Ref. Ares(2025)8186865 - 29/09/2025

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D9.2 - NEW PAVEMENT COOLING MATERIALS AND NATURE-BASED SOLUTIONS FOR IMPROVING THE RESILIENCE IN URBAN SPACES

Development for the application to a real demo

September 2025 | (TECNALIA)

MULTICLIMACT

D9.2 – NEW PAVEMENT COOLING MATERIALS AND NATURE-BASED SOLUTIONS FOR IMPROVING THE RESILIENCE IN URBAN SPACES – DEVELOPMENT FOR THE APPLICATION TO A REAL DEMO

Project Title	MULTI-faceted CLIMate adaptation ACTions to improve resilience, preparedness and responsiveness of the built environment against multiple hazards at multiple scales
Project Acronym	MULTICLIMACT
Contract Number	101123538
Project Coordinator	Rina Consulting S.p.A.
WP Leader:	UNIVERSITA POLITECNICA DELLE MARCHE

Deliverable	D9.2 – New pavement cooling materials and Nature-based solutions for improving the resilience in urban spaces – development for the application to a real demo
DoA	Explanation in DoA
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Due date	September 2025
Report date	20/09/2025
Version	V4 (Final version ready for submission)

Document classification	PU Public

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REVISION TABLE

Version	Date	What
v1.0	24.02.2025	Table of Contents
v1.1	19.03.2025	First draft
v1.2	31.07.2025	First document for designed reviewer and WP9 leader internal review
v1.3	01/08/2025	Document including revisions by UNIVPM
v1.4	05/08/2025	Document including revisions by ENEA
v2.0	08/08/2025	Second draft ready for internal review
v3.0	31/08/2025	Third draft ready for quality check by the coordinator
v4.0	22/09/2025	Final version ready for submission

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ABBREVIATIONS AND ACRONYMS

ACRONYM	DESCRIPTION
AC	Asphalt Concrete mixtures
AS	Solar Absorptivity
BCN	Barcelona
BIM	Building Information Modeling
BOF	Basic Oxygen Furnace
BPMN	Business Process Model and Notation
Ca	Calcium
CT	Thermal conductivity
CC	Heat capacity
DT	Digital Twin
EC	Electrical Conductivity
EPA	US Environmental Protection Agency
ET	Evapotranspiration
FDR	Frequency Domain Reflectometry
HTTP	Hypertext Transfer Protocol
IoT	Internet of Things
ITSR	Water sensitivity test
J	Joule
KER	Key Exploitable Result
LPWAN	Low-Power Wide-Area Network
M&T	Materials and Technologies
N	Nitrogen
NBS	Nature-Based Solutions
NTC	Negative Temperature Coefficient
P	Phosphorus
PA	Porous mixtures
SUDS	Sustainable Urban Drainage Systems
Te	External Temperature

Tc	Temperatures for the vertical surface
URL	Urban River Lab
WPs	Work Packages
WTS	Wheel tracking test

Executive Summary

This document D9.2, entitled "New pavement cooling materials and Nature-based solutions for improving the resilience in urban spaces - development for the application to a real demo", aims to address the development of the innovative solutions designed in Task 3.2 to improve urban resilience to climate-related challenges, with a particular focus on mitigating urban heat islands and urban flooding. The work presented in this document includes the development and first outdoor test of cooling pavement solutions, the final design and construction of the bioswale units, and the implementation of the monitoring system necessary to adequately measure the most relevant parameters to be evaluated during the project for both M&T (Materials and Technologies), and also future KER (Key Exploitable Result), M#2 and M#7, namely the recycled urban pavements and the NBS (Nature-Based Solutions) for reducing the urban heat island effect (i.e., bioswale solutions).

The results achieved have been possible thanks to the collaboration and work of the Task partners, who have played a key role in this next step in the development of the proposed solutions to be further tested in Task 11.2 and other future Tasks within MULTICLIMACT.

COMSA was responsible for the development and construction of three 2 m x 2 m samples with three different asphalt mixes in an area close to Barcelona (BCN) in order to evaluate their application and effect in real conditions, with specific constraints, such as climate and structure of the pavement layers before being installed in the city of Barcelona. TECNALIA has contributed with measurements and their analysis, particularly with advanced thermal models within a joint work process with COMSA, which has resulted in a first evaluation of the initially proposed pavement with glass aggregates, the presentation of an alternative with another recycled material available in Barcelona, as well as the publication of two articles in indexed conferences. These publications are:

- Diego Zamora-Sánchez, Beñat Arregi, Mireia Fernandez et al. "Development and Outdoor Testing based on Monitoring Data and Finite Volume Models of Cool Asphalt Prototypes in HE MULTICLIMACT". IEEE MetroLivEnv 2025. (Zamora-Sánchez, et al. 2025)
- Beñat Arregi, Iñigo Lopez-Villamor, Diego Zamora-Sanchez et al. "Impact of Pavement Material Properties on Radiant Heat Exchanges with the Built Environment". SpliTech 2025.

NATURALEA has developed the NBS solutions that have been tested in Barcelona's Urban River Lab (URL) outdoor laboratory, which is included within the facilities of a Wastewater Treatment Plant, to optimize the design of the bioswales and to evaluate the components and structure of the bioswales, such as the gravels and plants herbaceous, shrubs, and other species used. Due to a permitting issue with the URL, as it is located within a critical water treatment facility, the bioswale variant with direct infiltration was carried out late in this project annuity outside this site.

Both solutions have been evaluated by comparing them with reference conditions, i.e., standard urban pavement in BCN and the absence of bioswale, through analysis of monitoring data, new tests and the same evidence of operational performance, leaving permanent monitoring systems in place to allow more detailed analysis as longer-term data and climatic events of interest accumulate, particularly for the bioswales whose monitoring was installed in July after the units were constructed at the URL.

The work done and the results presented below contribute to advance the development of these innovative solutions to improve resilience and address climate-related challenges in the built environment, focusing on the development of the solutions that will be installed and tested in the Spanish demo in Barcelona in Task 11.2 and Task 15.2 of the project and within the last phase of MULTICLIMACT.

1. INTRODUCTION

Task 9.2 "Materials and technologies for improving the resilience in urban spaces – development for the application to a real demo case", seeks to continue with the development of the design of solutions M#2 and M#7 proposed in Task 3.2 and the monitoring system for the Spanish demo, which will be tested in Task 11.2, concluding in Task 15.2. All this implies the construction and provision in this year of some first full-scale pavement and bioswales prototypes, evaluating their behavior through tests and evidence, configuring and communicating monitoring systems (within the possibilities of the sites), as well as analyzing the data collected with sensors and other tests in an outdoor environment close to the future demo in the city of Barcelona and/or laying the bases for their long-term collection in future phases of the project.

In particular, the M&Ts (Materials and Technologies) given a boost in Task 9.2 within this annuity are:

- M#2 Recycled urban pavements for reducing the urban heat island effect

During Task 3.2, an asphalt pavement was designed using recycled glass to help mitigate urban heat islands. Once designed in accordance with all technical and environmental considerations, a monitoring system and plan were developed, with the design of a modular system for real specimens exposed to the elements that was implemented in practice this annuity, enabling the integration of almost any sensor (these need to be chosen based on the availability of energy and other conditions at each site) and new features for Digital Twin contextualization. In the subsequent Task 11.2, a pavement demo will be installed in the city of Barcelona. It will be tested and compared with a reference and also with another existing cool pavement in Barcelona that was built as part of the HEATLAND project (LIFE16 CCa/ES/000077). The availability of this other pavement and its data still need to be confirmed by the Barcelona City Council during the next deployment phases.

In general, the data measured for M#2 needs to be compared with a physical-mathematical model developed in Task 9.2, to the extent that the knowledge and information gathered in this phase of the project allows. As already mentioned, M#2 is an ongoing live solution together with MULTICLIMACT, in which, during this Task 9.2, full-scale and outdoor samples of the glass aggregate-based cool pavement design (with two dosages) and a control pavement have been arranged, long-term data have been monitored and mathematical thermal models have been deployed, reaching relevant conclusions (along the lines of other recent ones in this field) and proposing a complementary design based in other recycled waste (steel slag aggregates) available in Barcelona.

- M#7 Nature-based solutions to reduce the urban heat island effect, purify water, and manage rainwater

Generally speaking, bioswales consist of a gravel trench of varying diameters that collects runoff water and, at the same time, improves water quality before it infiltrates the soil. These solutions are used, for example, in Barcelona Superilles (covered in this project, mainly in subsequent Tasks). Here, the objective of the MULTICLIMACT project is to obtain improved designs for bioswales and develop them through the evaluation in a controlled environment (open-air laboratory), assessing their effectiveness in improving water quality by reducing specific emerging pollutants/nutrients, their ability to regulate temperature thanks to self-sufficient vegetation layers, and their drainage functionality (only the bioswales will contribute to urban storm management within the project).

During Task 9.2, four real-scale bioswale units were built, three within the Urban River Lab (URL) and one outside, due to permit issues, as the laboratory is located within a critical water treatment infrastructure. Sensors capable of operating without a power supply have been selected and configured, given the restrictions of the site, and integrated into the modular monitoring system for urban solutions. However, data on long periods associated with climatic events of interest will not be available until later (given that the installation was carried out in July 2025 for one unit in the URL when the construction works were completed). The infiltration unit (located outside the URL) has demonstrated its drainage capacity during heavy rainfall compared to the previous situation at the

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site where it is located. Strong emphasis has also been placed on selecting plant species that do not require irrigation, which have survived the summer without any problems.

1.1. OBJECTIVE AND SCOPE OF THE DOCUMENT

This deliverable is completed by M24 of the project (period within phase 2 of "Develop and test," but with Task 9.2 being completed before the end of this phase, which concludes six months later with Task 11.2 in relation to M#2 and M#7). The general content is dedicated to the development and testing of the two M&T to improve the resilience of urban spaces: a new cool recycled pavement and a bioswale solution, to be addressed in a real-life demonstration scenario (in the city of Barcelona at the end of Task 11.2) to assess their impact on mitigating the heat island effect and urban flooding through stormwater management. The main challenge and objective of this deliverable is the development and construction of full-scale prototypes of these proposed M&T to mitigate the urban heat island effect, among other effects, and the development and assembly of the monitoring system to evaluate them. During this phase, if there is time, relevant data will be collected, and the foundations will be laid for monitoring during the next phase, "Deploy and Revise" phase of MULTICLIMACT in Task 15.2 (the construction of the demonstration will be carried out at the end of the "Develop and Test" phase in Task 11.2).

1.1.1. DEVELOP M#2 NEW COOL PAVEMENT SOLUTION (RECYCLED ASPHALT) TO MITIGATE HEAT ISLANDS FROM PLAN AND DESIGN CONCEPT

The initial design of the new recycled asphalt pavement with two dosages, based mainly on the addition of glass aggregates in the fine fraction, is evaluated using real data and thermal models that fit this data, in order to obtain information on its performance and the physical problem of street paving to mitigate heat islands in Mediterranean cities. Valuable conclusions are obtained, based mainly on a parametric study with variations in thermal parameters within a pavement, and on a specific study with the specimens (two full-scale cool asphalt prototypes and the corresponding contrast specimen) and the data collected.

Relevant conclusions have also been drawn regarding the performance of cool asphalt pavements to be installed at street level, the performance of the proposed pavement solution (including the proposal for another alternative). To increase the chances of constructing the best possible pavement in the Barcelona demonstration (at the end of Task 11.2) using locally available recycled materials, a new design based on the results obtained is also proposed.

1.1.2. DEVELOP M#7 NBS-BIO-RETENTION SWALE TO MITIGATE HEAT ISLANDS AND URBAN FLOODS FROM PLAN AND DESIGN CONCEPT

Full-scale bioswales have been constructed, which are observed to absorb and conduct water and show adequate development of their plant species without the need for assistance. Based on the initial designs, an implementation plan was drawn up for the bioswales at the URL, permits were requested, materials were purchased, and three units were built in this facility, in addition to one other unit at another outdoor location with fewer restrictions and no connection to the URL. It was observed that the full-scale bioswales that have been built absorb and conduct or infiltrate water (depending on the type), showing adequate development of their plant species without the need for assistance. Equivalent plant species tested in the URL give also good results for water purification.

1.1.3. IMPLEMENTATION OF A MONITORING SYSTEM FOR M#2 RECYCLED URBAN PAVEMENTS AND M#7 OUTDOOR SPECIMENS

Finally, to evaluate the performance of the developed solutions (M#2 and M#7) in real outdoor conditions, the comprehensive monitoring campaign designed during this Task was implemented. This sensor network is integrated into a modular digital architecture developed within the project, which

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has enabled the analysis, visualization, and contextualization of data through a Digital Twin environment of the developments carried out and will allow for the monitoring and validation of the developments in the Barcelona demonstration (at the end of Task 11.2). Sensor units may vary depending on the installation location and demo case requirements, which is why a flexible architecture has been implemented.

1.2. STRUCTURE OF THE DELIVERABLE

The Deliverable consists of 7 sections. It begins with Section 1, Introduction, providing the context and objectives of the document and the Task within the project, with a section dedicated to each solution and analyzing the connections and interdependence between related Tasks. This is followed by Section 2, which describes the technical expectations of the solutions and their implementations at this stage of the project. Section 3 focuses on describing the general approach of the working method, which is iterative and progressive in nature, in that the advancement and validation of solutions progresses throughout the project. Section 4 describes the developments in their current state, with prototypes, implementation of monitoring systems, analysis, and results obtained to date. Section 5 discusses deviations and Section 6 gives the conclusions and the status of actual work done and its fit and progression within future Tasks that are linked within MULTICLIMACT until the demo evaluation at the end of the project. Finally, Section 7 corresponds to the bibliography and Section 8 to the annexes.

