia.

La revisión de las normas y manuales actuales en materia de SUDS en España, ha permitido alcanzar el objetivo 1 de la Tesis.

Sobre el comportamiento hidráulico y ambiental de una superficie permeable durante el proceso de colmatación

- En la fase de diseño de un pavimento permeable, es importante caracterizar tanto el tipo de sedimento presente en la cuenca, como su potencial de acumulación en la superficie, determinando su capacidad para colmatar la estructura.
- Sedimentos de granulometría variable (entre 0 y 1000 µm), o gruesa (>250 µm), y con contenido en materia orgánica, favorecen el proceso de colmatación. No obstante, siempre sería recomendable evitar la instalación de pavimentos permeables en lugares donde puedan recibir aportes de cualquier tipo de sedimento.
- Es recomendable la implementación de un plan de mantenimiento y limpieza de pavimentos permeables con una periodicidad adecuada, adaptado a las condiciones meteorológicas y de cuenca locales. La monitorización de la calidad del efluente de un pavimento permeable podría informar del nivel de contaminación presente en superficie, y ayudaría a ajustar la frecuencia del plan de mantenimiento y limpieza.
- Una frecuencia del mantenimiento igual o menor a 6 meses minimizaría el riesgo de dispersión de contaminantes presentes en el efluente, y garantizaría su eficiencia hidráulica.

El análisis de la acumulación progresiva de diferentes tipos de sedimentos sobre la superficie de un pavimento permeable ha constituido el punto de partida para comprender los mecanismos que contribuyen a la colmatación de estas estructuras, identificándose los factores fundamentales a considerar para garantizar su funcionamiento eficiente desde los puntos de vista hidrológico e hidráulico, y ambiental. Por tanto, se alcanzan los objetivos 2 y 3 de la Tesis.

Sobre el papel de los SUDS en la gestión de microplásticos

- Los SUDS, concebidos como soluciones eficaces para la gestión sostenible del agua de lluvia, representan una posible solución para mitigar el problema ambiental de contaminación por microplásticos. Sin embargo, existen pocos estudios que hayan evaluado su capacidad para capturar y retener microplásticos, lo que subraya la necesidad de continuar investigando en este campo.
- Los sistemas basados en procesos de sedimentación, como humedales o estanques, y de filtración, como celdas de biorretención o jardines de lluvia, muestran una notable eficiencia en la retención de microplásticos. A pesar de ello, todavía es necesario profundizar en el comportamiento de los microplásticos una vez éstos se encuentran dentro de los SUDS, y cómo optimizar la capacidad de tratamiento de estos sistemas.

- Es esencial identificar qué tipo de microplásticos escapan con mayor facilidad del sistema, en función de la morfología y tamaño de las partículas, así como de la tipología de SUDS, y centrar los esfuerzos en su captura.
- Se requiere desarrollar una metodología internacionalmente acordada para el muestreo y análisis de microplásticos presentes tanto en agua de escorrentía urbana como en los SUDS, que facilite el procesamiento de la información, la comparación entre los resultados, y la extracción de conclusiones sobre el rendimiento de los SUDS y las variables que influyen en los resultados.

El análisis de los estudios realizados hasta la fecha ha permitido evaluar el potencial de los SUDS para el control de microplásticos presentes en la escorrentía urbana, cumpliendo con el objetivo 4 de la Tesis.

Sobre el potencial de los pavimentos permeables para el control de microplásticos

- La presente investigación constituye un hito al abordar por primera vez la evaluación de la eficacia de los pavimentos permeables en la retención de microplásticos presentes en el sedimento y en la escorrentía urbana.
- Los pavimentos permeables constituyen una técnica eficaz para reducir la descarga de microplásticos en el medio ambiente. No obstante, debe prestarse atención a la captura de microplásticos de tipo fragmento, y los de tamaño inferior a 0.1 mm, ya que fueron los que más fácilmente escaparon de los pavimentos permeables estudiados.
- En general, los microplásticos tienden a acumularse en la superficie del pavimento permeable (principalmente fragmentos) y en las capas geotextiles (mayormente fibras).
- La retirada de microplásticos de la capa superficial durante un mantenimiento adecuado y frecuente, podría reportar importantes beneficios desde el punto de vista ambiental.
- Superficies de tipo poroso destacan por su mayor capacidad para atrapar microplásticos en comparación con superficies de adoquín con junta permeable.
- Los geotextiles juegan un papel significativo en la intercepción de microplásticos. Estructuras de pavimento permeable que incluyen 2 capas geotextiles muestran eficiencias de retención de microplásticos superiores a las que solamente contemplan 1 capa. Por tanto, el diseño óptimo de un pavimento permeable debería incorporar, al menos, 2 capas de geotextil.
- En escenarios donde los pavimentos permeables se diseñen con fines de almacenamiento y reutilización del agua, deberían extremarse las

precauciones, incorporando geotextiles en los principales elementos de salida de agua. Por ejemplo, en el caso de un aljibe, sería recomendable que los conductos de toma de agua y de desagüe, quedaran envueltos con geotextil.

- Además, los primeros análisis sobre la integración de materiales adsorbentes, como el fango deshidratado de potabilizadora, en la estructura interna de pavimentos permeables, han revelado un potencial prometedor para la captura de partículas de neumáticos inferiores a 0.1 milímetros.

El estudio experimental de varias estructuras de pavimento permeable ha permitido, a partir de lo expuesto, alcanzar los objetivos 5, 6 y 7 de la Tesis.

VII.2 Futuras investigaciones

En virtud de los avances alcanzados en esta tesis doctoral, se proponen los siguientes trabajos abiertos a futuras investigaciones:

- El proceso de colmatación en pavimentos permeables se ha estudiado empleando sedimentos procedentes de áreas de aparcamiento y de zonas residenciales. Si bien, dentro del entramado urbano, existen otros usos del suelo, como el industrial o el comercial, que generan sedimentos con diferentes características. Por consiguiente, se sugiere ampliar esta investigación considerando sedimentos provenientes de emplazamientos más diversos, prestando especial atención al contenido en materia orgánica y su influencia en el *bioclogging*, así como en el desarrollo de caminos preferenciales. Además, sería interesante abordar el estudio de otros fenómenos que podrían intervenir en la movilización de los sedimentos, como el efecto de su pisado por el tráfico rodado o peatonal, o un proceso de acumulación superficial de tipo no lineal.

- El óptimo funcionamiento de los pavimentos permeables va a depender, entre otros aspectos, de un adecuado mantenimiento de su superficie. Por este motivo, sería interesante que futuras líneas de investigación se centren en el desarrollo de protocolos de mantenimiento y limpieza teniendo en cuenta las características de los sedimentos (granulometría y contaminantes presentes), así como la tasa de acumulación en superficie, y las condiciones de la pluviometría local. En aras de reducir la acumulación de partículas de plástico en el sedimento, resultaría sumamente interesante complementar los protocolos de mantenimiento y limpieza con iniciativas de sensibilización ciudadana, junto con la promulgación de regulaciones destinadas a los productos plásticos de un solo uso.

- En el contexto de una gestión eficiente de microplásticos presentes en escorrentía urbana, los elementos de biorretención, los estanques, y los humedales artificiales, destacan como las tipologías de SUDS que han sido objeto de un mayor número de investigaciones hasta el momento. Está suficientemente contrastado que estas técnicas gestionan eficientemente las primeras aguas de escorrentía o *first flush*. Sin embargo, es importante destacar que este flujo de agua puede resuspender los sedimentos previamente depositados durante eventos de lluvia anteriores, dando lugar a un incremento de la carga contaminante en el punto de vertido hacia el medio natural. Por ello, se propone incrementar el nivel de tratamiento de las estructuras mencionadas anteriormente, complementándolas con otros SUDS. Las investigaciones tratarían de encontrar las combinaciones más eficientes, fomentando los procesos de laminación de caudales de escorrentía y su infiltración, además de la decantación y retención de microplásticos.

- Destaca fundamentalmente la falta de información respecto al impacto que tienen ciertos elementos característicos en los SUDS a escala real, como geotextiles, capas de material granular o la vegetación, en la retención microplásticos. El estudio integral de los SUDS, considerando cada uno de los componentes de su estructura, permitiría identificar qué elementos del sistema, o qué partes del proceso de tratamiento, podrían mejorarse para potenciar su capacidad de retención.

- Otro aspecto fundamental para abordar su investigación, se centra en la gestión de los microplásticos suspendidos en las masas de agua de estanques y humedales artificiales. Se propone la reconsideración del diseño de estas estructuras, estudiando la integración de vegetación flotante para interceptar las partículas suspendidas. Esta estrategia se fundamenta en la capacidad de las raíces vegetales para atrapar los microplásticos, al tiempo que fomentan un régimen de flujo laminar que propicia la sedimentación de estos. Adicionalmente, se sugiere el estudio de la integración de estructuras filtrantes, con o sin vegetación, en puntos estratégicos de salida del sistema, con el propósito de impedir que un mayor volumen de partículas alcance el medio natural.

- Sin duda, una futura línea de investigación se abre con el estudio de otras estructuras de SUDS, tales como las cunetas vegetadas y los alcorques estructurales. El enfoque principal de la investigación trataría de comprender cómo pueden influir los procesos de tratamiento que ofrecen en estas técnicas en la gestión de microplásticos. Además, los resultados obtenidos podrían ser incorporados en las guías de diseño actuales, enriqueciendo la información disponible y completando el amplio catálogo de técnicas de SUDS para el control de microplásticos.

- En el ámbito de los pavimentos permeables, futuras investigaciones deberían focalizarse en la optimización de su diseño para una gestión más efectiva de los microplásticos. Para ello, es especialmente importante el estudio del efecto de la intensidad y duración de la lluvia, así como de la porosidad de los materiales que componen la estructura, en la movilización de los microplásticos. Es importante destacar que en este trabajo no se caracterizó la estructura porosa de las capas de los pavimentos permeables ensayados. La determinación del índice y del tamaño de los huecos, podría ayudar a discernir la distribución de los microplásticos en función de la profundidad de las capas, además de identificar la morfología y el tamaño de partículas con mayor probabilidad de ser retenidas.

- Partiendo de la línea de investigación anterior y de la significativa correlación entre microplásticos y SST, futuras investigaciones podrían suponer el punto de partida para detectar el posible potencial de los microplásticos para colmatar estructuras de pavimento permeable. Este enfoque, centrado principalmente en la caracterización de tamaños y formas de las partículas, podría proporcionar información fundamental sobre la interacción entre microplásticos y pavimentos permeables.

- La relevancia del geotextil en la retención de microplásticos ha quedado suficientemente demostrada, sin detectarse indicios de su desgaste tras simular un periodo de funcionamiento de 5 años. Sin embargo, sería interesante llevar a cabo un análisis exhaustivo de la durabilidad de este elemento durante un mayor largo plazo, que permita determinar su vida útil. Complementariamente, sería recomendable investigar en la implementación de materiales no poliméricos, como fibras naturales, con el fin de sustituir esta capa y reducir el consumo de plástico.

- Un aspecto que merece un análisis detallado, es cómo la velocidad de entrada de la escorrentía en los pavimentos permeables afecta al transporte de microplásticos. Esta investigación permitiría adaptar el rango de pendientes de diseño que sugieren las guías actuales, con el fin de minimizar el riesgo asociado a la movilización de contaminantes. Este estudio proporcionaría la base necesaria para ajustar dicho parámetro de diseño, contribuyendo así a una gestión más eficiente y sostenible de los pavimentos permeables.

- Los hallazgos preliminares sobre la viabilidad de utilizar fango deshidratado de potabilizadora en pavimentos permeables para la captura de microplásticos, especialmente los procedentes del desgaste de neumáticos, han arrojado resultados prometedores. Sin embargo, es necesario continuar investigando más detalladamente en esta línea. Por ejemplo, analizar la estructura microscópica del material, qué mecanismos de retención de partículas imperan, posibles preferencias hacia la captura de ciertos polímeros y tamaños de partículas, evaluar diferentes proporciones de material adsorbente y su combinación con otras capas, o incluso emplear otros materiales como el biocarbón o *biochar*. Este paso representaría una etapa fundamental para optimizar el diseño de los pavimentos permeables en aras de prevenir la propagación de este contaminante en el medio natural.

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Anexo 1

Material suplementario

A1. Material suplementario del Capítulo III

Table III.S1. Standardized methods used in water quality (WQ) analyses of filtrated water and sediments.

WQ variable	**Method**
COD	Spectroquant® test: ISO 15705, 2002
BOD5	Respiratory test (OxiTop® control system)
TSS and VSS	UNE-EN 872, 2006 and UNE 77034, 2002
$N\text{-}NH_4^+$	Spectroquant® test: ISO 7150-1, 1984
$N\text{-}NO_2^-$	Spectroquant® test: ISO 7150-1, 1984
$N\text{-}NO_3^-$	Spectroquant® test
TN	Spectroquant® test: ISO 11905-1, 1997 photometry
$P\text{-}PO_4^{3-}$	Spectroquant® test: ISO 6878-1, 1986
TP	Spectroquant® test: digestion ISO 6878/1
Al	Spectroquant® test: APHA 3500-AI-B
Turbidity	TN100 Eutech turbidy-meter
Temperature and OD/%ODsat	WTW-Multi 340i probe (CellOx® 325)
EC	WTW-Multi 340i probe (TetraCon®)
pH	WTW-Multi 340i probe (SenTix® 41)

Physicochemical parameters analysed in the deposited mass	**Method**
Particle size distribution	UNE 77314,2001
LOI	550oC for 1h
Organic Carbon	Walkley-Black method as described in Schumacher, 2002
Moisture	105oC for 24h
TN	ISO 11261, 1995
TP	UNE-EN 14672, 2006

A2. Material suplementario del Capítulo IV

A2.1 Description of SUDS analysed in the paper

Urban park water bodies: Natural element in the urban ecosystem that can function as reservoir of domestic sewage and/or stormwater.

Constructed wetland: Defined as a pond with alternation of deep and shallow areas that promote aquatic plants growth.

Stormwater pond: Permanently wet ground depression designed to temporarily store surface water runoff and allow settlement of suspended solids and biological removal of pollutants.

Stormwater basin: A ground depression that is normally dry, designed to store surface water before infiltration and/or provide attenuation.

Bioretention structure: A shallow ground depression provided with vegetation that allows runoff to pond temporarily on the surface, before filtering through vegetation and underlying soils prior to collection or infiltration.

Rain garden: Small depression in the ground that serve water infiltration from roof or driveway.

Biofilter: Pollution control technique consisting of a filter media that contains living material (microorganisms) to capture and degrade pollutants through biological processes.

Bioretention cell: A vegetated and shallow ground depression larger than a rain garden.

Bioretention basin: Performs the same function as a rain garden and a bioretention cell, but it is designed to manage larger amounts of surface runoff.

Sand filter: Filtering pollution control technique consisting of a sand filled trench.

A2.2 Figures

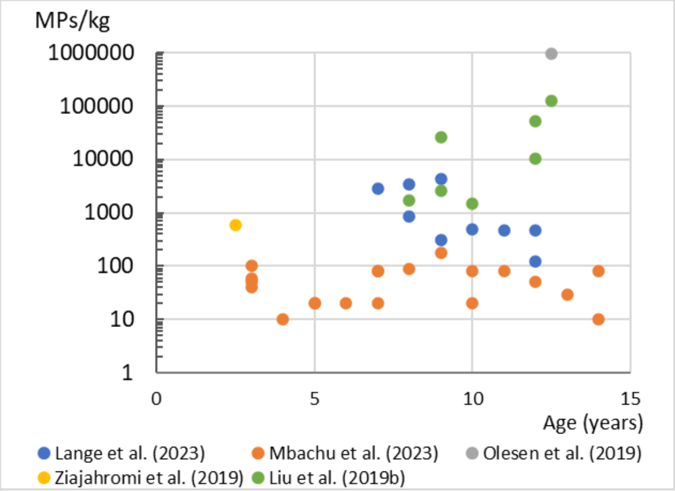


Figure IV.S1. Relation between microplastic concentration in sediments and SUDS age. Data from Ziajahromi et al. (2019) and Lange et al. (2023) correspond to the location closest to inlet.

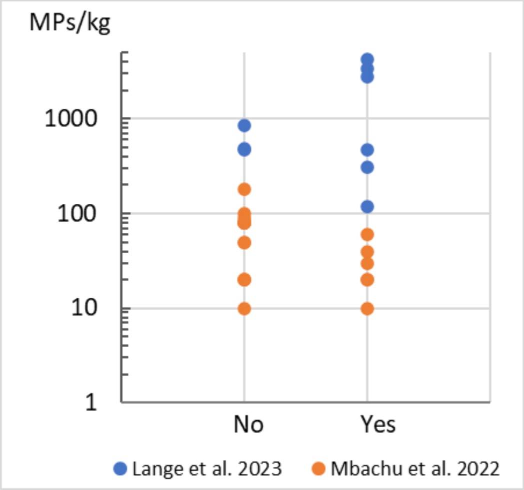


Figure IV.S2. Comparison of microplastic concentration in sediments of bioretention systems with forebay or gross pollutant traps (Yes) and without them (No). Data from Lange et al. (2023) correspond to the location 1 (1 m from the inlet).

A3. Material suplementario del Capítulo V

A3.1 Figures

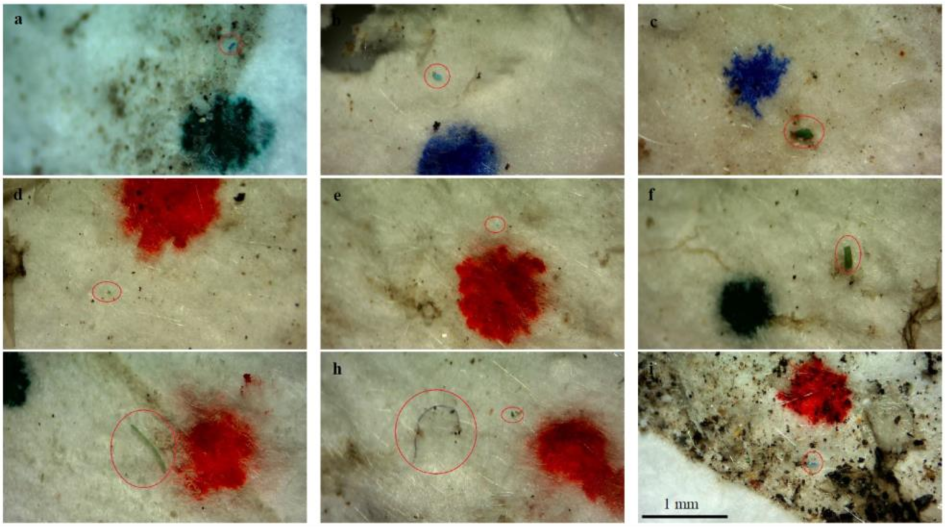


Figure V.S7. MPs detected in road dust and sediment confirmed by Raman spectroscopy: a) PP; b) PP; c) PMS; d) PVOH; e) PP; f) PVOH; g) PVOH; h) PET; i) PP

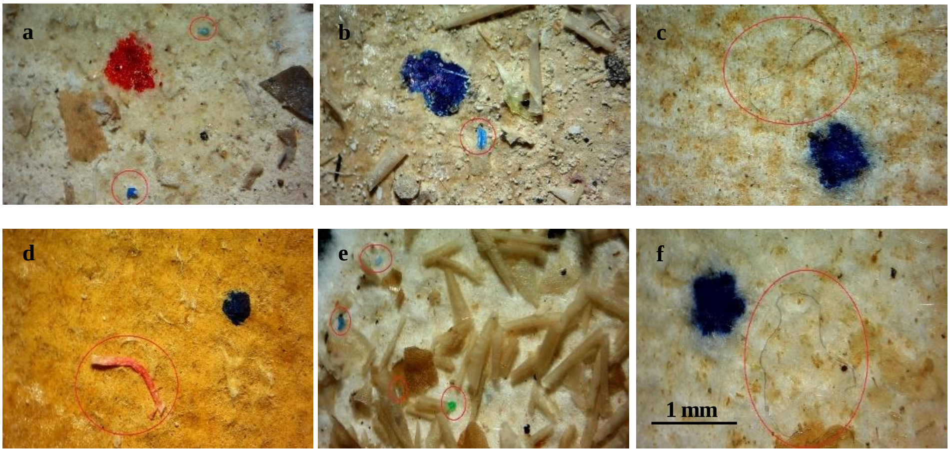


Figure V.S2. MPs detected in stormwater runoff confirmed by Raman spectroscopy: a) PP; b) PP; c) PET; d) PP; e) PP and PVOH (green); f) PET. Own elaboration.