1.3. INTERACTION WITH OTHER TASKS

The main interactions occur with the rest of the WP9 Tasks, namely T9.1 - “Materials and technologies for improving the resilience at territorial level - development for the application to a real demo case” and T9. 3 - “Materials and technologies for improving the resilience of buildings, including cultural heritage - development for the application to a real demo case”, as the three Tasks should jointly respond to the purpose of WP9 - “Materials and Technologies for supporting the built environment preparedness and responsiveness to disrupting events - Develop” (WP led by UNIVPM) within the Develop and Test Phase of MULTICLIMACT, but ending six months before the completion of this phase.

The main input outside WP9 was received from WP3, where the “Materials and Technologies to support built environment preparedness and resilience to disruptive events” were defined within the Plan and Design Phase of MULTICLIMACT. The results of this T9.2 / D9.2 are also direct inputs for the future Task 11.2 - “Demonstration of the MULTICLIMACT framework at urban scale”, both during the MULTICLIMACT Develop and Test Phase, as well as Task 15.2 - “Deployment of the MULTICLIMACT framework at urban scale”, during the MULTICLIMACT Deploy and Revise Phase.

1.4. CONTRIBUTIONS OF PARTNERS

The following table depicts the main contributions from project partners in the development of this deliverable.

PARTNER SHORT NAME	CONTRIBUTIONS
TEC	Task coordination, data monitoring system, physical-mathematical development of thermal models for evaluation of measures, parametric study for the evaluation of pavement proposals.
COMSA	Design and construction of the pavements, evaluation of thermal models results, preparation of new proposals, and laboratory testing of alternatives.

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NATURALEA	Design and construction of bioswales, selection and evaluation of vegetation, infiltration and purification tests.
BCN	Co-create and provide scope and context for the solutions to the other partners as the main stakeholder. Analyze the potential feasibility of the advances at the end of this task 9.2, which represents 75% of the progress within the develop and test phase, for the further application of these M&T to a real demo scenario in BCN.

Table 1. Contributions of Partners. Source: MULTICLIMAT

2. EXPECTED OUTCOMES AND IMPACT

This section presents the main technical objectives achieved in Task 9.2 and describes the expected impact of the implemented solutions. It outlines the progress made in the evaluation and improvement of the proposed designs through full-scale prototypes and the evidence, data and analysis results obtained, laying the groundwork for their future urban-scale installation in Task 11.2, and deployment and final revision in Task 15.2.

2.1. TECHNICAL OBJECTIVES

2.1.1. EVALUATION/IMPROVEMENT OF M#2 NEW COOL PAVEMENT SOLUTION (RECYCLED ASPHALT) TO MITIGATE HEAT ISLANDS BASED ON REAL SCALE PROTOTYPES

The objective is to setup full-scale specimens outdoors in a location near Barcelona, measure the temperature data in them, and analyse these data based mainly on physical-mathematical models. These models serve to evaluate and understand specifically the constructed case, with a specific study, and the problem in general terms, since it is considered that it is not well addressed by some current practices in this area.

As a result, specific conclusions are drawn about the original designs mainly based on glass aggregates, and general conclusions are also justified based on data and models that match these and can guide parametric analyses. Consequently, an evaluation of the designs of Task 3.2 is carried out once the specimens have been constructed and monitored, and a new pavement proposal is defined as plausible for implementation in Barcelona in subsequent Tasks.

Likewise, a monitoring system was assembled, capable of communicating data and contextualizing it in drone captures, and various temperature sensors have been configured and installed that are capable of measuring with battery power alone and communicating with 0G networks (this could the most viable option for future deployment in the city, which is why they have been included for testing in this Task, but the system can include any sensor capable of communicating data with slight modifications to the middleware).

2.1.2. EVALUATION/IMPROVEMENT OF M#7 NBS-BIO-RETENTION SWALE TO MITIGATE HEAT ISLANDS AND URBAN FLOODS BASED ON REAL SCALE PROTOTYPES

The objective is to build full-scale bioswales with both conductive and infiltration capabilities. These will feature native vegetation that can survive without irrigation or maintenance, and their performance will be evaluated as far as possible within the time allowed for this task (but will continue in subsequent tasks in accordance with the project).

This annuity, sensors have been set up to measure both the internal and external temperature of the bioswale, as well as other variables related to water infiltration, such as soil moisture and piezometers, all of which can send data remotely using 0G networks and batteries or solar

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accumulators. However, since the construction of the bioswales was completed after the mid-term general assembly organized by Tecnalia in Bilbao on April 2-3, the sensors were installed during the hot season, and it was necessary to collect more data on the evolution of infiltration variables with rainfall events in the following annuities (within the frame of Task 11.2). As for the assessment of the impact on the outside temperature, this will be mainly due to the presence of vegetation, so it was decided to install ambient temperature sensors, connected to MULTICLIMACT's online system for urban-scale solutions, in the Superilles of Barcelona (to be covered in a subsequent task) and in contrasting areas following direct indications by the BCN City Council's climate change office, since the scale factor is essential in this regard, i.e., it does not make much sense to measure the impact on the environment of a single bioswale specimen.

2.2. Expected Impact

Within MULTICLIMACT, solutions are sought that can help mitigate the heat island effect, in the case of paving with locally recycled materials and, in the case of biofilters with native plant species, the latter also contributing to stormwater management and water purification.

Within this framework, Task 9.2 aims to bring the designs developed in Task 3.2 to an initial validation under real conditions, through the construction of full-scale units in controlled outdoor case studies. These solutions will be evaluated based on real data, models calibrated to that data, and evidence gathered during their operation in small outdoor areas, in order to provide a solid foundation for demonstrations in the upcoming phases of the project.

As for the urban-scale monitoring system, within this Task 9.2, the impact lies in having a first test of the architecture designed in the previous Task 3.2 implemented for #M2 and #M7, as well as a selection of tested sensors that are capable of measuring the main variables of interest and communicating with it remotely or uploading data offline when this is not possible. Within MULTICLIMACT, the impact will be to have an operating system that is versatile enough to adapt different sensors depending on the final location of the demonstration (energy availability, network availability, site protection, possibility of installing at ground level or not, etc.) at the time of its deployment in Barcelona urban demonstrations at the end of the following Task 11.2 (and collecting data to contribute to Task 15.2).

3. OVERALL APPROACH

3.1. Business Process Model and Notation (BPMN) diagram

This section presents the workflow designed for the validation of the recycled pavement prototype and the bio-retention swale, specifically in the context of the Spanish demonstrator to be carried out in Barcelona (WP11). A BPMN diagram (Figure 1)Figure 1. Workflow for M#2 new recycled asphalt pavement prototype validation Source: MULTICLIMACT illustrating the key activities was developed to represent each phase of the process in a clear and detailed way. This diagram facilitates the visualization and understanding of the validation workflow, serving as a preparatory step for the real-life implementation of both systems in the urban demonstration.

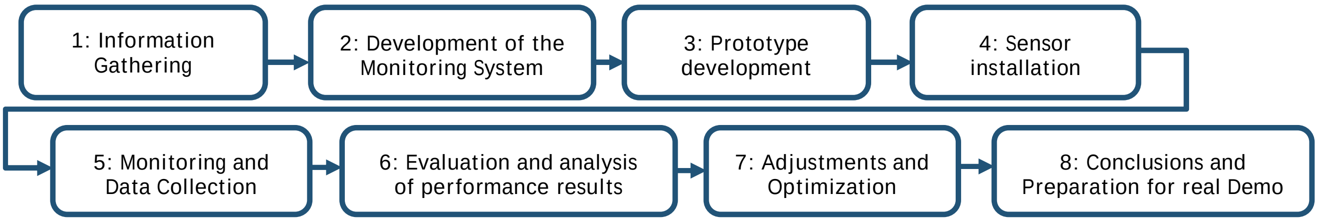

Figure 1. Workflow for M#2 new recycled asphalt pavement prototype validation Source: MULTICLIMACT

In the following points, the Tasks carried out in each phase of the validation process are presented:

- 1 Information Gathering
  Collection of initial data on the reference conditions of traditional pavement.
  - Review of the solution designed in Task 3.2.
  - Evaluation of materials and technologies for recycled pavements.
  - Evaluation of materials and structure of Bio-Retention Swale
- 2 Development of the Monitoring System
  Develop the monitoring system to evaluate the recycled pavement, including sensors to measure parameters such as solar reflectance index, thermal resistance, and other relevant variables.
  - Purchase of sensors.
  - Integration of monitoring technology.
- 3 Prototype Development
  Development and manufacturing of recycled pavement prototypes.
  - Installation of recycled pavement in the demo space.
  - Installation of the NBS solutions in the URL
  - Initial check of the pavement system functionality.
- 4 Sensors Installation
  Implementation of the monitoring system to evaluate the recycled pavement.
  - Installation of sensors.
  - System check of the monitoring system functionality.
- 5 Monitoring and Data Collection
  For a specific period, real-time data from the pavement system are monitored.
  - Collection of sensor data: sensor readings are continuously collected to monitor long-term system performance. Data collection will continue in subsequent Tasks until the project is completed to contribute to Task 15.2.
  - Continuous analysis of key parameters such as solar reflectance and pavement durability: these parameters continue to be evaluated to assess performance and aging. Monitoring and analysis will continue throughout the remaining Tasks of the project.

  - Continuous analysis of key parameters such as temperature regulation and water quality in the Bio-Retention Swale: the impact of the system on microclimatic conditions and runoff quality is being evaluated. More data will continue to be collected and analyzed until the end of the project to confirm trends and long-term effectiveness.
- 6 Evaluation and Analysis of Performance Results

  Compare the performance of the recycled pavement with traditional pavement regarding thermal efficiency, resistance, and other relevant parameters.
  - Comparison of surface temperature, solar reflectance indices, durability and mechanical behavior of the recycled asphalt pavement: these parameters continue to be evaluated throughout the remaining Tasks of the project.
  - Analysis of the performance of the recycled pavement versus the traditional pavement: these parameters continue to be evaluated throughout the remaining Tasks of the project. In addition, new alternatives for recycled asphalt will be analyzed.
  - Comparison of temperature and water quality in the Bio-Retention Swale system: these parameters continue to be evaluated throughout the remaining Tasks of the project.
  - Analysis of the performance of the Bio-Retention Swale system versus the traditional system: data will continue to be collected and analyzed during the following Tasks until the end of the project to contribute to Task 15.2, to confirm long-term performance and effectiveness.
- 7 Adjustments and Optimization

  Evaluation of the results from the data collected in the monitoring system.
  - Identification of necessary improvements or adjustments: based on the results obtained and new proposals established, the materials and systems developed will continue to be verified in the following Tasks until the project is completed.
  - Optimization of materials or technologies: based on the results obtained and new proposals established, the materials and systems developed will continue to be verified in the following Tasks until the project is completed.
  - Additional testing if needed: testing and validation of the improvements identified in the following project Tasks will continue.
- 8 Conclusions and Preparation for Real Demo

  Collection of validation results.
  - Preparation of the final validation report.
  - Preparation for the next phase of implementation in the real demo in Task 11.2.

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4. SYSTEM DEVELOPMENT, TESTING, AND VALIDATION OF THE NEW RECYCLED ASPHALT PAVEMENT AND BIO-RETENTION SWALE

This section addresses the comprehensive process of design, implementation, and evaluation of the developed technological solutions. This process includes the prototyping phase and experimental testing, which have allowed for the verification of the solutions' performance under controlled conditions in real-world environments. Furthermore, this section details the results obtained from the initial tests, the adjustments made based on the collected data, and the subsequent phases to ensure the effectiveness and viability of the proposed solutions.

4.1. M#2 NEW RECYCLED ASPHALT PAVEMENT TO MITIGATE HEAT ISLANDS DEVELOPMENT AND TESTS PRIOR TO DEMO-SITE

The results of the development, implementation, and validation of the Recycled Asphalt Pavement system are presented below.

4.1.1. OUTDOOR REAL-SCALE PROTOTYPES

During the initial phase of the project, and in coordination with the Barcelona City Council, it was agreed that the cool pavement solution – designed to mitigate urban heat island effect – would focus exclusively on the wearing course. The existing support structure would remain unchanged, replicating the standard pavement section typically found in local city streets. This strategic decision to intervene only in the asphalt wearing course ensures that the proposed solution is both easily replicable across the city and compatible with conventional pavement rehabilitation techniques.

Three full-scale outdoor prototype samples, each measuring 2 m x 2 m, were constructed in a location near Barcelona. These prototypes aim to evaluate and validate the proposed solutions under conditions similar to the real demo planned for later stages of the project in the city. The structural configuration and layer properties of the real-scale prototypes are as follows:

	THICKNESS [M]	THERMAL CONDUCTIVITY [W/MK]	VOLUMETRIC HEAT CAPACITY [J/M³·K]
Layer 1: Cool Asphalt	0.05	3 different mixtures (obtained in lab)	3 different mixtures (obtained in lab)
Layer 2: AC22	0.07	1.0	2,200,000
Layer 3: Base (HM20)	0.22	2.0	2,200,000
Layer 4: Sub-base (granular)	0.20	1.5	2,000,000
Layer 5: Natural soil	5.00	2.0	2,000,000

Table 2. Standard section in BCN is maintained below surface layer (reference thermal properties and thicknesses indicated above). Source: COMSA, (Zamora-Sánchez, et al. 2025)

As a result of the work collected in D3.2, AC mixtures modified with local recycled glass aggregates were identified as the most suitable for use in the development of the new recycled asphalt pavement. The use of porous mixes was discarded because they were considered not adequate to mitigate heat islands in Mediterranean cities with very little rain during the hot season, except intense sporadic rainfalls, as is the case of BCN. Since the solution to be proposed in MULTICLIMACT must be broadly applicable to have an impact on the city and, more generally, at the urban level, other possibilities were also examined (as mentioned in the earlier Task 3.2), but were deemed unfeasible due to their higher cost.

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Each of the samples replicates the same standard pavement section typically used in the streets of BCN. However, the top layer –the wearing course- contain three different asphalt mixes. Specifically, two innovative formulations or mixes were designed and mechanically tested and will be compared against a mechanically equivalent standard mix (Figure 2). The wearing course for each of the three samples is as follows:

- Mix 1: baseline (AC mix in BCN).
- Mix 2: 25% of recycled glass (in the sand or fine fraction) with normal aggregates (in the coarse fraction).
- Mix 3: 20% of recycled glass (in the sand or fine fraction) with white aggregates (in the coarse fraction).

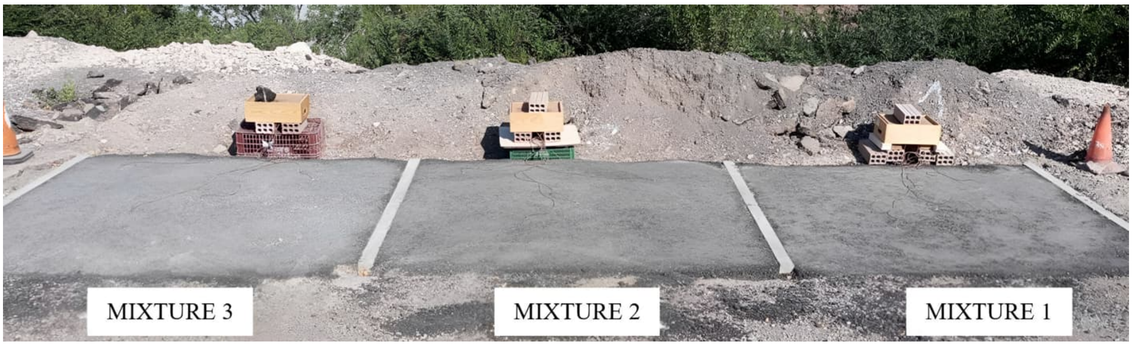

Figure 2. Three outdoor real-scale prototypes. Source: COMSA, (Zamora-Sánchez, et al. 2025)[

In accordance with regulations and BCN City Council approval, the amounts of recycled glass utilized in each instance are limited to achieve sufficient mechanical results for urban traffic T4 level (Ministerio de Transportes y Movilidad Sostenible 2015).

	MIXTURE 1	MIXTURE 2	MIXTURE 3
Density (T/m³)	2.50	2.38	2.39
Voids (%)	5.20	4.10	4.00
Voids in mineral aggregates (%)	16.50	15.40	15.60
Voids filled with bitumen (%)	68.50	73.50	74.20
Stability (average in kN)	17.40	13.34	11.10
Deformation (average in mm)	2.60	3.00	2.90
ITSR (%)	85.00	86.00	98.00
WTS (unitless)	0.06	0.19	0.12

Table 3. Mechanical tests: acceptable for T4 traffic levels in the center of Barcelona if approved for construction by the City Council. Source: MULTICLIMACT

Since there is no traffic on these slabs or samples, deformation monitoring is not provided. Furthermore, the location lacks electrical power and security to leave a fiber optic interrogator (high-cost instrumentation, already tested and incorporated to the monitoring architecture in the laboratory in the previous Task 3.2). This instrumentation will be reserved for monitoring in a real urban environment (after the final installation of the demonstration in Barcelona at the end of Task 11.2).

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4.1.2. SELECTION OF SENSORS/VARIABLES TO TEST THE SPECIMENS

To accurately evaluate the thermal behavior of the two formulations developed for the new recycled asphalt to mitigate the effect of heat islands on nearby citizens and buildings, the test specimens were exposed to real ambient conditions, and specific sensors were selected to monitor temperature variations inside the wearing course over time.

Specifically for this testing and validation phase, the manufactured prototypes were fully exposed to sunlight and were instrumented with four wired thermocouples each, placed under the wearing course. These thermocouples record the asphalt temperature at 10-minute intervals.

As for the placement of these thermocouples for the sample slabs, it is important to note that they were positioned at the intersection of the underlying AC22 layer and the wearing course: they are 5 cm deep. As it can be seen in the physical-mathematical thermal models that will be presented in section 4.1.4 to analyze the data, the authors are aware that significant measurements are the surface temperature, and the heat radiated to pedestrians and buildings. For this reason, it was proposed to later improve the monitoring system with the testing of complementary IoT (Internet of Things) sensors, both to measure the temperature radiated to vertical surfaces near the pavement and to obtain a more superficial direct temperature measurement in the pavement with shorter probes (at 2-cm deep). Nearby temperature and humidity are also measured, just to test IoT sensors for future city deployment (as small specimens like these cannot affect the open environment significantly). The punctual use of thermal imaging cameras to measure surface temperature could be considered in later phases (i.e., city demo implementation and deployment in Task 11.2 and 15.2).

The details of the instrumentation and its layout can be seen in Figure 3.

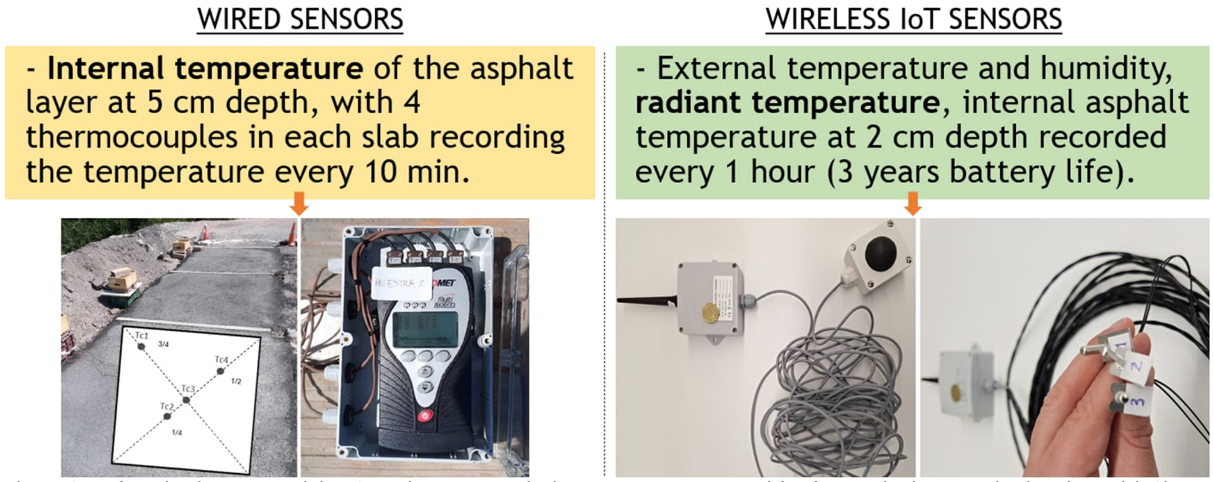

Figure 3. Left. Wired sensors. Right. Complementary wireless IoT sensors, tested for future deployment in the city, with SigFox nodes (capable of sending data every 1-2 hours and lasting more than 3 years on one battery) connected to: short probes prepared to measure asphalt temperature, resisting also installation on new poured asphalt, and a radiant temperature sensor. Source: TECNALIA

4.1.3. MONITORING CAMPAIGN INTEGRATED IN DIGITAL TWIN SYSTEM

To carry out the monitoring campaigns, 4 thermocouples (a type T thermocouple was used, with a 4x30 mm stainless steel sheath, 2 m of Teflon/silicone cable, and a type T Mini b compensated connector compatible with the Multilogger M1200E of COMET) were placed in each of the test samples. To achieve an optimal result, the thermocouples were distributed in each of the different prototypes, as show in Figure 4:

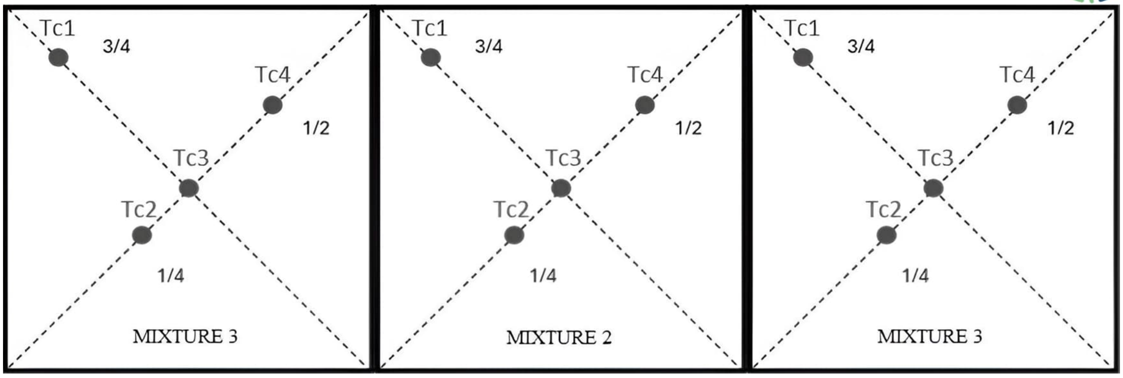

Figure 4. Plan layout of the wired thermocouples in the three slab specimens. Source: MULTICLIMACT

As previously reported, an important aspect is that in the arrangement of the thermocouples for each sample slab, the sensors were placed at the interface between the cool pavement wearing course and the underlying AC22 layer, ensuring accurate monitoring of temperature variations at this depth (5 cm). The later physical-mathematical analysis carried out in this document, referred to as the “specific study,” matches the thermal models to these measurements, since surface temperatures are not measured. As will be seen, the thermodynamic behavior of pavements is complex and temperatures vary throughout the pavement body and its exchange environment.

The monitoring architecture system, designed in Task 3.2 and implemented this annuity for the constructed specimens, is based on a modular architecture that allows for the capture, analysis and visualization of data in real time when data communication takes place (this will be guaranteed in the future urban demo in BCN through the IoT sensors initially configured and tested this annuity for internal temperature, external temperature, and radiant temperature). This architecture is able to integrate (online or offline) the indicated sensor network, signal processing, data analysis and visualization through Digital Twin contextualization, that can be based on Building Information Modeling (BIM) or other forms of visualization (the system is also versatile for this latter point of digital contextualization).(Figure 5 and Figure 6)

As explained, the monitoring system architecture (Zamora-Sanchez, Armijo and Fernandez, et al. 2024) has been developed following an approach based on the Digital Twin concept, which allows an accurate virtual representation of the data of the samples, facilitating the analysis and validation of the results obtained. In particular, the functionality of integrating real-time data windows into images captured by drones is another feature that was developed and added this year, making it a promising feature for larger areas where BIM models are not available, and a lot of work needs to be done from scratch to create them. For example, in urban areas, where no permits are required to fly even a small drone. During this Task 9.2, with full-scale prototypes for the M#2 and M#7 solutions, permission was granted to fly at the asphalt plant near Barcelona where the pavement slabs were built, but not to fly over the URL for the bioswales, as it is located within critical infrastructure for water treatment.

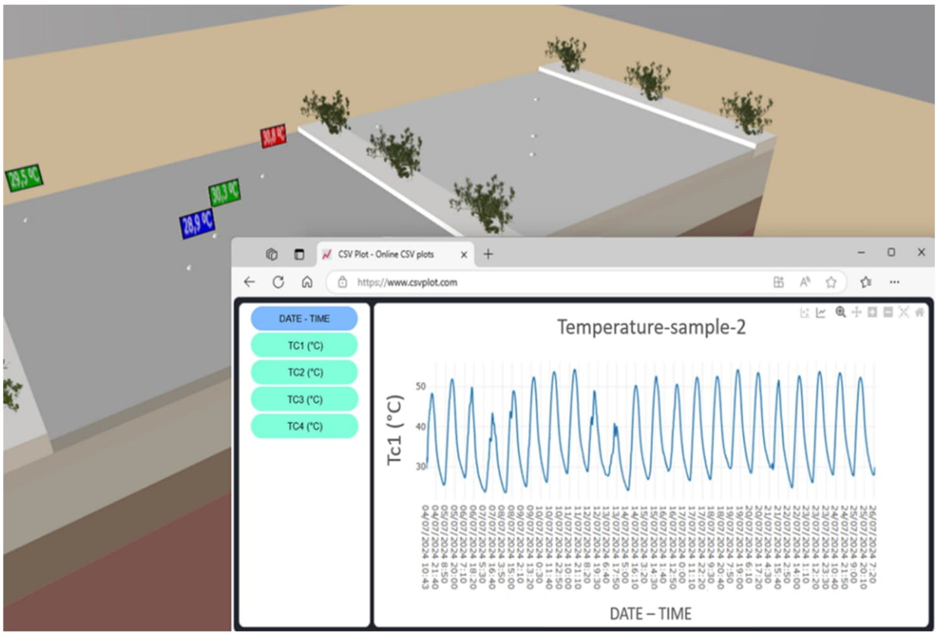

Figure 5. BIM contextualization of measurements (temperatures under the wearing course or upper layer on slab 2 for 23 days in early summer, from about 25 to 55°C) in the Digital Twin (DT) feature of the monitoring system. Source: MULTICLIMACT, (Zamora-Sánchez, et al. 2025)

Figure 6. Above. Contextualization of real-time data in the monitoring system architecture with reality captured by drone flight. Below. Details of the position of each of the sensors installed, either to perform integration tests in the monitoring system and/or to take their data into account in the analysis of the samples described later. Source: MULTICLIMACT

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4.1.3.1. Extended thermal model contrasted with real long-term data

This monitoring model's goal is to ascertain how the temperatures of the surrounding surfaces—people, buildings, etc.—are impacted by the pavement top layer material's characteristics, particularly its thermal conductivity, volumetric heat capacity, and solar absorptivity. These "off-pavement" effects must be considered when coming up with a final solution, especially in sunny and dry climates such as BCN, where a real pilot case will be implemented at the end of Task 11.2.