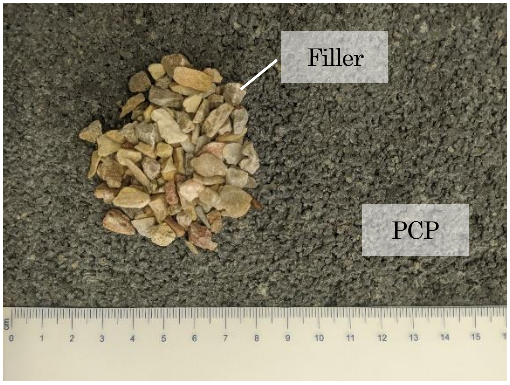


Figure V.S3. Comparison between porous structures of the filler used in PICP and PICP-DWTS infiltrometers, and PCP surface. Own elaboration.

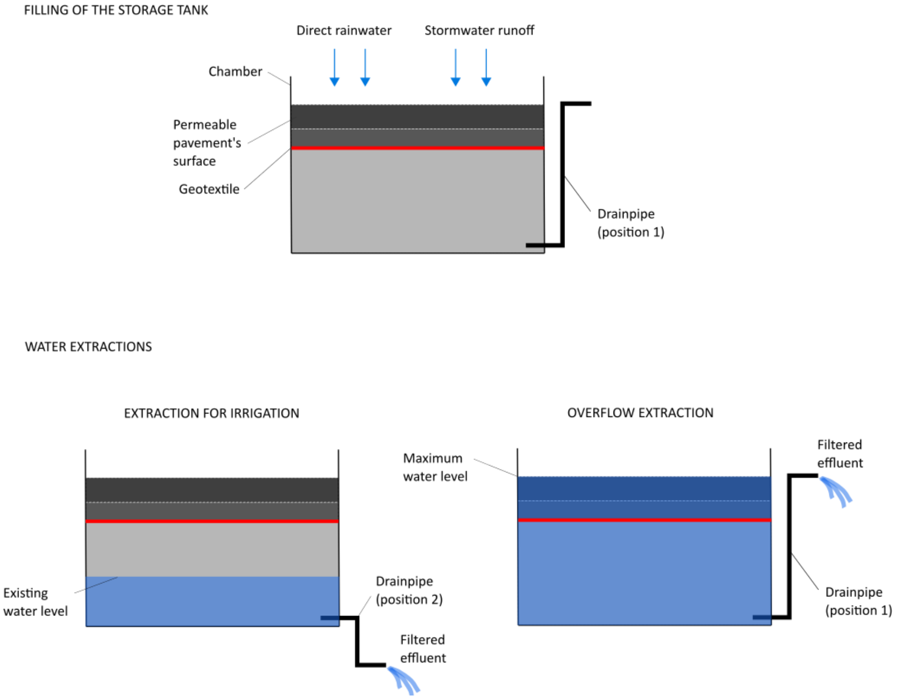
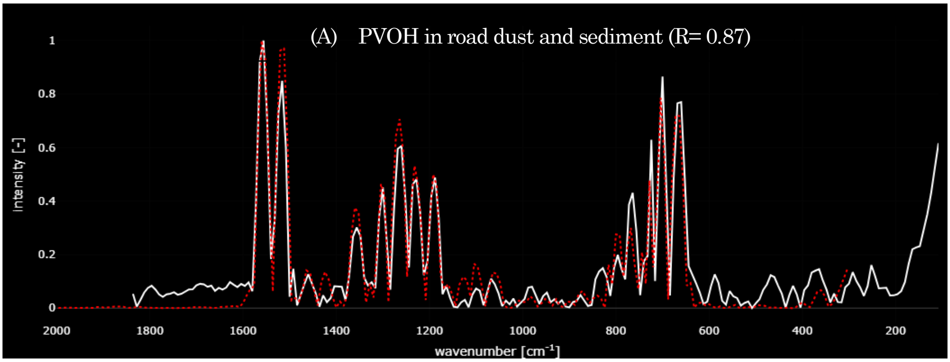
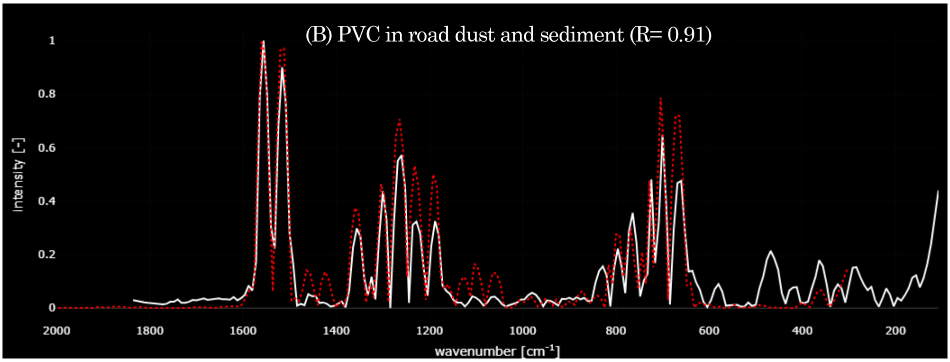
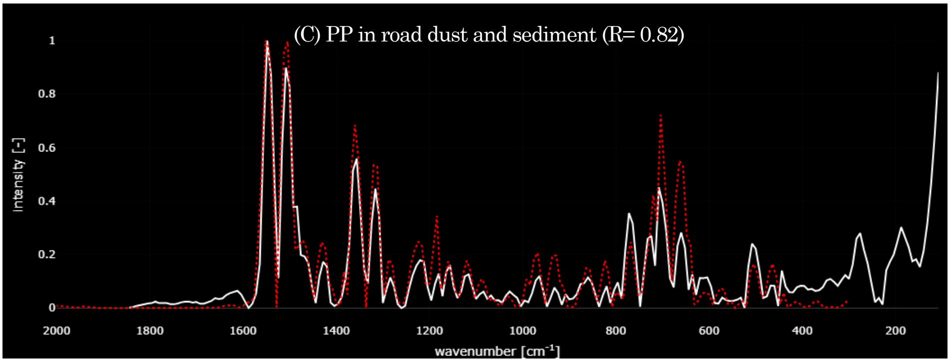
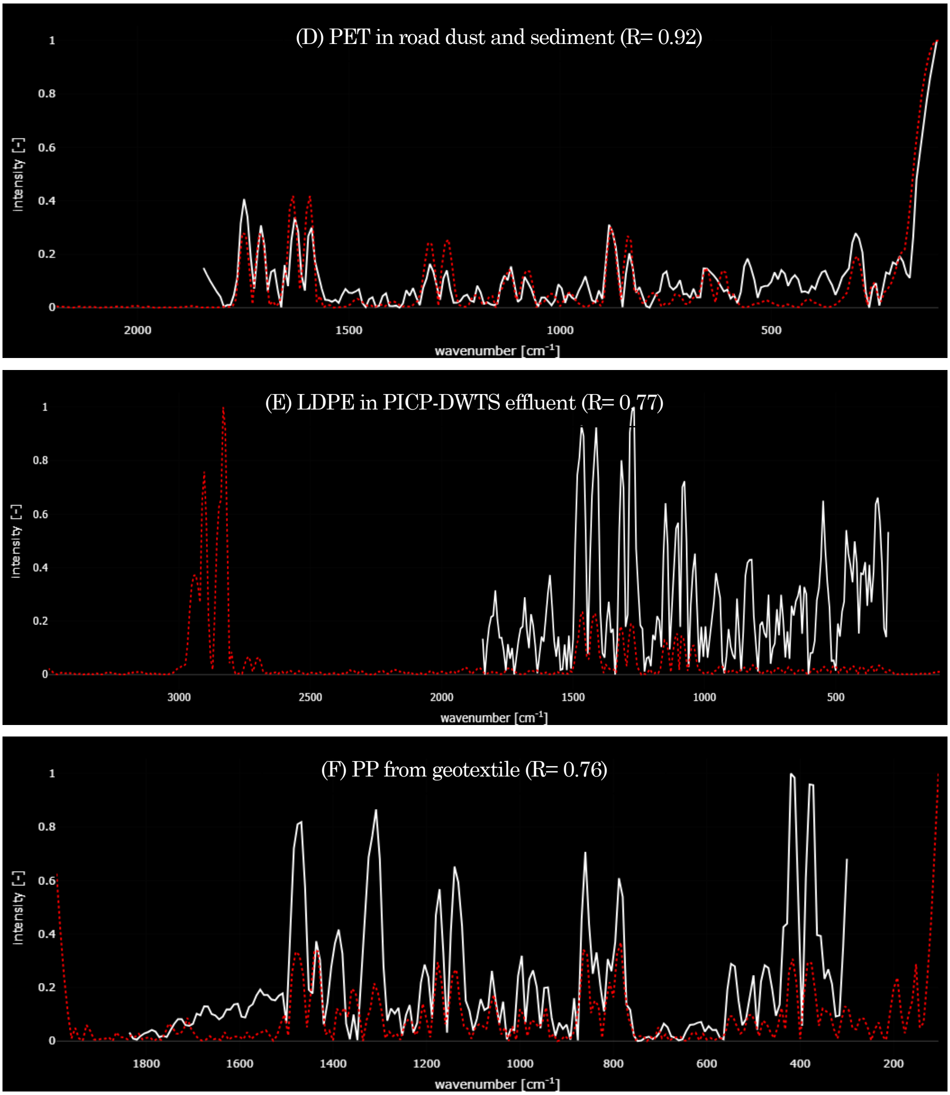


Figure V.S4. Experimental procedure of the storage tank. Filling process with direct rainwater and stormwater runoff, and water extractions for irrigation purposes and overflows. Drainpipe position 1 considers one end of the drainpipe at the pavement's surface level. Drainpipe position 2 considers one end of the drainpipe below the bottom of chamber. Water extractions for irrigation occur according to position 2 conditions, and overflows occur according to position 1. Own elaboration.


(A) PVOH in road dust and sediment (R= 0.87)


(B) PVC in road dust and sediment (R= 0.91)


(C) PP in road dust and sediment (R= 0.82)


(D) PET in road dust and sediment (R= 0.92)
Intensity [-]
1
0.8
0.6
0.4
0.2
0
2000
1500
1000
500
wavenumber [cm^{-1}]
(E) LDPE in PICP-DWTS effluent (R= 0.77)
Intensity [-]
1
0.8
0.6
0.4
0.2
0
3000
2500
2000
1500
1000
500
wavenumber [cm^{-1}]
(F) PP from geotextile (R= 0.76)
Intensity [-]
1
0.8
0.6
0.4
0.2
0
1800
1600
1400
1200
1000
800
600
400
200
wavenumber [cm^{-1}]

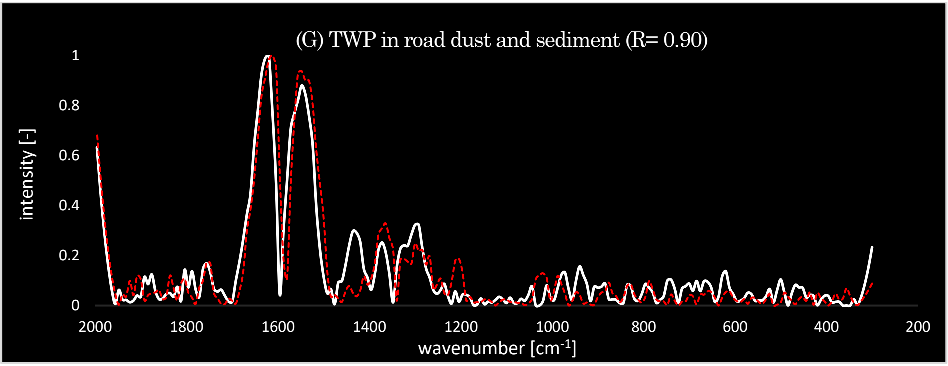


Figure V.S5. Examples of spectra corresponding to representative microplastic particles detected in the study. Spectra of microplastics obtained with Raman spectroscopy (white line) are compared to spectra from the Open Specy database (red dotted line). Graph G shows spectra from a suspected tire wear particle (white line) and a particle from a sample collected from a tire (red dotted line). The degree of similarity between the spectra is expressed by the coincidence factor "R" (Huppertsberg and Knepper, 2018). Own elaboration.

A3.2 Tables

Table V.S5. Replicas and sampled mass of road dust and sediment S1 analysed, and total MPs identified.

Replica	Sampled mass (g)	MPs identified
S1b1	6.42	43
S1b2	6.65	24
S1b3	6.28	25
TOTAL		92

Table V.S2. MP distribution in road dust and sediment according to polymer, shape, colour, and size (mean concentration and standard error; n=3).

Polymer	Road and dust sediment	
	Mean (MPs/kg dw)	SE
PET	105.000	52.509
Polyester	312.684	237.556
PP	3521.337	969.110
PVC	252.362	180.181

PVOH	518.912	278.865
HDPE	0.000	0.000
LDPE	0.000	0.000
PMS	51.921	51.921

Shape	**Road and dust sediment**	
	Mean (MPs/kg dw)	SE
Fragments	4295.076	891.641
Fibres	363.952	138.345
Films	103.189	51.658

Colour	**Road and dust sediment**	
	Mean (MPs/kg dw)	SE
Yellow	313.841	179.875
Red	106.157	106.157
Blue	3465.290	994.382
Green	720.007	217.212
Orange	0.000	0.000
Grey	53.079	53.079
Pink	0.000	0.000
Black	51.921	51.921
Transparent	51.921	51.921

Size range	**Road and dust sediment**	
	Mean (MPs/kg dw)	SE
<0.1 mm	4088.045	839.335
0.1 - 0.5 mm	363.952	138.345
0.5 - 1 mm	50.110	50.110
1 - 5 mm	260.110	54.926

Table V.S3. MP distribution in stormwater runoff according to polymer, shape, colour, and size (mean concentration and standard error; n=6).

Polymer	**Stormwater runoff**	
	Mean (MPs/L)	SE
PET	0.259	0.179
Polyester	1.030	0.391
PP	14.703	10.741
PVC	1.376	1.147
PVOH	5.506	5.019
HDPE	0.425	0.387
PMS	0.542	0.336
ABS	0.033	0.033

Shape	**Stormwater runoff**	
	Mean (MPs/L)	SE
Fragments	21.044	16.527
Fibres	1.569	0.441
Films	1.263	0.752

Colour	**Stormwater runoff**	
	Mean (MPs/L)	SE
Yellow	0.033	0.033
Red	1.898	0.714
Blue	14.562	11.215
Green	6.082	5.844
Grey	0.426	0.206
Pink	0.875	0.381

Size range	**Stormwater runoff**	
	Mean (MPs/L)	SE
<0.1 mm	7.000	4.794
0.1 - 0.5 mm	15.099	12.522
0.5 - 1 mm	1.079	0.542
1 - 5 mm	0.697	0.314

Table V.S4. Characterisation of rain events that generated runoff, sampled volumes of stormwater runoff, no. of microplastics identified and microplastic estimated levels (MPs/L).

Event		Duration (h)	Volume (mm)	Antecedent dry days	Stormwater runoff sampled volume (L)	MPs	[MPs/L]
Id	Date						
1	25/02/2022	4	5.5	35	5.00	23	4.60
2	03/03/2022	13	30	6	2.67	18	6.74
3	22/03/2022	24	76.1	19	2.00	4	2.00
4	19/04/2022	2	3.7	28	0.43	47	110.59
5	20/04/2022	7	37.4	1	0.95	6	6.33
6	02/05/2022	50	200.7	12	1.00	13	13.00

Table V.S5. Fate and distribution of MPs within layers of the permeable pavements tested in experiments E1 and E2. (IN= input microplastic sources; OUT= output of microplastics in infiltrated and extracted water)

		PICP		PICP-DWTS		PCP		Storage tank	
	Layer	**MPs**	**%**	**MPs**	**%**	**MPs**	**%**	**MPs**	**%**
IN	Sediment S1	4345		4345		11030		-	-
	Stormwater runoff	-	-	-	-	-	-	2502	
	Sediment accumulated on surface	1114	31%	1085	32%	4577	76%	0	0%
	Concrete brick	49	1%	74	2%	-	-	25	1%
	Porous concrete brick	-	-	-	-	181	3%	-	-
	Fine gravel (filler)	167	5%	-	-	-	-	30	2%
	Fine gravel (filler) + DWTS	-	-	63	2%	-	-	-	
	Fine gravel	135	4%	72	2%	33	1%	72	4%
	Upper geotextile	1258	35%	1310	38%	891	15%	1467	89%
	Coarse gravel	157	4%	359	10%	62	1%	58	4%
	Lower geotextile	681	19%	472	14%	314	5%	-	-
	Total layers	3561		3435		6058		1653	
OUT	Infiltrated water	186		145		1240		-	-
	Extracted water	-	-	-	-	-	-	556	
	MP retention efficiency		**96%**		**97%**		**89%**		**78%**
	Recovery ratio		**86%**		**82%**		**66%**		**88%**

Table V.S6. Details of the blanks considered in the study, regarding to source, number of blanks, procedure, and number of microplastics detected.

Source	Number of blanks	Procedure	No. of microplastics detected
Laboratory environment	4 (one blank for each permeable pavement structure) PICP PICP+DWTS PCP Storage tank	The procedure consists of placing a glass container at the effluent collection point, filling it with a volume of deionised water similar to the effluent obtained in the experiments, and keeping it for approximately the same time as the effluent collection time. A 1 litre sample was then analysed for microplastic identification.	PICP: 4 PICP+DWTS: 2 PCP: 5 Storage tank: 4
Granular materials of the permeable pavement layers	6 (one blank for each layer) - Concrete brick - Concrete Porous surface - Joint filler (fine gravel) - Joint filler (fine gravel + DWTS) - Fine gravel - Coarse gravel	The materials were washed with deionised water. The volume from the washing was analysed for identification of microplastics.	- Concrete brick: 0 MP in 0.03 m^2 - Concrete Porous surface: 0 MP in 0.04 m^2 - Joint filler (fine gravel): 2 MP in 510 g - Joint filler (fine gravel + DWTS): 0 MP in 510 g - Fine gravel: 1 MP in 2500 g - Coarse gravel: 3 MP in 2600 g

Anexo 2

Tratamiento y reutilización de escorrentías urbanas mediante pavimentos permeables

Conferencia 1

CAN PERMEABLE PAVEMENTS ACT AS WATER STORAGE SYSTEMS? EVALUATION OF WATER TREATMENT CAPACITY AND REUSE

E. García-Haba[1*] · C. Hernández-Crespo[1a] · M. Martín[1b] · E. Albentosa[1c]
I. Andrés-Doménech[1d]

Abstract

As a nature based solution, permeable pavements offer multiple benefits and ecosystem services when the water resource needs to be managed. Nevertheless, the urgency in transforming urban areas under a more sustainable model, has stimulated the need of the development of this technology. This work fouses on the study of the functioning ability of permeable pavements, as a water storage system. Several filling and emptying cycles of a permeable pavement pilot plant, at a laboratory scale, are simulated, analysing whether its capacity of treatment allows the reuse of managed water to satisfy an irrigation demand from Mediterranean areas.

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[1d] igando@hma.upv.es

INTRODUCTION

Urban areas concentrate human activities, consuming a large amount of environmental resources (Grimm et al. 2008). Of particular concern are the challenges faced by these areas, such as climate change, population aging, or consumption of natural resources. In this context, a transformation of urban ecosystems is necessary to face these challenges (Elmqvist et al. 2008). The implementation of nature based solutions (NBS) must be addressed as a pillar of the paradigm of new sustainables cities. For example, permeable pavements as a sustainable urban drainage systems (SuDS) technique, offer multiple benefits and ecosystem benefits in terms of water quality and quantity. Several researches focus their studies on the capacity of pollutant removal in permeable sections, such as suspended solids, pathogens and even heavy metals. Additionally, the installation of permeable pavements in small urban agglomerations, provides operational protection of water treatment plants, based on artificial wetlands or lagooning. Permeable pavements reduce peak flow during rain events, and control suspended solids from entering the drainage system. Within the HOFIDRAIN Project framework, this study aims to investigate the suitability of giving permeable pavements a new function: underground storage of urban runoff and its reuse for a typical irrigation demand of the Mediterranean área. Despite the fact that urban runoff can contain high concentration of pollutants (Andrés-Doménech et al. 2018), the starting hypothesis states that stored runoff in the system, will be suitable for different urban uses, due to the treatment capacity of permeable pavements.