To evaluate the new recycled asphalt pavement, two parallel studies were carried out:

- A parametric study, comparing the behavior of the reference pavement with that of significant parametric modifications in the thermal properties of the wearing course.
- A specific study of the performance of the three bituminous mixtures, thermally characterized by laboratory testing, which were exposed to real conditions in a controlled outdoor scenario as described above.

Each of these studies was conducted using the method below, comprising two stages applied sequentially:

- A finite volume model (Cardiff y Demirdžić 2021) with hourly sampling for a complete year, based on normalized climate files. The model explicitly takes into account the effect of convective heat transfers with the environment, taking wind speed into account, the dynamic implications of thermal storage in the pavement through the heat capacity and density of every layer, the influence of incident solar radiation on the pavement surface, incorporating its absorption and reflection characteristics, and the effect of atmospheric radiation in the infrared wavelength.
- A model of radiant interactions with the environment, considering both long wavelengths (associated to infrared radiation and radiant exchanges) and short wavelengths (due to solar radiation).

To analyze the thermal behaviour of the pavement and its interaction with the environment, two general equations describing the energy balances on different surfaces were formulated. The first equation (Figure 7) represents the dynamic energy balance on the pavement surface, considering the main heat transfer processes. The second equation (Figure 8) describes the energy balance on nearby vertical surfaces, modelled with certain simplifications to facilitate their analysis.

4.1.3.2. General equation of the pavement thermal model

The thermodynamic model is founded on a dynamic energy equilibrium, expressed in the following exterior surface formula, where the different thermal processes converge: (Qs,a) as thermal inertia stored heat, (Qs,cond) as lower layers conduction gains, (Qs,conv) as exterior environment convection gains, (Qs,sw) as short-wave solar radiation thermal gains, and (Qs,lw) as long-wave infrared radiation.

$$Qs,a = Qs,cond + Qs,conv + Qs,sw + Qs,lw$$

Figure 7. General equation of the pavement thermal model. All heat exchange units in joule (J). For a more detailed explanation, see (Arregi, et al. June 2025) and (Zamora-Sánchez, et al. 2025).

4.1.3.3. General equation for nearby vertical surfaces

One of the main aims of this research is to determine the effect of pavement temperature on nearby vertical surfaces, understood as those that could correspond to people or adjacent buildings. To do this, the model finds the characteristic temperature of a vertical surface close to the ground by extending the modelling beyond the ground. The height and volume of this vertical surface are unimportant due to the ground model's abstract semi-infinite approximation. The physical phenomenon is formulated in Figure 8 as an adiabatic steady-state process, which assumes neither heat conduction nor storage. Thus, convective exchanges (Qc,conv) are balanced with radiative exchanges that are short-wave (Qc,sw) and long-wave (Qc,lw).

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$$Qc,conv + Qc,sw + Qc,lw = 0$$

Figure 8. General equation for nearby vertical surfaces. All heat exchange units in joule (J). For a more detailed explanation, see (Arregi, et al. June 2025) and (Zamora-Sánchez, et al. 2025).

The temperature at the pavement surface (Ts) and the temperature of a surrounding vertical surface (Tc) will be the primary outputs of the validation model of the cool asphalt proposals. Thermal comfort of pedestrians and the potential cooling loads required in buildings are influenced by this vertical surface temperature, which is an indicator of the boundary conditions experienced by a person's skin or a building façade.

As for the environmental conditions for conducting the parametric study detailed below, a typical meteorological year for the city of Barcelona was generated using the PVGIS tool (European Commission s.f.). This file contains all the parameters necessary to carry out the simulation.

The weather conditions for the specific study (later explained) were determined using the Weatherbit API (Weatherbit API s.f.) for the latitude and longitude corresponding to the test site where the specimens were constructed, namely an asphalt plant close to Tarrasa (41.575, 1.922), near BCN. All simulation parameters are included in this weather file, with the exception of long-wave infrared radiation. This means that using this data may lead to an underestimation of cooling during the night.

4.1.4. ASSESSMENT

To evaluate the performance of the tested specimens, a comprehensive assessment was conducted based on the collected data. This analysis focuses on interpreting the recorded measurements and comparing them against the expected behaviour, allowing for a detailed validation of the system effectiveness.

The following are the results of the parametric study and the results of the specific study of monitored prototypes.

4.1.4.1. Results of the parametric study

The box plot in Figure 9 enables to compare the cases of possible changes in thermal properties, which is the parametric study, presenting the distribution of the pavement surface temperatures (Ts) for each case generated together with the external temperature (Te). The following parametric variations or cases have been studied:

- 20% decrease in thermal conductivity (CT).
- 20% decrease in volumetric heat capacity (CC).
- 20% decrease in solar absorptivity (AS), i.e., increase in albedo.
- Associations of the abovementioned (CT+CC, CT+AS, CC+AS, CT+CC+AS).

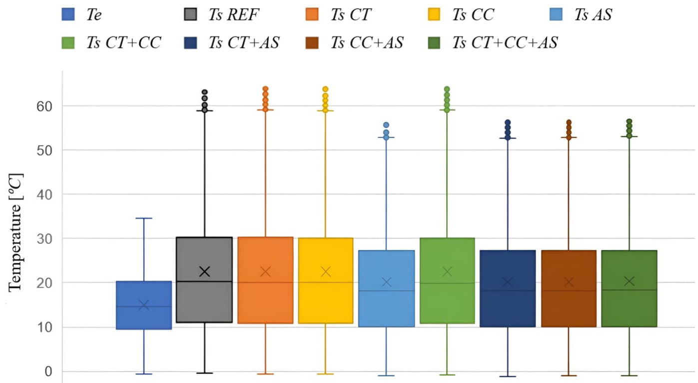

Figure 9. Parametric study for pavement surface temperatures (annual distribution). Source: MULTICLIMACT, (Zamora-Sánchez, et al. 2025).

Please note that temperatures are not measured at the pavement surface (since thermocouples are installed at a certain depth) but can be generated by the physical-mathematical model.

The graph illustrates how decreasing thermal conductivity and volumetric heat capacity have a similar impact on pavement surface temperatures, raising the daytime peaks and decreasing the nocturnal valleys. Conversely, lowering the solar absorptivity considerably lowers the surface temperature, particularly the highest values.

On the other hand, Figure 10 enables to analyze the comparison between the same cases, but plotting the distribution of the vertical surface (surrounding cylinder) temperatures (Tc) together with the external temperature (Te).

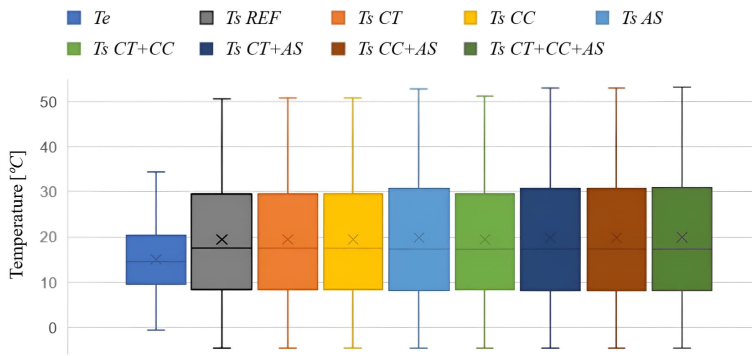

Figure 10. Parametric study for vertical surface temperatures (annual distribution). Source: MULTICLIMACT, (Zamora-Sánchez, et al. 2025).

It can be shown that the reduction in thermal conductivity and volumetric heat capacity has a very similar effect to that observed in research on the surface temperature of pavement. In contrast, an increase in pavement albedo, resulting from a reduction in solar absorptivity (or an increase in reflectivity), leads to a significant rise in the temperature of vertical surfaces. This factor is most noticeable at peak values, which has a detrimental effect on the residents of cities with a Mediterranean climate and high insolation, as is the case of BCN

We would like to emphasize that the results shown are derived from theoretical variations of the thermal properties in the reference model. This analysis can provide insight into the potential effects of altering one or another thermal property. We will use this approach again to analyze various possible alternatives for installation in the real-world demonstrator in Barcelona in Task 11.2, after evaluating the current design with the specific study.

This methodology based on physical-mathematical thermal models, as well as these results of the parametric study and the specific study (see next chapter) for the slab samples and the pavement section in Barcelona, are published in conference papers within Task 9.2 of MULTICLIMACT and made available through Zenodo by the project's D&C coordinator. The indexed articles, already cited within this document, are:

- Beñat Arregi, Iñigo Lopez-Villamor, Diego Zamora-Sanchez et al. "Impact of Pavement Material Properties on Radiant Heat Exchanges with the Built Environment". SpliTech 2025.
- Diego Zamora-Sánchez, Beñat Arregi, Mireia Fernandez et al. "Development and Outdoor Testing based on Monitoring Data and Finite Volume Models of Cool Asphalt Prototypes in HE MULTICLIMACT". IEEE MetroLivEnv 2025.

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4.1.4.2. Results of the specific study of monitored prototypes

A specific study was carried out on the monitored prototypes exposed to real outdoor conditions. This section presents the results obtained from the temperature measurements, providing a detailed evaluation of the thermal behavior of the specimens under real operating conditions.

To carry out the specific study on the full-scale prototypes tests, five representative days were selected within the framework of the experimental campaign, those combining a hot ambient temperature (varying between 20 and 35 °C) and intense solar radiation, which are the climatic conditions that can trigger the heat island effect in cities like BCN.

Several simulations were carried out using the model developed in this study, obtaining as output the temperature of each of the three samples between layers 1 and 2, where the thermocouples were installed (please note that we will not provide surface temperatures at this time; we want to adjust the model to the measurement as it was done: at a depth of 5 cm). In comparison to sample 1 (the reference mixture), samples 2 and 3 (cool mixtures) exhibit a decrease in the heat peaks, as seen in Figure 11.

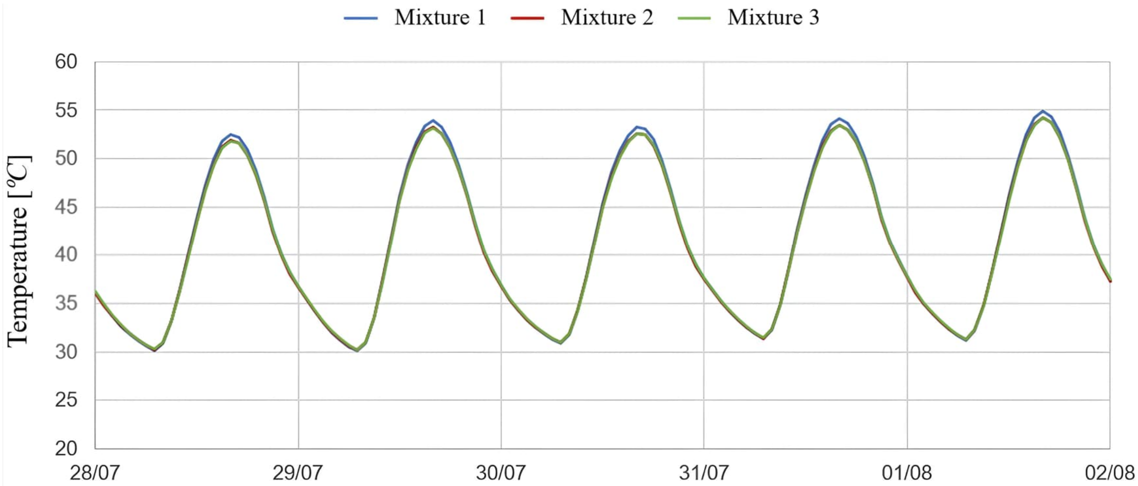

Figure 11. Temperature evolution simulated with the model under the upper layer of the asphalt pavement (at the interface of layers 1 and 2). Source: MULTICLIMACT, (Zamora-Sánchez, et al. 2025)

On the other hand, the following graph (Figure 12) shows the temperatures monitored during the experiment in the monitoring campaign for each of the three samples and the selected days, with the thermocouples placed under the top layer of the asphalt pavement. The data represented corresponds to the readings collected by the sensor placed in the center of each test sample (other values could have been considered, such as the average of the sensors installed in each slab, given that the position of a specific probe may be affected by falling next to an aggregate, etc., but the behavior has been judged consistent in the central thermocouples).