METHODOLOGY AND MATERIALS

The subterranean storage system provides collection and preservation of rain water, which can be used for different urban purposes, such as street washing and gardening. Since there is no legal framework that regulates its reuse in Spain, the water quality requeriments set out in R.D. 1620/2007, which establishes the Legal Regime for Treated Water Reuse for urban use, will be taken as reference (MINISTERIO DE MEDIO AMBIENTE Y MEDIO RURAL Y MARINO, 2010).

The simulation of the operation of the permeable pavement storage tank (PPST) during a rain event, considers that it receives both direct precipitation on the pavement, and runoff that reaches it. The ratio between the impervious surface that drains towards the permeable pavement is 2 to 1, that is, 2 m^2 of impervious surface for every m^2 of permeable pavement. Once the storage capacity of the PPST is completed, water levels inside it are managed according to a typical irrigation demand in Mediterranean areas. Direct precipitation is simulated by adding deionized water into the PPST, while runoff is simulated from real samples, taken in a small impervious catchment of 79 m^2 within the facilities of the Universitat Politècnica de València (UPV) (see figure 1).

Figure 1. *Photographs of the impervious catchment and the sampling chamber (Andrés-Doménech et al. 2018).*

To study the treatment capacity of the permeable pavement system, two samples are analysed: PPST input (PPSTi) and PPST output (PPSTo). The PPSTi sample consists of a representative mixture of runoff collected by an automatic sampler (ISCO3270) equipped with a liquid detector, and a set of 24 1-litre bottles. The Monitoring System is complemented with a 0.2 mm precision Dectronic rain gauge, with a Bühler Montec datalogger. This allows to record the hietogram of the rain and to determine the corresponding volume of deionized water to be added into the PPST. The water quality parameters analyzed are: organic matter, nutrients, total suspended solids (TSS), turbidity, electrical conductivity (E.C.), pH, dissolved oxygen, temperature and *Escherichia coli*.

The pilot plant is located in the Sanitary Engineering Laboratory, at UPV. It consists of a 0.25 m^2 permeable pavement system, designed to evaluate the hydraulic capacity of a permeable surface and quality of infiltrated water. The PPST is configured, from bottom to top, by 25 cm of washed limestone gravel + geotextile layer + 5 cm of fine washed limestone gravel + permeable block paving which joints are topped with small size gravel. Likewise, a drain pipe is placed on the bottom of the system, and connects to a flexible pipe that allows regulation of the water level inside the PPST. Periodically, samples from the PPST are taken to monitor the water quality inside the system. The extracted volume corresponds to the existing irrigation demand. In case of the hydraulic capacity of the PPST is exceeded (29 litres), water flows through the flexible pipe. Then, another sample is also taken (see figure 2).

Figure 2. *Different views of the PPST.*

RESULTS

At the time of writing this abstract, three rainfall events have been replicated in the pilot plant, which rainfall volumes were 8.36 mm, 15.22 mm and 28.45 mm respectively. The water quality parameters of the PPST input and ouput are shown in table 1. The results indicate a significant improvement in the water quality, confirming the capacity of treatment of the permeable pavement. It is noted that part of the improvement is due to the effect of dilution with rainwater. Therefore, other processes such as biodegradation and filtration help to improve water quality.

Tabla 1. *Aljibe's input and output water quality parameters (average values of the analysed events).*

Water quality parameter	PPSTi	PPSTo
COD (mg/l)	49	7.5
TN (mg/l)	3.00	0.9
TP (mg/l)	0.278	0.015
TSS (mg/l)	111	5.5
Turbidity (NTU)	108	2.7
E.C.$_{25^\circ C}$ (µS/cm)	222	200
E. coli (UFC/100 ml)	4.3	1

For water reuse purposes, it is remarkable the reduction of suspended solids and organic matter, since they could cause clogging problems in irrigation systems. It is also worth noting the low hydraulic conductivity of the stored water, which is beneficial to avoid soil salinization. In this case, it is not observed a decrease between PPSTi and PPSTo. The effect of dilution by rainwater is balanced by the contribution of salts, contained in the materials that configure the pilot plant. Finally, in relation to microbiological quality, the stored water meets the requirements established in RD 1620/2007 for urban uses in Spain (E. coli <200 CFU / 100 ml, TSS <20 mg / l, turbidity <10 NTU).

CONCLUSIONS

The main conclusion that can be drawn from the first tests, is that permeable pavements hold high treatment capacity. This fact means that permeable pavements can act as water storage systems for later reuse for urban uses, complying with legal requirements on the reuse of treated water. The availability of this high-quality water resource at a city scale, can lead to significant energy savings in drinking water supply and well pumpings. Therefore, a new functionality of the technology is presented, which is recommended to be incorporated in the transformation path towards the more sustainable city models. The study reveals a new ecosystem service, provided by this type of nature based solutions, in addition to those already known, such as heat island effect reduction, infiltration improvement or flood risk reduction.

ACKNOWLEDGEMENTS

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Conferencia 2

#204 - Permeable pavements as stormwater storage systems for water reuse in a Mediterranean city and evaluation of their treatment capacity

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Highlights

- A permeable pavement pilot system is tested to analyse its capacity of treatment.
- Permeable pavements significantly reduce suspended solids and organic matter.
- Permeable pavements can provide collection and preservation of stormwater for water reuse.

Introduction

According to UNESCO (2020), a huge number of people will suffer the alteration of the water cycle as consequence of climate change. Changes in precipitation and temperature will affect the availability of water, quality and quantity of water for basic human needs. Concretely, urban areas concentrate the main human activities, consuming a large amount of environmental resources (Grimm et al. 2008). In this context, a transformation of urban ecosystems is necessary to face these challenges (Elmqvist et al. 2008). The implementation of nature based solutions (NBS) must be addressed as a pillar of the paradigm of new sustainable cities. For example, permeable pavements allow effective management of urban runoff, providing attenuation, volume retention and pollutant load removal (Liu et al. 2020). Within the HOFIDRAIN Project framework, this work aims to study the suitability of permeable pavements as stormwater and runoff storage system for later reuse, under Mediterranean climate conditions. The underground storage system, hereafter referred to as PP storage tank (PPST), provides collection and preservation of stormwater, which can be used for different urban purposes, such as street washing and gardening. Despite urban runoff can be highly polluted (Andrés-Doménech et al. 2018), the starting hypothesis states that runoff stored in the system, will be feasible to use for different urban uses, due to its own capacity of treatment. It is expected that biodegradation processes will suppose a significant effect in the treatment process, due to the contact between stored water and formed biofilm. Previous existing studies propose using permeable pavements for water treatment, and separate underground tanks to provide storage capacity (Beecham et al. 2010), (Winston et al. 2020) and (Ghishi et al. 2020). However, this study evaluates the behaviour of the PP functioning as an underground storage tank, and aims to contribute to a wider disposal of information regarding these systems. Since there is no legal framework that regulates water reuse in Spain, the water quality requirements set out in R.D. 1620/2007, which establishes the Legal Regime for Treated Water Reuse for urban use, will be taken as a reference.

Methodology

At a laboratory scale, a pilot plant has been performed in order to simulate the operation of the PPST (Figure 1).

Figure 1. Different views of the permeable pavement storage tank (PPST).

Located in the Sanitary Engineering Laboratory, at Universitat Politècnica de València (UPV), the PPST consists of a 0.25 m^2 permeable pavement system, designed to evaluate the hydraulic capacity of a permeable surface and the quality of the infiltrated water. From bottom to top, the PPST is composed of 25 cm of washed limestone gravel + geotextile layer + 5 cm of fine washed limestone gravel + permeable block paving. Joints between blocks are topped with small size gravel. The storage capacity of the system, according to the layers porosity, is 29 litres. To allow regulation of the water level inside the PPST, a drain pipe is placed on the bottom of the system. The PPST is designed to receive inputs from both direct rain on the pavement, and runoff from a surrounding impervious asphalt in relation 2:1 (impervious area: pervious area). The simulation of the inputs of the system, considers the addition of deionized water as direct rain, and real samples for runoff, taken from a small impervious catchment of 79 sqm within the facilities of the UPV.

To monitor the operation of the PPST, corresponding samples of direct rain on the pavement (DR) and runoff (RI), generated by a single rain event, are determined. The RI sample consists of a representative mixture of runoff, collected by an automatic sampler (ISCO3270), equipped with a liquid detector and a set of 24 1-litre bottles. The Monitoring System is complemented with a 0.2 mm precision *Detectronic* rain gauge, with a *Bühler Montec* datalogger. This allows to collect rain data and to determine the corresponding volumes of RI and DR to be added into the PPST.

To study the treatment capacity of the system, two samples are analysed, corresponding to runoff input (RI) and PPST's output (PPSTO). Systematically, analysis of RI samples take place after a rain event. In relation to PPSTO samples, they are periodically analysed. Every 15 days, a sample of the water inside the PPST is extracted and analysed as control process of the water quality inside the system. In case the hydraulic capacity of the PPST is exceeded, water flows through the drain pipe. Then, another sample is also taken and analysed. The water quality parameters analysed are: organic matter, nutrients, total suspended solids (TSS) and turbidity, electrical conductivity (E.C.), pH, dissolved oxygen, temperature and *Escherichia coli*.

Results and discussion

At the time of presenting these results, eight rainfall events have been replicated in the pilot plant, which rainfall volumes were 15.22 mm (07/03/21), 28.45 mm (18/03/21), 5.17 mm (09/04/21), 3.90 mm (16/04/21), 20.60 mm (21/04/21), 9.50 mm (10/05/21), 15.70 mm (23/05/21) and 2 mm (17/06/21) respectively. Therefore, total volume of treated water applied to the PPST, is 70.44 litres, of which 37.55 litres correspond to runoff and 32.89 litres to direct rain. The total elapsed time since the start of the analysis is 102 days, while the average, maximum and minimum time between rain events is 14.57, 25 and 5 days respectively. The water quality parameters of the PPST's input and output are shown in Table 1. The results indicate a significant improvement in the water quality, confirming the treatment capacity of the PPST. It is noted that part of the improvement is due to the effect of dilution with rainwater.

Table 1. PPST's input and output water quality parameters (average values of the analysed events).