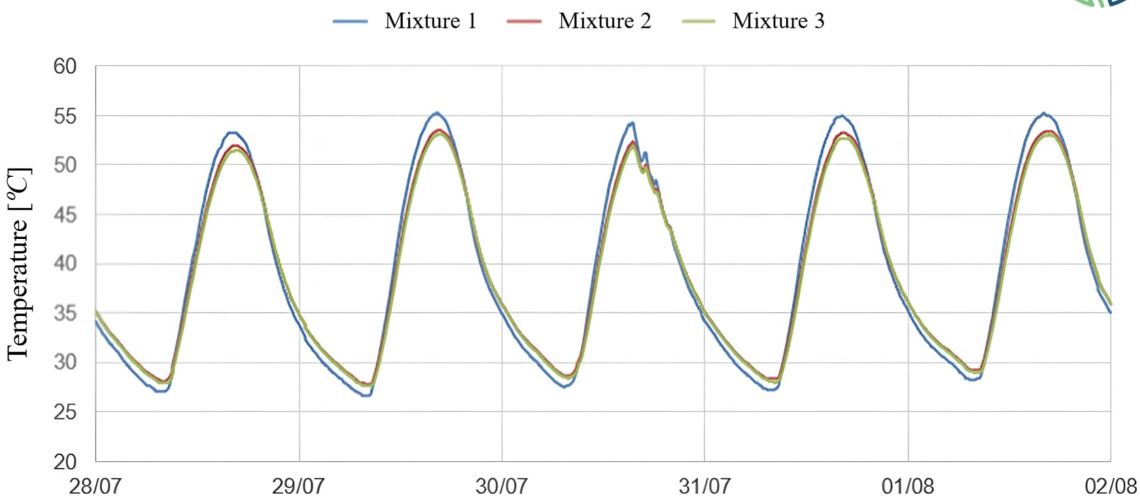

Figure 12. Evolution of temperatures monitored under the upper layer of the asphalt pavement (near the interface of layers 1 and 2). Source: MULTICLIMACT, (Zamora-Sánchez, et al. 2025)

The predictions of the model and the samples' measurements for temperatures under the upper layer (those now monitored) and their broad trends are consistent. In addition to the difference between sample 1 (which has larger heat peaks) and samples 2 and 3 (which have similar heat peaks of lesser intensity), the peak values for each day agree between the model and reality. As a result, the finite volume model constructed can be considered a reliable tool for simulating physical reality. As demonstrated by the parametric analysis, this means that it is also valid for simulating other possible changes in the design of cool asphalt pavements.

The slight discrepancies between simulations and measurements can be explained by several factors: (i) differences between assumed and actual environmental conditions, (ii) the influence of soil moisture levels not accounted for in the model, (iii) computational edge effects due to the finite size of the samples, and (iv) the location of thermocouples in the experiments (approximately at the bottom of layer 1), compared with the strict simulation of the interface between layers 1 and 2. In addition, the model appears to underestimate the nighttime cooling effect of the three specimens and does not capture their differences. This limitation is attributed to the climate archive, which lacks infrared radiation data, responsible for cooling the ground surface below ambient temperature during the night.

The trends are similar in the long-term temperature data, bearing in mind that no measurements of the surface of the slabs were taken at the time of this study, but AC mixtures with recycled glass aggregates appear to analytically produce a very slight increase in the temperature fluctuations of the pavement surface and that of the surrounding surfaces, increasing the peaks (at midday) and decreasing the troughs (at night) in the temperature of vertical surfaces. This could potentially help reduce heat at night, when air conditioning could be avoided in these cities. This effect, which could be calculated by the model, was shown to conform to measured reality, is approximately 1 °C. In the next phases of the project (city demo deployment), we could measure the surface temperature with thermal cameras (in addition to embedding probes at one depth or another), or focus only on the effects of the pavement on the radiant and ambient temperature of vertical surfaces, and/or also implement a pure Digital Twin application that incorporates models such as those developed.

4.2. M#7 BIO-RETENTION SWALE TO MITIGATE HEAT ISLANDS AND URBAN FLOODS DEVELOPMENT AND TESTS PRIOR TO DEMO-SITE

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The results of the development, implementation, and initial validation of the Bio-Retention Swale system are presented below.

4.2.1. OPEN-AIR URBAN RIVER LAB PROTOTYPES

During the initial phase of the project, an innovative bio-retention channel solution was defined to more efficiently manage stormwater in urban environments and mitigate the heat island effect through the construction of optimized bioswales. This solution integrates hydrological, environmental, and urban factors, with the objective of retaining, accumulating and treating water runoff on site, returning it to water bodies, infiltrating it or using it directly. It also provides additional ecosystem benefits, such as regulating urban temperature through evapotranspiration (ET) and creating shade (this depends on the scale of implementation), thus improving urban resilience to climate change.

Based on the results of the bio-retention swale solution collected in D3.2, several full-scale bio-retention channel prototypes were built at the URL in Barcelona. Different linear bio-retention systems with a 40 m total length (30 m constructed in URL and 10 m outside) were constructed during this T9.2 within MULTICLIMACT develop and test phase. These full-scale prototypes will be used to check the feasibility and validate the solutions along the project under conditions similar to those occurring in the city of BCN, which is where the real demo scenarios are planned for the later phases of the project. Each of the prototypes has a design that integrates the structure and typical components of a bio-retention system adapted to Mediterranean urban conditions. The prototypes were designed with native plant species, selected for their ability to adapt to the local climate without the need for drainage or additional irrigation, which increases the sustainability of the solution. However, units intended for direct water use may also have a drainage conduit, since they would not be infiltration units. On the other hand, units installed on more permeable soils would contribute by draining accumulated water through the soil and relieving drainage systems. By way of summary, the development focuses on easy to install units, with:

- Natural components, native and hardy plant species, generating maintenance-free vegetation reducing the impact of heat islands.
- Better drainage control, as infiltration ponds or as NBS conduits, with complementary cooling of the environment by accumulation of water and humidity in the soil as far as possible in climates such as that of the city of BCN.

These new M&T prototypes were constructed this annuity in the URL and a complementary location (where the validation of the developed solution will be carried out), present the following structure. Model A (Figure 13) is a bio-retention channel without waterproofing, designed to allow direct infiltration of rainwater into the soil. This model favors aquifer recharge and improves stormwater management by allowing water to soak into the ground naturally. On the other hand, Model B (Figure 13) is a waterproof bio-retention channel, which retains water on the surface, allowing for more controlled treatment and storage of water prior to reuse or release into the urban water system. It should be noted that during the construction phase (completed in May of this year), it was not finally allowed to install direct infiltration units in the URL, as this installation is included in the Montornès del Vallès Treatment Plant (*https://maps.app.goo.gl/TF6in9YvusX6qTNW8*), managed by the Besos-Tordera Consortium, considered a critical infrastructure by the authorities, who have not allowed this option (they prefer to channel the water). Therefore, an alternative location was also found to build the bioswale variant with direct infiltration (Model A), as will be described later.

Both models were implemented to evaluate their performance in real conditions, and the designs of the executed prototypes are presented in Figure 13:

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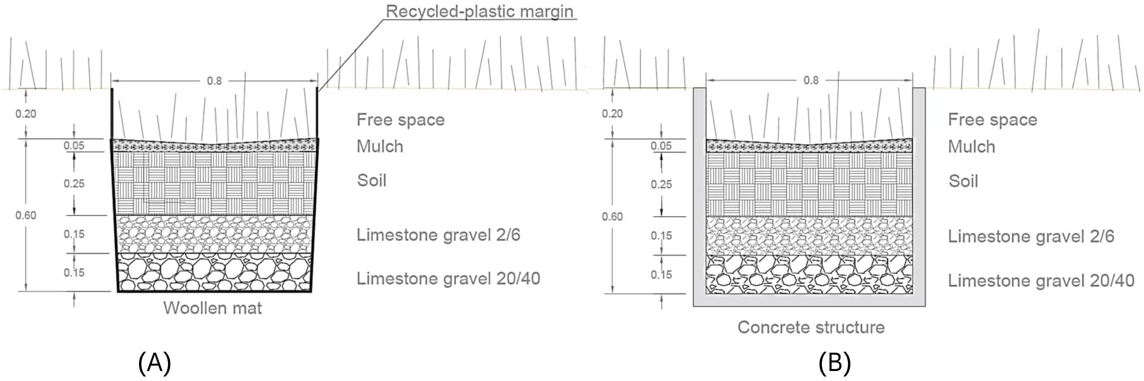

Figure 13. Structure of Bio-retention swale without waterproofing (Model A) and system of Bio-retention swale waterproofed (Model B). Source: NATURALEA

The following images (Figure 14, Figure 15 and Figure 16) show the project plan in which these solutions were implemented:

Figure 14. Plan of the project where bio-retention solutions were implemented in the URL. Source: NATURALEA

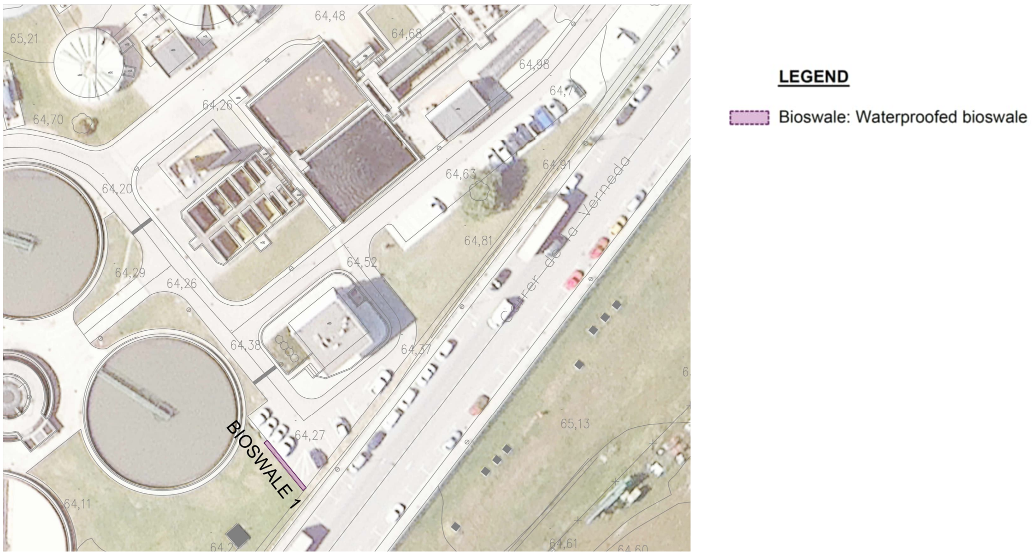

Figure 15. Detailed plan of the location of the bio-retention system with waterproofing that was planned at the URL. Source: NATURALEA

Figure 16. Detail plan of the location of the bio-retention system waterproofing that were planned at the URL. Source: NATURALEA

As explained, another representative external location was found to construct a prototype unit with direct infiltration, given the final regulatory constraints of the URL. Below (Figure 17) are some images of the construction process of the full-scale prototypes of the bio-retention systems:

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Figure 17. Construction of full-scale prototypes of the bioswales at the URL. Source: NATURALEA

As explained these units are of the waterproofed model, given the existing restrictions for infiltration and flooding within the critical infrastructure, a Wastewater Treatment Plant, which contains the URL.

Below are images of the bioswale units built at the URL, and subsequently instrumented (see next chapter) to test and integrate the sensor equipment into the monitoring system, and start obtaining data (Figure 18), which will be expanded and valuable for later phases of the project.

Figure 18. Photos of finisished bioswale units within URL during this WP9. Source: NATURALEA

As explained above, a fourth bioswale was built to collect rainwater from a parking lot in a location outside the URL (Figure 19, Figure 20, Figure 21 and Figure 22), which was completed in July. In this case with a totally draining function (in addition to the phytodepurative and cooling function of the system), which was not allowed to implement in the URL because it was located on the grounds of a sewage treatment plant:

Figure 19. Excavation of the outdoor bioswale prototype with direct infiltration capacity (end of June 2025). Source: NATURALEA

Figure 20. Arrangement of the gravel base. Source: NATURALEA

In this case, without concrete, allowing infiltration into the surrounding soil, is the solution implemented for this unit outside the URL.

Figure 21. Planting of plant species in the bioswale prototype. Source: NATURALEA

Native plant species were planted, which have a high survival rate without the need for additional care. This is considered to be the most natural, cost-effective, and sustainable way to help mitigate the heat island effect.

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Figure 22. Image of the bioswale unit with direct infiltration once completed. Source: NATURALEA

4.2.2. SELECTION OF SENSORS/VARIABLES TO TEST THE SPECIMENS

The monitoring, punctual or continuous, of bioswales is complex because it involves several objectives:

- To see if they can contribute to the reduction of heat island effects.
- To evaluate their drainage capacity, which can also be done based on direct soil zone tests, and to calculate a result according to the geometry of the trench.
- To check the phytodepuration function of the system, only on the basis of sampling and corresponding laboratory analysis.

Bioswales are NBS designed to manage stormwater runoff and improve water quality in urban areas. They are typically shallow channels filled with plants (but not always), gravel and soil to capture, regulate and filter stormwater. MULTICLIMACT prototypes are units with native vegetation, making them an effective and sustainable solution capable of contributing to stormwater management in urban areas, and promote environmental resilience and biodiversity. It was demonstrated through decades of research that vegetation presence is a key factor in the mitigation of heat island effects (Gallo, et al. 1993) (Massaro, et al. 2023) , so vegetated bioswales, by providing self-sufficient vegetation, will help in this line, together with other contributions of this type of systems, which would be summarized as follows:

- Shade: because they are covered with vegetation, bioswales provide varying degrees of shade (depending on the size of the plants and the scale of the real implementation) and reduce the amount of direct sunlight reaching nearby surfaces, which lowers the temperature.
- Evapotranspiration: in bioswales, moisture is absorbed and retained by plants and soil before being expelled into the atmosphere.
- Stormwater management: by capturing and absorbing rainfall, bioswales help control stormwater runoff, preventing it from accumulating on hot surfaces and worsening the heat island effect.
- Air cooling: shading, evapotranspiration and stormwater management contribute to cooling the surrounding air (mitigating the heat island effect).
- Improved air quality: overall air quality in urban areas is improved by vegetation, which filters pollutants from the atmosphere.
- Reduced flash flooding: by slowing and absorbing stormwater runoff, bioswales also help reduce point flooding and, as mentioned above, prevent runoff from accumulating on hot surfaces.