Water quality parameter	Runoff input (RI)	PPST's output (PPSTO)
COD (mg/l)	83	15.7
TN (mg/l)	4.28	1.4
TP (mg/l)	0.369	0.015
TSS (mg/l)	110	5.0
Turbidity (NTU)	124	2.7
E.C.25ºC (µS/cm)	397	242
E. coli (UFC/100 ml)	188	<1

For stored water reuse purposes, it is remarkable the reduction of suspended solids and organic matter, since they could cause clogging problems in irrigation systems. It is also worth noting the low hydraulic conductivity of the stored water, which is beneficial to avoid soil salinization. In this case, a decrease between RI and PPSTO is not observed. The dilution effect by rainwater is balanced by the contribution of salts contained in the materials that configure the pilot plant. Finally, in relation to microbiological quality, the stored water meets the requirements established in RD 1620/2007 for urban uses in Spain (E. coli <200 CFU / 100 ml, TSS <20 mg / l, turbidity <10 NTU).

Conclusions and future work

From the results, it can be concluded that permeable pavements hold high treatment capacity. The compliance with the Spanish legal requirements on the reuse of treated water, reaffirm permeable pavements as a powerful tool to act as water storage systems for later reuse, especially for urban uses. Therefore, it is recommended to incorporate this new functionality of the technology in the transformation path towards the more sustainable city models. Additionally, this study shows a new ecosystem service provided by this type of nature based solution, aside from those already known, such as water quantity management, heat island effect reduction or infiltration improvement. Future works should focus on the impact of the availability of this high-quality water resource at a city scale, on energy savings in drinking water supply and well pumpings.

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Anexo 3

Efecto del fango deshidratado de potabilizadora en la capacidad de tratamiento de un pavimento permeable

Conferencia 3

Permeable pavements as stormwater storage systems for water reuse in a Mediterranean city and evaluation of their treatment capacity

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Highlights

- A permeable pavement pilot system is tested to analyse its capacity of treatment.
- Permeable pavements significantly reduce suspended solids and organic matter.
- Permeable pavements can provide collection and preservation of stormwater for water reuse.

Introduction

According to UNESCO (2020), a huge number of people will suffer the alteration of the water cycle as consequence of climate change. Changes in precipitation and temperature will affect the availability of water, quality and quantity of water for basic human needs. Concretely, urban areas concentrate the main human activities, consuming a large amount of environmental resources (Grimm et al. 2008). In this context, a transformation of urban ecosystems is necessary to face these challenges (Elmqvist et al. 2008). The implementation of nature based solutions (NBS) must be addressed as a pillar of the paradigm of new sustainable cities. For example, permeable pavements allow effective management of urban runoff, providing attenuation, volume retention and pollutant load removal (Liu et al. 2020). Within the HOFIDRAIN Project framework, this work aims to study the suitability of permeable pavements as stormwater and runoff storage system for later reuse, under Mediterranean climate conditions. The underground storage system, hereafter referred to as PP storage tank (PPST), provides collection and preservation of stormwater, which can be used for different urban purposes, such as street washing and gardening. Despite urban runoff can be highly polluted (Andrés-Doménech et al. 2018), the starting hypothesis states that runoff stored in the system, will be feasible to use for different urban uses, due to its own capacity of treatment. It is expected that biodegradation processes will suppose a significant effect in the treatment process, due to the contact between stored water and formed biofilm. Previous existing studies propose using permeable pavements for water treatment, and separate underground tanks to provide storage capacity (Beecham et al. 2010), (Winston et al. 2020) and (Ghishi et al. 2020). However, this study evaluates the behaviour of the PP functioning as an underground storage tank, and aims to contribute to a wider disposal of information regarding these systems. Since there is no legal framework that regulates water reuse in Spain, the water quality requirements set out in R.D. 1620/2007, which establishes the Legal Regime for Treated Water Reuse for urban use, will be taken as a reference.

Methodology

At a laboratory scale, a pilot plant has been performed in order to simulate the operation of the PPST (Figure 1).

Figure 1. Different views of the permeable pavement storage tank (PPST).

Located in the Sanitary Engineering Laboratory, at Universitat Politècnica de València (UPV), the PPST consists of a 0.25 m^2 permeable pavement system, designed to evaluate the hydraulic capacity of a permeable surface and the quality of the infiltrated water. From bottom to top, the PPST is composed of 25 cm of washed limestone gravel + geotextile layer + 5 cm of fine washed limestone gravel + permeable block paving. Joints between blocks are topped with small size gravel. The storage capacity of the system, according to the layers porosity, is 29 litres. To allow regulation of the water level inside the PPST, a drain pipe is placed on the bottom of the system. The PPST is designed to receive inputs from both direct rain on the pavement, and runoff from a surrounding impervious asphalt in relation 2:1 (impervious area: pervious area). The simulation of the inputs of the system, considers the addition of deionized water as direct rain, and real samples for runoff, taken from a small impervious catchment of 79 sqm within the facilities of the UPV.

To monitor the operation of the PPST, corresponding samples of direct rain on the pavement (DR) and runoff (RI), generated by a single rain event, are determined. The RI sample consists of a representative mixture of runoff, collected by an automatic sampler (ISCO3270), equipped with a liquid detector and a set of 24 1-litre bottles. The Monitoring System is complemented with a 0.2 mm precision *Detectronic* rain gauge, with a *Bühler Montec* datalogger. This allows to collect rain data and to determine the corresponding volumes of RI and DR to be added into the PPST.

To study the treatment capacity of the system, two samples are analysed, corresponding to runoff input (RI) and PPST's output (PPSTO). Systematically, analysis of RI samples take place after a rain event. In relation to PPSTO samples, they are periodically analysed. Every 15 days, a sample of the water inside the PPST is extracted and analysed as control process of the water quality inside the system. In case the hydraulic capacity of the PPST is exceeded, water flows through the drain pipe. Then, another sample is also taken and analysed. The water quality parameters analysed are: organic matter, nutrients, total suspended solids (TSS) and turbidity, electrical conductivity (E.C.), pH, dissolved oxygen, temperature and *Escherichia coli*.

Results and discussion

At the time of presenting these results, eight rainfall events have been replicated in the pilot plant, which rainfall volumes were 15.22 mm (07/03/21), 28.45 mm (18/03/21), 5.17 mm (09/04/21), 3.90 mm (16/04/21), 20.60 mm (21/04/21), 9.50 mm (10/05/21), 15.70 mm (23/05/21) and 2 mm (17/06/21) respectively. Therefore, total volume of treated water applied to the PPST, is 70.44 litres, of which 37.55 litres correspond to runoff and 32.89 litres to direct rain. The total elapsed time since the start of the analysis is 102 days, while the average, maximum and minimum time between rain events is 14.57, 25 and 5 days respectively. The water quality parameters of the PPST's input and output are shown in Table 1. The results indicate a significant improvement in the water quality, confirming the treatment capacity of the PPST. It is noted that part of the improvement is due to the effect of dilution with rainwater.

Table 1. PPST's input and output water quality parameters (average values of the analysed events).

Water quality parameter	Runoff input (RI)	PPST's output (PPSTO)
COD (mg/l)	83	15.7
TN (mg/l)	4.28	1.4
TP (mg/l)	0.369	0.015
TSS (mg/l)	110	5.0
Turbidity (NTU)	124	2.7
E.C.25ºC (µS/cm)	397	242
E. coli (UFC/100 ml)	188	<1

For stored water reuse purposes, it is remarkable the reduction of suspended solids and organic matter, since they could cause clogging problems in irrigation systems. It is also worth noting the low hydraulic conductivity of the stored water, which is beneficial to avoid soil salinization. In this case, a decrease between RI and PPSTO is not observed. The dilution effect by rainwater is balanced by the contribution of salts contained in the materials that configure the pilot plant. Finally, in relation to microbiological quality, the stored water meets the requirements established in RD 1620/2007 for urban uses in Spain (E. coli <200 CFU / 100 ml, TSS <20 mg / l, turbidity <10 NTU).

Conclusions and future work

From the results, it can be concluded that permeable pavements hold high treatment capacity. The compliance with the Spanish legal requirements on the reuse of treated water, reaffirm permeable pavements as a powerful tool to act as water storage systems for later reuse, especially for urban uses. Therefore, it is recommended to incorporate this new functionality of the technology in the transformation path towards the more sustainable city models. Additionally, this study shows a new ecosystem service provided by this type of nature based solution, aside from those already known, such as water quantity management, heat island effect reduction or infiltration improvement. Future works should focus on the impact of the availability of this high-quality water resource at a city scale, on energy savings in drinking water supply and well pumpings.

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Anexo 4

Gestión de microplásticos mediante pavimentos permeables

Conferencia 4

Permeable pavements for microplastic pollution control: a laboratory analysis under mediterranean rainfall conditions

Chaussées perméables pour le contrôle de la pollution microplastique: une analyse en laboratoire dans des conditions pluviométriques méditerranéennes

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RÉSUMÉ

Le ruissellement des eaux pluviales lave les surfaces urbaines et entraîne les microplastiques vers les plans d'eau récepteurs. L'impact négatif causé par ce polluant dans l'environnement, souligne la nécessité de le contrôler. L'utilisation potentielle des Systèmes de Drainage Urbain Durables, et des chaussées perméables en particulier, parvient à réduire considérablement les particules en suspension transportées par le ruissellement. L'étude vise à étudier l'efficacité des chaussées perméables à la rétention des microplastiques. La réponse d'un chaussée perméable est testée sous un régime pluviométrique moyen à Valence (Espagne). Les résultats montrent une réduction significative du nombre de microplastiques infiltrés à travers la chaussée perméable. Les fragments de polypropylène étaient les particules les plus retenues. Bien qu'il soit encore nécessaire d'améliorer l'efficacité de la rétention des fibres, la mise en place de chaussées perméables en milieu urbain peut contribuer à réduire la présence de microplastiques dans les déversements d'eaux pluviales.

ABSTRACT

Stormwater runoff washes off urban surfaces and drives microplastics to receiving water bodies. The negative impact caused by this pollutant in the environment, raises the need to control it. The potential use of Sustainable Urban Drainage Systems, and permeable pavements in particular, manage to significantly reduce suspended particles carried by runoff. The study aims to investigate how effective are permeable pavements at microplastic retention. The response of a permeable pavement was tested under the average rainfall regime of Valencia (Spain). The results showed a significant reduction in the number of infiltrated microplastics through the permeable pavement (94%). Polypropylene fragments were the most retained particles. Although it is still necessary to improve fibre retention efficiency, the implementation of permeable pavements in the urban environment may help to reduce microplastic content in stormwater runoff discharges.