Therefore, it seems clear that they can at least contribute to reducing the impact of heat islands, and the sensors proposed to measure this are:

- Ambient temperature and humidity sensors (NTC Thermistors by Vishay, with operating temperature range at zero dissipation from -25 to +105 ºC). It is worth noting that they will start to measure differences in areas that are considerably vegetated versus others that are not or were not. That is, they need to be compared at a certain scale, which will be done in later phases of the project. In addition, beyond accuracy, it is important to consider the degree of shade or insulation that each sensor receives in order to make effective comparisons at a later stage of the project. For example, if the temperature drops due to shade from vegetation, this is a positive effect, but it should be known that this is due to the shade rather than a reduction in the ambient temperature itself, etc.

- Radiant temperature sensors, which are closer to measuring the effect felt by nearby passers-by and, in general, the irradiance to nearby vertical surfaces (building facades) from elements placed on the city floor. A question of scale also applies, as in the previous point.

In contrast to typical temperature probes, radiant temperature sensors are black bodies that capture the radiation emitted by different surfaces. In the image below you can see the image of one of these sensors installed in a bioswale unit at the URL (Figure 23) (Datenblatt-AST from D-Sensors GmbH, for outdoor use detects temperatures in the range of -30...+90°C with accuracy accoding DIN EN 60751 and DIN EN 43760, with NTC ±1%), as well as of an IoT transmission node (HC-ANA Sigfox units from HC Technologies), in this case in charge of transmitting the data coming from ambient temperature and humidity. This commercial model of IoT solution, to which different sensors can be connected, has been chosen for its versatility for installation in this phase of the project, demonstrating the system architecture's ability to integrate most types of sensors and communication protocols. However, it can be complemented or replaced by other sensors in the future demonstration phase, depending on the needs and conditions of the demonstration itself and the site.

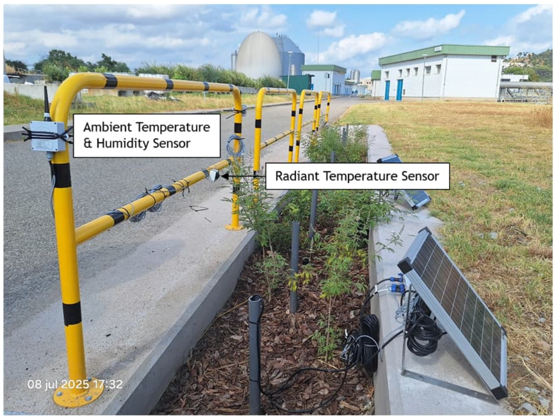

Figure 23. Sensors installed in a bioswale prototype at the URL. Source: MULTICLIMACT

The problem is the lack of representative contrast data, that is, to evaluate the mitigation capacity of the heat island simply with a measurement for an isolated bioswale unit within the URL. In any case, it is attributed a capacity dependent on the amount of vegetation that can be provided, having already been installed in the city of Barcelona ambient temperature and humidity sensors at various points of the Superilles and near contrast points (without vegetation) (Figure 24), to evaluate if the presence of vegetation surfaces has an impact on the temperature during next phases of the project.

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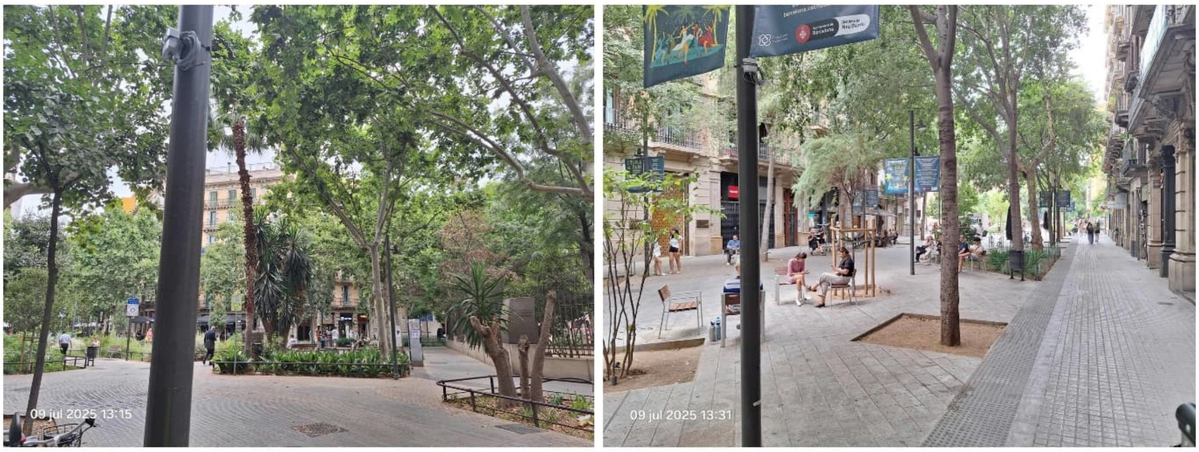

Figure 24. Examples of ambient temperature sensors located in superilles (BCN). Positions indicated by BCN technicians (City Council Climate Change Office). Source: MULTICLIMAT

Thus, a more significant form of monitoring would be to measure in a normal street and in other street nearby, equipped with multiple bioswales, but this is not within the scope of this T9.2, which is to complete the developments and fabrication of minimum functional prototypes, having also proven that the IoT sensors proposed for deployment in the city are capable of measuring, running on batteries and transmitting data.

Other devices installed are sensors for the measurement of:

- Soil moisture, which gives us an indication of the water (in liquid state, not in gas state) stored in the soil. Sensor: RK510-01 Soil Moisture Sensor from RIKA, with range 0-100% and accuracy +-2% (at 50%), is considered a high stability and high sensitivity soil moisture measuring instrument, which based on FDR measures the soil volumetric moisture content in m3/m3.
- Electroconductivity of the soil, which is mostly related to the salt content (which affects or deteriorates long-term performance of the bioswale). Sensor: RK500-23 Soil EC/Salinity Sensor from RIKA, with accuracy ±1% and range up to 0-10000us/cm for EC and 0 to 5000ppm(mg/L) for Salinity, being commonly used for on-site monitoring of soil water-salt dynamics.
- Piezometer, capable of measuring the height of water accumulated in a perforated pipe, being an alternative to measure the infiltration capacity in the case of a bioswale with direct infiltration, and a measure to check the correct conduction of water in a bioswale with concrete at its base. Sensor: S-8010 from SMERI INTERNATIONAL, which it is a hydrostatic level transmitter with pressure range 0-1 bar (10 m of water column), small diameter of 24 mm, and accuracy equal to ±0.5% and ±0.25% of full scale/year.
- Soil temperature and humidity. RK520-01 Soil Moisture & Temperature Sensor, which is a widely used sensor that can be permanently installed and is minimally affected by soil properties. The range is 0-100% (accuracy of ±3% at 50%) for humidity and -30 to 70°C (accuracy of ±0.3°C) for temperature.

Below are images of these sensors, embedded in the soil of the bioswale (in the case of the soil moisture, soil electrical conductivity, and soil temperature and humidity sensors), and inside a perforated tube (in the case of the piezometer). All of them have IoT communication and are focused on searching in the future for relationships between their measurements and the water storage capacity of the bioswale, and also to relate it to rainy periods (information retrievable through API available for nearby weather stations) when they occur. In any case, the purpose of this year was to further advance urban-scale developments, with materials and sensors tested and communicated to study their future performance. That is, a modular monitoring system, capable of providing contextualized information in a wide variety of graphical formats, was finalized for these first local

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and reduced experiences, being already available for larger scale demos later on according to the project schedule. The monitoring scheme installed and the sensors employed are shown in Figure 25 and Figure 26:

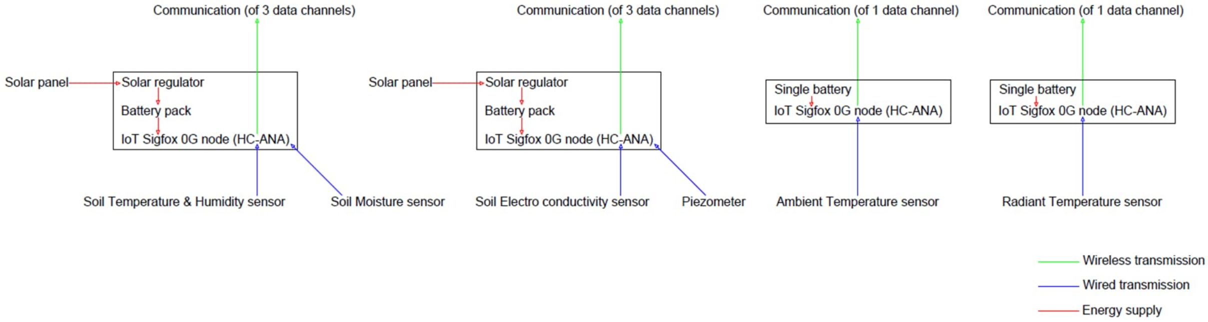

Figure 25. Scheme with the sensors included in the bioswale. Configured to transmit one data point per hour using the low-power wide-area network (LPWAN) Sigfox.

Figure 26. Sensors installed to indirectly evaluate the biofilter stormwater management. From left to right: EC/salinity sensor, soil moisture sensor, soil temperature and humidity sensor, and piezometer. Source: MULTICLIMAT

Sensors have already been listed and focused in different ways on indirectly evaluating the bioswale stormwater management. It is expected that relevant long-term data will be collected after the completion of this WP9 in order to establish trends that can facilitate the achievement of the objectives and verify them in the real case in BCN during Task 11.2 and Task 15.2.

4.2.3. MONITORING CAMPAIGN INTEGRATED IN DIGITAL TWIN SYSTEM

To carry out the monitoring campaign, to propose a measurement setup for a bioswale integrating different types of sensors with the potential to measure both temperature and variables related to the water content of this nature-based solution, the sensors described above were installed in a unit present at the URL. Below (Figure 27) is a view of the instrumented bioswale:

Figure 27. Above. View of the instrumented biological channel. Bottom-left. Image of a sensor in the terrain. Bottom-right. Image of the pipe with a piezometer inside. Source: NATURALEA

Unlike the ambient and outdoor radiant temperature sensors, the measurement sensors inside the bioswale cannot be powered only by batteries (these sensors have higher energy consumption), so they need to be wired to boxes containing the board that reads the measurement and sends the data via Sigfox (the aforementioned HC-ANA units from HC Technologies) together with a battery pack connected to a regulator that is powered by the energy produced by a small solar panel. Two of these boxes were used to test and verify the functioning of the sensors, which are distributed between the two boxes according to their energy consumption. Figure 28 shows a detail of this type of assembly.

Figure 28. Detail of the centralizing boxes, before covering them (left) and after installation (right), for the sensors installed inside the bioswale unit in the URL. Source: NATURALEA

As indicated above, the objective of this T9.2 is to develop solutions for application in a real-world demonstration in subsequent Tasks, so that progress on solutions at the urban scale has continued, with the manufacture of full-scale outdoor prototypes of the M&T and the testing of sensors for monitoring future demonstrations, so that they can be seamlessly integrated into the monitoring architecture already designed and implemented, preparing for large-scale demonstrations later this year.

Due to the permits within the URL, which is included within a critical water treatment infrastructure, in this case, neither the flight of the drone to generate the geometry of the digital twin was allowed, although this functionality has already been tested for the pavement M&T in the previous section, nor was it allowed to build bioswale units without concrete at their base. The latter is to avoid taking on greater risk of flooding and infiltration into the ground, so the bioswale units collect rainwater into an attached sump in all cases, having been proven to work and the piezometer measurements being irrelevant. In relation to the other variables measured, some of which are contextual but may reveal trends in a longer-term study, those considered to have the greatest potential are soil moisture and soil electrical conductivity (the second measure mainly because it can affect the long-term durability of the bioswale if salts accumulate). Particularly, an understanding of soil moisture conditions is crucial for hydrological modeling and hydrological processes. However, soil moisture response to precipitation infiltration changes under different types of vegetation and depends on the depth at which it is measured. Rain significantly influences soil moisture, with variations dependent on factors such as rainfall amount, intensity, and soil depth, leading to rapid increases in shallow soil layers and more gradual changes in deeper layers, with thresholds such as 5 mm often needed to substantially alter soil water content (Dai, et al. 2022) (Brocca, et al. 2014).

Due to delays in obtaining permits, a bioswale unit could be instrumented at the URL in July of this year. In any case, long-term studies, such as those in Xiao et al. (Xiao, et al. 2017) and Shakya et al. (Shakya, et al. 2023) are necessary to establish relationships between the measured variables and the functionality of the biofilter in terms of drainage, as well as its evolution, which can be altered by the accumulation of salts in the long-term (for which electrical conductivity is also proposed to be

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measured). In general terms, soil moisture increases with occasional rainfall, but long-term measurements are needed, which will be collected in the following MULTICLIMACT annual reports. As previously mentioned, the electrical conductivity (EC) of the soil is closely related to its salinity and therefore significantly affects its infiltration capacity, especially in saline soils. High electrical conductivity indicates a high concentration of salts in the soil, which can lead to soil structure degradation and a subsequent reduction in infiltration and root development in the long term (to be studied over time). Vegetation also has an effect on bioswale performance, as it intercepts rainfall, reducing net precipitation, absorbs water through transpiration (reducing soil moisture), and increases groundwater storage capacity, and root channels can also improve the quality of first flush, that clean the polluters of the streets. However, the vegetation had already been established in the previous year in terms of survival rate, so this particular bioswale design, with its vegetation, is what will be studied in the longer term.

Rainfall significantly influences soil moisture, with variations depending on factors such as rainfall amount, intensity, and soil depth, leading to rapid increases in surface soil layers and more gradual changes in deeper layers, with thresholds such as 5 mm often necessary to substantially alter soil water content.