KEYWORDS

Microplastics, permeable pavements, pollution control, Sustainable Urban Drainage Systems.

1 INTRODUCTION

Microplastics (MPs) are, by definition, plastic particles whose longest dimension is below 5 mm (Malankowska et al., 2021). This pollutant contributes significantly to the deterioration of natural resources and wildlife (Grbić et al., 2020; Müller et al., 2020). In wet weather, stormwater runoff conveys important loads of contaminants, reaching water bodies without previous treatment (Piñon-Colin et al., 2020). Engineered nature-based solutions such as sustainable urban drainage systems (SUDS) offer stormwater management, providing water quality treatment among other benefits (Andrés-Doménech et al., 2021). Permeable pavements are a particular SUDS solution, widely used within the urban environment. This technique is presented to effectively trap solid particles and hence MPs (Grbić et al., 2020; Hernández-Crespo et al. (2019) and Fernández-Gonzalvo et al. 2021). In this study, MPs retention capacity of permeable interlocking concrete pavement (PICP) was tested at laboratory scale, under mediterranean rainfall conditions.

2 MATERIAL AND METHODS

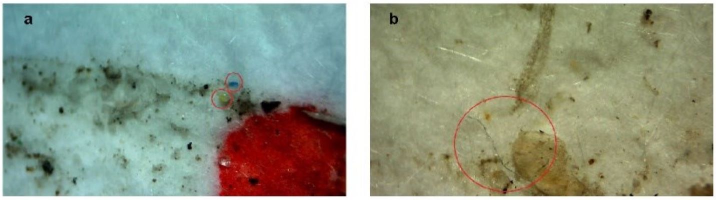
The experimental setup consists of a permeable pavement infiltrometer (PPI). From the top to the bottom, the pavement structure is comprised of interlocking concrete pavement (FIT-BLOCK by QUADRO); 5 cm of fine gravel (2-4 mm size); geotextile, 25 cm of coarse gravel (25-40 mm size), and geotextile. The interlocking separation is filled with fine gravel (3-6 mm size). A rainfall simulator was set, which was composed of a grid of drip irrigation pipes, a water storage tank, and two peristaltic pumps (LLG-uniPERISTALTICPUMP 3). A complete description of the experimental device can be found in Fernández-Gonzalvo et al. (2021).

Progressive pollution build-up was simulated applying real sediment of dust and dirt on the PPI surface. The sediment was collected under dry conditions using a mechanical sweeper on paved roads at Universitat Politècnica de València, and its deposition rate on the pavement was 5 g/m^2/d, according to Hernández-Crespo et al. (2019). Simplified rainfall inputs aimed at reproducing the average rainfall regime in València (Spain), in terms of rainfall volume, storm duration and inter-event periods. As demonstrated in Andrés-Doménech et al. (2010), average rainfall volume is 16 mm and average storm duration 30 min duration (32 mm/h). These synthetic rainfall conditions were reproduced every two weeks for a 2-year period. Deionized water was used to simulate rainwater.

Solid samples (real sediment) and water samples (infiltrated water) were analysed for microplastic identification. Due to high concentration of organic matter in solid samples, a sequential digestion process was applied using H_2SO_4 1:1 H_2O_2 (Hernández-Arenas et al., 2021) and H_2O_2 with Fe^{2+} as a catalyst (Hurley et al., 2018). In order to separate plastic particles from the solid matrix, a density method was developed using a saturated solution of deionized water and NaCl, with a concentration of 322 g/L (Bellasi et al., 2021). Then, samples from sediment and infiltrated water were filtered through 1.2 μm fiberglass filters. Microplastics were visually identified using stereomicroscope (MOTIC SMZ 143 N2GG) and Raman spectroscopy.

3 RESULTS AND DISCUSSION

After the 2-year testing period, a total mass of 912.5 g of sediment was deposited on the PPI surface, and a total volume of 59.81 L of water was infiltrated through the PPI. The characterisation study of the real sediment showed a concentration of 4.76 items/g, which supposes an accumulation of 4345.32 items. Identified polymers were polypropylene (PP) (71%), polyvinyl alcohol (PVOH) (10%), polyester-epoxy (7%), polyvinyl chloride (PVC) (5%), PP+cellulose (3%), polyethylene terephthalate (PET) (2%), polymethylstyrene (1%) and PVOH+cellulose (1%). According to shape, fragments were the most common (91%), followed by fibres (8%) and films (1%). It can be noticed that the most common polymer and shape found in the sediment used in this study, coincide with other sediments studied in Mbachu et al. (2022), Ziajahromi et al. (2020), Liu et al. (2019), Olesen et al. (2020) and Townsend et al. (2019).



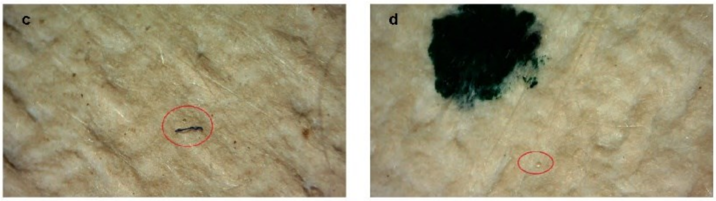


Figure 1. Examples of PP and polyester-epoxy fragments (a) and PP+cellulose film (b) found in the sediment matrix ; and examples of PP fibre (c) and acrylonitrile butadiene styrene (ABS) pellet (d) found in the infiltrated water samples.

In the infiltrated water, microplastic concentration was estimated to be 4.202 items/L, which means 251.32 microplastics released from the PPI. Particles of PP represented the 15% of the total, PVC+PP (13%), whereas ABS, PVOH, PET, polyester-epoxy, PVC, polymethylstyrene, nylon+acrylonitrile+polyester, PET+nylon+polyurethane, PP+PET+nylon, and polyester+PVC were in the same proportion (7.3%). Looking at identified shapes, they were fibers (55%), fragments (37%) and pellets (8%). The results represented in Figure 2 show an important reduction (94%) in the number of microplastic items between the sediment (INPUT) and the infiltrated water (OUTPUT). Assuming total suspended solids (TSS) as a potential indicator of MP pollution due to its strong correlation (Wang et al. 2020), this result is in the same order of magnitude as those obtained by Kamali et al. (2017), between 72% and 100%, and Hernández-Crespo et al. (2019) and Fernández-Gonzalvo et al. (2021), who demonstrated TSS retention efficiencies up to 99% considering high pollution build up and intense rainfall conditions. Minor presence of fragments and films in OUTPUT, in comparison with INPUT, suggests that permeable pavements hold high retention capacity of these shapes. Nevertheless, the proportion of fibres is major in OUTPUT than in INPUT, which is in the same line as in other case studies regarding SUDS for MP retention (Smyth et al. 2021 and Werbowski et al. 2021). This fact indicates that fibres are easily dragged by water across granular and geotextile layers.

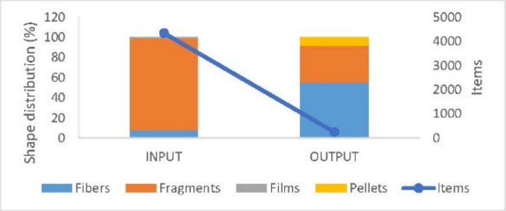


Figure 2. Microplastic shape distribution and total microplastic items found in the deposited sediment (INLET) and in the infiltrated water (OUTLET).

4 CONCLUSION

From the preliminary results of this study, it can be concluded that permeable pavements play a significant role as microplastic retention devices. These permeable structures allow retention of those particles which shape and dimension are prone to be trapped in the surface pavement and underlying layers. In order to improve the effectiveness of permeable pavements, future works should focus on the retention of fibers that scape from the system, considering a better design and the incorporation of new materials with greater retention capacity.

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Conferencia 5

Eficiencia de los pavimentos permeables para la retención de microplásticos de la escorrentía urbana

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Línea temática | Agua y ciudad.

RESUMEN

Durante eventos de precipitación, la escorrentía lava la superficie urbana transportando microplásticos hacia el medio receptor. El impacto negativo que provoca este contaminante en el medio ambiente plantea la necesidad de controlarlo. El uso potencial de los Sistemas Urbanos de Drenaje Sostenible (SUDS), y en particular de los pavimentos permeables, logran reducir significativamente las partículas en suspensión arrastradas por la escorrentía. El estudio tiene como objetivo investigar la efectividad de los pavimentos permeables para la retención de microplásticos, ensayando su respuesta en condiciones de laboratorio y bajo el régimen de precipitaciones medias de Valencia (España). Los resultados mostraron una reducción significativa en el número de microplásticos infiltrados a través del pavimento permeable (94%). Los fragmentos de polipropileno de tamaño superior a 0.1 mm fueron las partículas más retenidas. Aunque todavía es necesario mejorar la eficiencia de retención de microplásticos en forma de fibras, la implementación de pavimentos permeables en las ciudades puede ayudar a reducir el contenido de microplásticos en las descargas de escorrentías pluviales.

ABSTRACT

Stormwater runoff washes off urban surfaces and drives microplastics to receiving water bodies. The negative impact caused by this pollutant in the environment, raises the need to control it. The potential use of Sustainable Urban Drainage Systems, and permeable pavements in particular, manage to significantly reduce suspended particles washed-off by runoff. The study aims to investigate how effective are permeable pavements at microplastic retention. The response of a permeable pavement was tested under the average rainfall regime of Valencia (Spain). The results showed a significant reduction in the number of infiltrated microplastics through the permeable pavement (94%). Polypropylene fragments were the most retained particles. Although it is still necessary to improve fibre retention efficiency, the implementation of permeable pavements in the urban environment may help to reduce microplastic content in stormwater runoff discharges.