In other words, rainfall significantly influences soil moisture, which is a priori the most useful variable to control, with variations depending on factors such as topography (in the bioswale this factor is controlled), soil properties, vegetation, land use, and weather conditions. These factors interact to affect how water infiltrates, moves, and is stored in the soil profile. The key influencing factors are rainfall characteristics (the amount, intensity, and timing of rainfall directly influence the increase in soil moisture, which increases rapidly after rainfall, as was preliminarily observed); soil properties (both of the biofilter and the land where water infiltrates); vegetation (more or less fixed in our case); meteorological factors affecting evaporation rates; and the initial water content of the soil. In conclusion, this should be studied also in the long term, taking into account at least meteorology, soil moisture, and existing water level, while also considering electrical conductivity, as salinity affects yield if it accumulates in the soil.

We can verify for the instrumented bioswale that soil moisture (Figure 29) (which is the percentage of liquid water in the soil, not in the form of vapor) and soil humidity increase with a rainfall event. They decrease in parallel after this, indicating that the bioswale is draining. The temperature, although high (inside the soil), decreases with the increase in water content. However, it is very likely that these high terrain temperature values are due to the fact that, in these initial tests, which also focused on the subsequent selection of sensors for the long-term study, the corresponding sensor was not completely buried, i.e., it is exposed to direct radiation, which caused an increase in the recorded temperature (it will be buried for later studies and a standard depth for measurement will be determined, based on recommendations and the depth of the biofilter itself, which is limited). As liquid water (soil moisture) is lost, the temperature rises again, and both graphs cross. Thus, the observed behavior is consistent.

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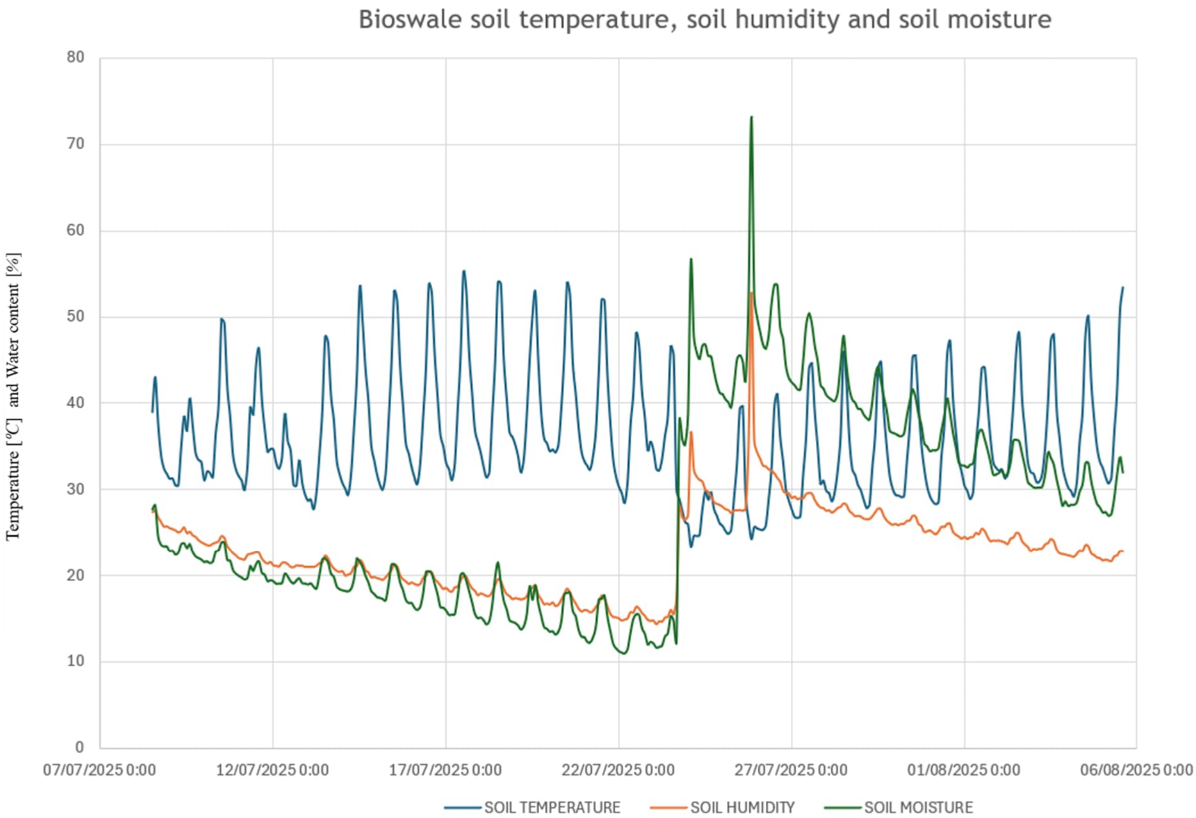

Figure 29. Soil temperature, soil humidity, and soil moisture measured in the bioswale.

As mentioned above, since it was not possible to build the bioswale variant with direct infiltration due to permission reasons at the URL, a full-scale prototype of this was built in July in another location. For this one, without sensorization because it is located in an unprotected parking area (Figure 30 and Figure 31) where it is not possible to place the control boxes and solar panels. In any case, it was possible to verify in situ that it does not puddle in case of a heavy rain, being able to collect the water that previously collapsed the existing ditch bordering the parking area. An in-situ infiltration capacity test is planned using a standardized methodology for this unit outside the URL, and a soil moisture sensor will also be installed at a later stage to try to find the match between the two values (this will depend on the depth at which the sensor is installed and the drainage time considered; subsequently, the infiltration rate per square meter after the rain has stopped could be determined by taking into account the measurement in m3/m3 and the dimensions of the bioswale).

Figure 30. Left. Ditch before the bioswale that flooded giving problems to the adjacent parking lot. Right. New bioswale with direct infiltration capacity. Source: NATURALEA

Figure 31. From left to right, water driven down a ditch to the new bioswale in the parking lot after a heavy rain. The bioswale withstood the rain and absorbs the water that continues down the ditch to its surface. Source: NATURALEA

To analyze and verify the impact on temperature reduction, given that it is necessary to take into account the scale factor in a real case, sensors have already been installed in Barcelona's Superilles as part of Task 9.2, which forms part of the real case that will be considered in the project in Task 11.2. This first test was carried out to further study the effect of vegetation in nearby streets and squares with and without vegetation, as well as biofilter-type structures for which an optimized design is being developed within the project.

The graphs in Figure 32 show measurements above 29°C on a normal street near Superilles during the last week of July and the first week of August, and their equivalents measured on two streets in Superilles. It can be observed that the peaks are slightly lower on certain streets with vegetation. However, it will be necessary to understand the phenomenon and possible fluctuations over time, and it is important to distinguish between the different levels of direct exposure to the sun or the degree of shading for each sensor installed at requested by BCN (City Council's climate change office). That is, this is a preview of studies to be carried out in subsequent tasks.

Figure 32. Comparison of randomly selected peak surface temperatures on two streets in Superilles and one contrasting street. Source: MULTICLIMACT

Finally, the upcoming stages of the project will allow for the continuation and deepening of the evaluation of the bioswale systems already implemented. In this regard, a series of infiltration tests are planned, based on a designed artificial rain event that reproduces realistic environmental concentrations of inorganic salts, heavy metals, and organic contaminants. These tests will be conducted in coordination with the research team responsible for next phase. The composition of the used artificial rain is presented below.

Inorganic Salts

COMPOUND	ENVIRONMENTAL CONCENTRATION (MG/L)	STOCK SOLUTION (G/L)
NH_4Cl	3	30 g
KNO_3	5	50 g
KH_2PO_4	1	10 g
Na_2SO_4	25	250 g
NaCl	100	1,000 g (1 kg) (optional: reduce to 300 g to avoid saturation)

Heavy Metals

METAL (SALT)	ENVIRONMENTAL CONCENTRATION (MG/L)	STOCK SOLUTION (G/L)	APPROXIMATE QUANTITY OF SALT

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Pb ($Pb(NO_3)_2$)	0.05	500	~1.6 g
Zn ($ZnSO_4 \cdot 7H_2O$)	0.1	1,000	~4.4 g
Cu ($CuSO_4 \cdot 5H_2O$)	0.1	1,000	~4 g
Ni ($NiSO_4 \cdot 6H_2O$)	0.05	500	~2.2 g
Cd ($CdCl_2 \cdot H_2O$)	0.01	100	~360 mg

Organic Contaminants

OMPOUND	ENVIRONMENTAL CONCENTRATION (MG/L)	STOCK SOLUTION (G/L)
Naphtha	2	20 g (~25 mL)
Phenanthrene	0.1	1 g
Benzothiazole	0.05	0.5 g
Benzo[a]pyrene	0.01	0.1 g
PAH EPA6	0.5	5 g (if standard mix)
Diesel/gasoline	2	20 g (~25 mL)

Table 4. Composition of artificial rain for the infiltration test on the ground. Source: NATURALEA

Likewise, complementary tests were carried out on pollutant filtration, future tests in this regard have been planned, and a choice of self-sufficient vegetation that seems to be resisting and developing so far was ensured.

In order to achieve a self-sufficient system that ensures plant survival without irrigation, Mediterranean-climate shrub species were planted, adapted to solar radiation and drought.

The distribution of the species was carried out in groupings in order to generate homogeneous masses at specific points along the ditches. With this distribution, we will obtain representative data on how the selected species perform in relation to the variables we will study. From our experience, working in groupings—especially knowing there will be no irrigation—is the best strategy to ensure the survival of the planted species.

The planting density was 1 unit every 40 cm, that is, for each 10 m bio-retention strip, a total of 25 units were planted.

List of species to be implemented in the bioswales:

SPECIES	QUANTITY IN EACH BIOSWALE	TOTAL
Vitex agnus-castus (1)	9	27,00
Rosmarinus officinalis (2)	4	12,00
Viburnum tinus (3)(4)	7	21,00
Pistacea lentiscus	5	15,00

Table 5. Selected species and quantities planted in each bioswale and the total quantity required per species. Source: NATURALEA

DESCRIPTION	MESUREMENTS
Supply and planting of shrubs in C-2,5L	75 u

Table 6. Measurements of the intervention. Source: NATURALEA

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The experience gained over the years was key to the choice of plant species, since the positive results in the implementation of the same species in the bioswale in Masonou (Barcelona), years ago have allowed us to verify their effectiveness for phytoremediation within the system.

4.2.4. EVALUATION OF PROTOTYPES

Based on the real-scale prototypes developed and tested, the current bioswale designs have demonstrated a series of practical advantages and functional capabilities under real conditions, proving to be:

- Quick to build with local materials and vegetation (delays were due to building permits, provision of materials, and labour).
- Self-sufficient in terms of vegetation.
- Absorb, conduct, clean and infiltrate water, in the latter case solving a practical scenario in a parking lot that was flooded due to insufficient drainage.
- Having water purification capabilities: further tests will be carried out on this aspect throughout the project.
- Logically, their temperature regulation capacity depends on the scale at which they are implemented, for which the impact of vegetation on urban remodelling in Superilles is to be be studied in subsequent tasks according to the project schedule.
- They can be instrumented, in the sense that, in addition to the classic measurement of water column height inside perforated tubes, other variables (soil moisture, soil electrical conductivity, soil temperature, etc.) can be measured that could be related in the long term to their hydraulic performance and durability, associating them with climatic events and long periods of performance. In particular, soil moisture appears to be a good potential indicator of performance, which we will attempt to associate with the infiltration rate of bioswales using our Type A design (with direct infiltration into the soil) in longer-term studies combined with experimental in situ infiltration tests.

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5. DEVIATIONS TO THE PLAN

The work carried out in Task 9.2and presented in this deliverable was carried out according to the planned schedule and without deviations from the expected program. Designed solution of T3.2. and the monitoring system is developed further and prepared for its application in T11.2. Thus, the development of first outdoor prototypes and testing of the two selected materials and technologies (M&T)— new recycled asphalt pavement and a bioswale solution—have progressed as scheduled in the initial work plan.

As for monitoring, it was installed late in the bioswales, as they were built after the second half of the work period and there were problems with the supply of some electronical components, but they will continue to collect data that, in any case, is only valuable in the context of a longer-term study. Regardless of the long-term study to be carried out in future tasks, soil moisture already appears to be the best indicator among the variables measured.Regardless of the long-term study to be conducted in future tasks, soil moisture already appears to be the best indicator of stormwater management performance among the variables measured.

MULTICLIMACT is a project defined with progressive development and testing, so what is being discussed is considered part of its natural development and not a significant deviation within a research project of this complexity and increasing scale. The work carried out in Task D9.2 has followed the defined plan without any deviations. Furthermore, there was no negative impact on other related Tasks within the project, and no delays have occurred.

6. CONCLUSION

Finally, based on the progress and results presented above, this section summarizes the main conclusions of the Task and describes the key points for the next Task of the project. The functionality and feasibility of the proposed systems were validated to the extent possible given the stage of the project, through both laboratory experiments and real-world implementations. Initial results confirm its potential in terms of environmental performance and ease of deployment. The next phases will focus on long-term monitoring, in-depth analysis of environmental impact, and optimization of design variables based on data collected during real-world demonstrations. These steps will be essential to consolidate the performance of the developments and guide their scalability and replication in future applications.

Full-scale prototypes of both solutions were successfully designed, built, and evaluated under real environmental conditions. These prototypes represent a fundamental step toward improving the thermal and hydraulic resilience of urban environments. Their performance was validated through laboratory characterization, outdoor exposure, and continuous data collection using a customized monitoring system. In addition, progress was made by installing sensors in the Superilles in Barcelona to start analyzing the impact of vegetated areas taking into account the scale factor in a real case.