INTRODUCCIÓN

Los microplásticos (MP) son aquellas partículas de plástico cuya dimensión más larga es inferior a 5 mm (Malankowska et al. 2021). Este contaminante contribuye significativamente al deterioro de los recursos naturales y la vida silvestre (Grbić et al. 2020; Müller et al. 2020). En periodos de lluvia, la escorrentía urbana transporta cargas importantes de contaminantes, llegando a las masas de agua sin un tratamiento previo (Piñon-Colin et al. 2020). Las Soluciones basadas en la Naturaleza (SbN), como los Sistemas Urbanos de Drenaje Sostenible (SUDS), permiten una gestión sostenible de las aguas pluviales, proporcionando tratamiento de la calidad del agua entre otros beneficios (Andrés-Doménech et al. 2021). En particular, los pavimentos permeables como técnica SUDS, consiguen una retención eficaz de partículas sólidas y, por tanto, de MP (Grbić et al. 2020; Hernández-Crespo et al. 2019 y Fernández-Gonzalvo et al. 2021). En este estudio se analizó la capacidad de retención de MP de un pavimento permeable por junta a escala de laboratorio, simulando la acumulación de sedimento en superficie, bajo condiciones mediterráneas de precipitación típicas de la ciudad de València (España).

MATERIAL Y MÉTODOS

El montaje experimental consiste en un infiltrómetro de pavimento permeable (IPP) (Figura 1), estructurado de arriba hacia abajo por un pavimento de adoquines de hormigón impermeable con junta permeable (FIT-BLOCK de QUADRO); 5 cm de grava fina (tamaño 2-4 mm); geotextil (Polyfelt TS 30 TENCATE), 25 cm de grava gruesa (tamaño 25-40 mm) y geotextil. Las juntas entre adoquines se encuentran rellenas con grava fina (tamaño 3-6 mm). Se instaló un simulador de lluvia compuesto por una red de tuberías de riego por goteo distribuidas en 7 filas con 13 hidrantes por fila, una malla para romper y distribuir las gotas de agua según Naves et al. (2020), un tanque de almacenamiento de agua y dos bombas peristálticas (LLG-uniPERISTALTICPUMP 3) (Fernández-Gonzalvo et al. 2021).

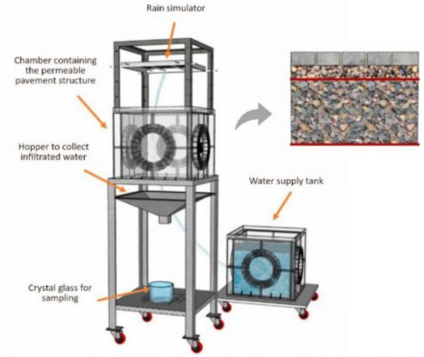

Figura 1 | Esquema y sección del infiltrómetro de pavimento permeable (adaptado de Fernández-Gonzalvo et al. 2021).

Se simuló la acumulación progresiva de contaminantes en la superficie del IPP, aplicando suciedad real en forma de sedimento. Este sedimento se recogió en seco mediante barredora mecánica, procedente de calzadas pavimentadas de la Universitat Politècnica de València (Yang et al. 2022). La aplicación de la suciedad se realizó mediante dispersión manual, aplicando una tasa de deposición de 5 g/m²/d, según Hernández-Crespo et al. (2019). De este modo, el sedimento actuó como input de MP.

La simulación de los eventos de lluvia consistió en reproducir el régimen pluviométrico medio de València (España), en términos de volumen de lluvia, de duración de las tormentas y de periodos entre eventos. En este sentido, se generaron lluvias sintéticas simplificadas de 16 mm de volumen y 30 minutos de duración (32 mm/h), cada 15 días (Andrés-Doménech et al. 2010). Se empleó agua desionizada para la lluvia sintética simulada. El experimento se llevó a cabo durante un periodo total equivalente a 2 años de simulaciones. Tras la simulación de los eventos de lluvia, se recogieron muestras del agua infiltrada por el pavimento permeable (output), empleando vasos de cristal. Un total de 6 muestras fueron recopiladas.

Para la extracción e identificación de MP, se consideró el análisis de dos tipos de muestras: matriz sólida (sedimento real) y matriz líquida (agua infiltrada). Debido a la alta concentración de materia orgánica en las muestras sólidas, se aplicó un proceso de digestión secuencial utilizando H_2SO_4 1:1 H_2O_2 (Hernández-Arenas et al. 2021) y H_2O_2 con Fe^{2+} como catalizador (Hurley et al. 2018). Para separar las partículas plásticas de la matriz sólida, se desarrolló un método de densidad utilizando una solución saturada de agua desionizada y NaCl, con una concentración de 322 g/L (Bellasi et al. 2021). A partir de este momento, tanto las muestras sólidas como las líquidas, se filtraron a través de filtros de fibra de vidrio de 1,2 µm. Los MP se identificaron visualmente mediante estereomicroscopio (MOTIC SMZ 143 N2GG) y espectroscopía Raman.

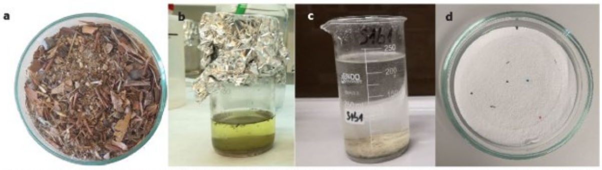

Figura 2 | Proceso de extracción de MP sometido a muestras de matriz sólida (a), tras aplicación del proceso de digestión (b), aplicación del método de densidad (c) y posterior filtrado (d).

RESULTADOS Y DISCUSIÓN

Tras el período de 2 años de experimento, la masa total de sedimento acumulado sobre la superficie del pavimento permeable fue de 912.5 g, y 59.81 L el volumen de agua total infiltrado a través suyo. El estudio de caracterización del sedimento real mostró una concentración media de 4762.2±973.8 MP/kg. Resultados similares obtuvieron Patchaiyappan et al. (2021) (2279.4±913.7 MP/kg), Dehghani et al. (2017) (entre 2776.7±333.3 y 20166.7±333.3 MP/kg) y Abbasi et al. (2017) (4400 MP/kg).

Según se muestra en la Figura 4., los polímeros identificados en el sedimento fueron: polipropileno (PP) (74 %), alcohol polivinílico (PVOH) (11 %), poliéster (7 %), cloruro de polivinilo (PVC) (5 %), tereftalato de polietileno (PET) (2%), y polimetilestireno (PME) (1%). Según PlasticsEurope (2022), Monira et al. (2021) y Gaaz et al. (2015), estos polímeros son los mayormente empleados para los usos industrial y doméstico, por lo que pueden resultar más fáciles de encontrar en el entorno urbano. Según la morfología, se detectaron fibras, films, y fragmentos, siendo estos últimos los más comunes (90%).

Estos resultados se muestran en la misma línea que en los obtenidos en otros estudios, cuyos polímeros y formas más frecuentes en los sedimentos analizados coinciden con los de este estudio (Mbachu et al. 2022; Ziajahromi et al. 2020; Liu et al. 2019; Olesen et al. 2020 y Townsend et al. 2019). Respecto del tamaño de las partículas, la gran mayoría de ellas resultaron ser menores que 0.1 mm (86%), coincidiendo con Dehghani et al. (2017), Abbasi et al. (2019) y Yukioka et al. (2020), en cuyos resultados muestran la alta representación de partículas por debajo de este tamaño.

En términos totales, el número estimado de MP que se acumularon en la superficie del pavimento tras la finalización del experimento, fue de 4345.32 partículas. Por otro lado, 251.32 partículas fueron liberadas por el pavimento permeable. Los resultados demuestran una importante reducción en el número de MP entre el sedimento aplicado y el agua infiltrada (94%). La inexistencia de estudios previos similares no permite la comparación entre los resultados obtenidos, poniendo de manifiesto lo novedoso de esta investigación. No obstante, debido a la fuerte correlación que existe entre MP y sólidos suspendidos totales (SST) (Wang et al. 2020), se asume que estos últimos pueden representar un indicador potencial de la contaminación por MP. De este modo, el resultado obtenido en este estudio es del mismo orden de magnitud que los obtenidos por Kamali et al. (2017), entre el 72% y el 100%, y Hernández-Crespo et al. (2019) y Fernández-Gonzalvo et al. (2021), quienes demostraron eficiencias de retención de SST de hasta el 99 % considerando una alta acumulación de contaminación y condiciones de lluvia intensa.

CONCLUSIONES

A partir de los resultados preliminares de este estudio, se puede concluir que los pavimentos permeables representan una solución factible y efectiva como dispositivos de retención de microplásticos en entornos urbanos, reduciendo así su descarga al medio natural. Estas estructuras permeables permiten la retención de aquellas partículas cuya forma y dimensión son propensas a quedar atrapadas en la superficie del pavimento y en las capas subyacentes. No obstante, son las partículas de tamaño inferior a 0.1 mm y de tipo fragmento, las que más frecuentemente escapan del sistema, por lo que su captura representa un importante desafío. Para mejorar la efectividad de los pavimentos permeables en este aspecto, deben plantearse futuras investigaciones enfocadas en la retención de las fibras que escapan del sistema, mejorando y optimizando el diseño, como la incorporación de nuevos materiales con mayor capacidad de retención.

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Glosario de términos

Al: Aluminio / *Aluminium*

DQO / COD: Demanda química de oxígeno / *Chemical oxygen demand*

DWTS: *Drinking water treatment sludge*

DSUs: Descargas de sistemas unitarios

EC: *Electrical conductivity*

EDAR: Estación depuradora de aguas residuales

ETAP: Estación de tratamiento de agua potable

HDPE: *High density polyethylene*

LDPE: *Low density polyethylene*

LOI: *Loss on ignition*

MPs: Microplásticos / *Microplastics*

NH_4^+: Amonio

NO_2^- : Nitritos

NO_3^-: Nitratos

NT / TN: Nitrógeno total / *Total nitrogen*

OD: Oxígeno disuelto

PCP: Porous concrete pavement

PET: Tereftalato de polietileno / *Polyethylene terephthalate*

PICP: *Permeable interlocking concrete pavement*

PO_4^{3-}: Fosfatos / *Phosphates*

PMS: Polimetilestireno / *Polymethylstyrene*

PP: Polipropileno / *Polypropylene*

PT / TP: Fósforo total / *Total phosphorous*

PVC: Policloruro de vinilo / *polyvinyl chloride*

PVOH: Alcohol polivinílico / *Polyvinyl alcohol*

SUDS: Sistemas urbanos de drenaje sostenible / Sustainable urban drainage systems

SST/ TSS: Sólidos suspendidos totales / *Total suspended solids*

TWP: *Tire wear particles*

BOD5: Biological oxygen demand

VSS: *Volatile suspended solids*