The results obtained provide a solid basis for the next phase of implementation and monitoring that will be carried out later in the project. Although, as indicated, there were no deviations from the schedule or planned objectives, the progress and results obtained have also highlighted the need to refine some of the initial assumptions, particularly with regard to cooling pavement solutions. The results reflect the confrontation between theoretical designs and reality, which fall within an area of knowledge that, according to the findings of Task 9.2, remains controversial

With regard to pavements, high-reflectivity solutions are ruled out to tackle the urban island and for the pilot case in Barcelona based on physical models that show excellent ability to match the data measured, apart from the conclusions, namely that high-albedo solutions installed at street level (not on roofs, etc.) radiate unacceptably to citizens and buildings, are in line with other recent conclusions (European Commission s.f.), regarding the application of these solutions. Porous pavements are also unsuitable for cooling in these climates, according to the exhaustive study carried out last year during the Plan and Design phase (Zamora-Sanchez, Armijo and Torres-Barriuso, et al. 2024).

As it was determined that none of these alternatives were viable given the construction limitations in Barcelona and the characteristics of its climate, an alternative to the initial proposal (recycled glass) was put forward and the option of testing and using another recycled material (steel slag aggregates) was analyzed. During this phase, full-scale prototypes of pavements with recycled glass and steel slag aggregates were evaluated. Although these materials showed a positive impact, the effect was relatively modest. As mentioned, theoretical models were also developed to refine these designs and explore alternative solutions without the need for physical construction and testing.

Steel slag aggregates can be added in larger proportions, replacing all the aggregate in the pavement, which was not possible with recycled glass. If this option is built instead of the originally proposed option using glass aggregates, or if both are built, which will be constructed and instrumented in Task 11.2 and monitored in Task 15.2. This will make it possible to quantify the extent to which they can contribute to improving the comfort of pedestrians and residents in buildings. These are feasible solutions tailored to site-specific conditions and can complement other strategies, such as bioswales, which provide vegetation in a simple way to the urban area, as well as supporting stormwater management.

The pavement solutions, recommended to be built as demos in Barcelona and monitored in real time, are considered balanced compromises between all the factors and conditions explained for the site and the physical phenomenon to be addressed. Rather than a deviation if their performance or impact (in any case only truly assessable on a large scale, for which they have the constructive and cost potential to be replicated in the city) were low, it would be a contribution to be added to other actions to increase the resilience of built environments to heat waves.

As for the monitoring system architecture developed and implemented, it demonstrates its adaptability to any sensor, type of transmission, and visual contextualization in different formats, now expanding the range of functionality of DT with drone geometrical capture and the possible inclusion of thermal models for consultation in the application. The IoT sensors were tested by connecting different types to the same HC Technologies node, which was tested to be powered by its batteries or supplemented by a solar panel or accumulator. The sensors used in the city demo can be either these or others, depending on the site conditions, with the computer system ready for integration and collection at the start of Task 15.2, which will be the most valuable real-world data, with monitoring at the level of the previous specimens documented in this document also operational as long as it remains relevant.

Below is a more detailed explanation of the results and adjustments made during this phase and the conclusions drawn for each of the developments and systems monitored, comparing the theoretical designs with real-world limitations.

6.1. M#2 NEW RECYCLED ASPHALT PAVEMENT

After completing the testing and evaluation process of the new recycled asphalt pavement solution, as well as the results obtained from the monitoring of the executed test samples, several key conclusions can be drawn about the pavement performance and its applicability in similar urban contexts.

It is feasible and accurate to model and monitor temperatures in asphalt pavement, as thermal models align with real measurements. This consistency confirms the reliability of the models for parametric studies.

Because there is little precipitation in Barcelona and other hot, arid Mediterranean cities, porous pavements are ineffective for cooling. Furthermore, it has been established that greatly raising the pavement's reflectivity (for example, by using white emulsions) while successfully cooling the pavement surface will cause it to radiate more heat, which could be intolerable to pedestrians and buildings in the vicinity. This effect can be seen in Figure 33, showing the parametric study's analytical temperature response for surrounding vertical surfaces (considering selected scenarios in summer season).

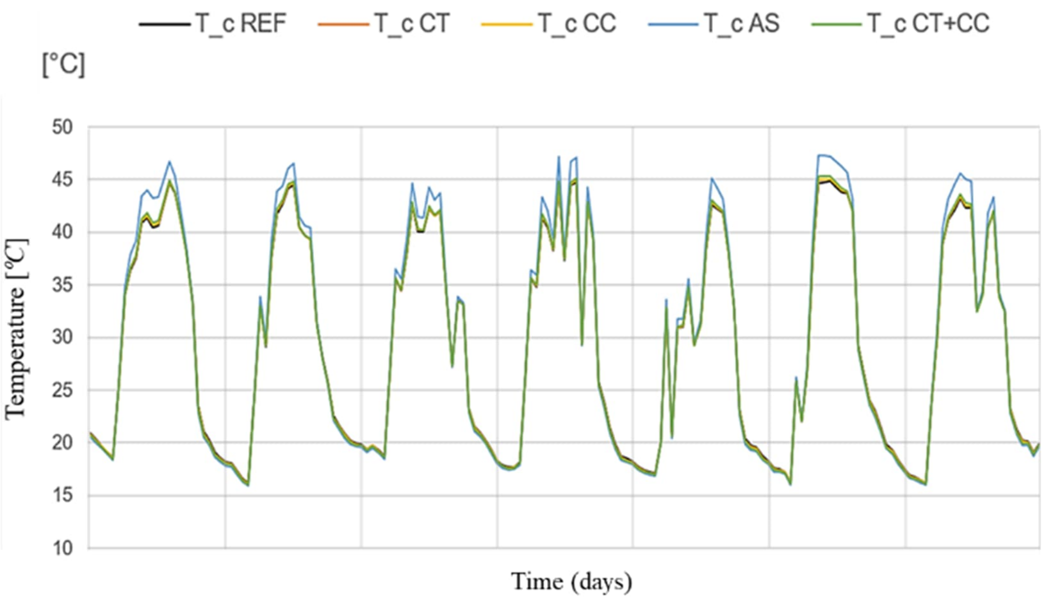

Figure 33. The parametric study shows the analytical (simulated) evolution of the characteristic temperatures of the surrounding vertical surface. Source: MULTICLIMACT, (Zamora-Sánchez, et al. 2025)

Figure 33 reveals that, if reflective paving is used, pedestrians and building facades experience an increase of more than 2 °C (light blue line above the others).

There was much enthusiasm for high-albedo solutions for new pavements, but recent evidence, such as that collected by the European Commission (European Commission s.f.), indicates that sun-reflective pavements can intensify heat exposure for pedestrians, i.e., that reflected heat has an impact on urban neighbourhoods, concluding that this type of pavement can intensify thermal stress for pedestrians during the hottest hours of the day by increasing radiant temperatures (thermal load on the body). This is what we have concluded in this study, following a robust physical-mathematical model, previously demonstrated to fit the actual data from the samples. In other words, reflective solutions would be unbeatable as a solution for a building roof, as they radiate reflected heat upwards, but when they are at ground level they are not such a good option. Similarly, elements of this nature on building facades undoubtedly help to cool them, but the reflected energy is transmitted to the street. In other words, the thermodynamic behaviour of asphalt or concrete mixtures, particularly pavements, is complex and can be influenced by multiple factors, and the impact of solutions depends on what one wants to mitigate. According to the authors, the problem of mitigating the effects of heat islands on citizens and buildings by installing ground-level solutions was addressed rather thoughtlessly in recent years, highlighting the difficulty of finding a universally applicable solution for all purposes and locations, as climate, solar radiation levels, location, and timing of heat reduction, along with the compatibility of the solution with local pavement renovation methods, are factors that must be taken into account.

Analyses suggest that AC mixes with recycled glass aggregates can slightly increase the temperature oscillations of the pavement surface and surrounding vertical surfaces, potentially reducing heat at night. The effect of the current mixtures could be positive, but its magnitude is low. Thus, the alternatives for a bigger impact seems to:

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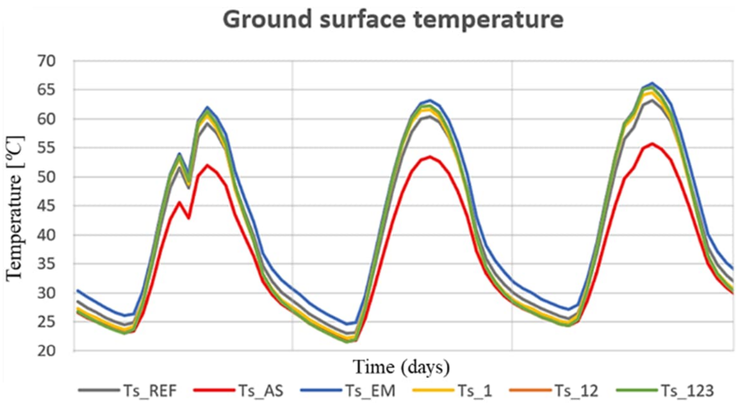
- Increase the thickness of cooling asphalt by replacing layer 2 in the road section, extending the renovation to the entire asphalt layer.
- It is possible to study changing the existing base course, which is concrete, although this might not be financially feasible.
- To modify AC, alternative recycled materials with various emissivities and other characteristics—like possibly steel slag aggregates—can be assessed.

These possibilities, limited by the factors mentioned above, were thoroughly studied using the models developed, which were validated with data from the experiments mentioned. In other words, the alternatives listed above for achieving greater impact were simulated with new parametric studies at final contribution within this Task 9.2, and the results are shown in the Figure 34 and Figure 35 for pavement surface temperatures and vertical temperatures (of the environment, i.e., people and buildings).



Parametric variations (results are for pavement surface temperature):

- Reducing solar absorptivity (Ts_AS) reduces the ground surface temperature, especially the peak values during the day.
- Reduced emissivity (Ts_EM) increases the ground surface temperature.
- Glass (Ts_1) increases the peaks (midday) and reduces the valleys (night) in surface soil temperature.
- Changes in Layers 2 and 3 (Ts_12, Ts_123) have no significant effect.

Figure 34. Effects on pavement surface temperature of reduced solar absorption (Ts_AS), reduced emissivity (Ts_EM), glass (Ts_1), and changes in the lower layer of asphalt and subbase of the section (Ts_12, Ts_123). Source: MULTICLIMACT

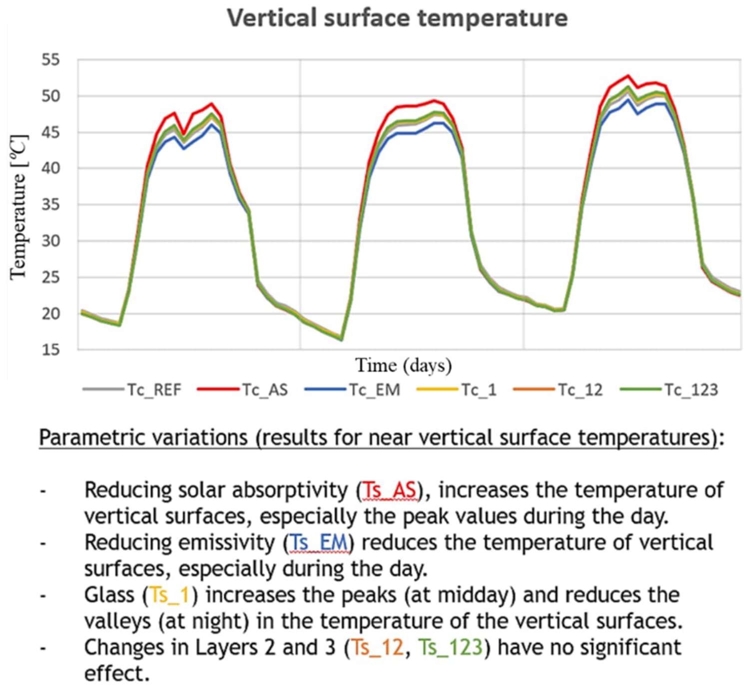


Figure 35. Effects on vertical surface temperature (on citizens and building facades) of reduced solar absorption (Ts AS), reduced emissivity (Ts_EM), glass (Ts_1), and changes in the lower layer of asphalt and subbase of the section (Ts_12, Ts_123). Source: MULTICLIMACT

Based on these results, increasing the thickness of the cool asphalt pavement made from recycled glass (from 5 cm to 12 cm) and changing the base course, currently made of concrete (which can act as a barrier to heat transfer to the ground), has almost no impact on improving the results. Both options are costly, and replacing the base is unfeasible according to the standard renovation techniques applied in Barcelona for existing streets. However, an impact could be achieved by testing other recycled materials to be included in asphalt mixtures with certain properties (the significant thermal properties are solar absorptance and emissivity, with a view to a solution that is placed at street level, not on a roof), to mitigate the effects on buildings and pedestrians. According to this study, to cool adjacent vertical surfaces (rather than the pavement itself), materials with high absorptance and low emissivity are preferred.

Potentially, steel slag aggregates could be an alternative material for new asphalt concrete pavements, as it was proven in other recent studies (Li, et al. 2021). This recycled materials can form a mechanically resistant AC-type mixture with a 100% replacement of standard aggregates. Intuitively, this could increase the effect, since glass aggregates could only cover a substitution of up to 25% in the fine fraction in order to meet the mechanical strength requirements.

In particular, a sample of locally available steel slag aggregates in Barcelona coming from electric arc furnace was tested and compared with standard aggregates. Steel slag showed 15% higher absorptance and 4% higher emissivity (a slight increase that is not considered important with the overall performance). These results are shown in Figure 36, based on conducted tests on the aggregates alone, and at this stage they are considered better options than standard aggregates for reducing the heat radiation to buildings and people.

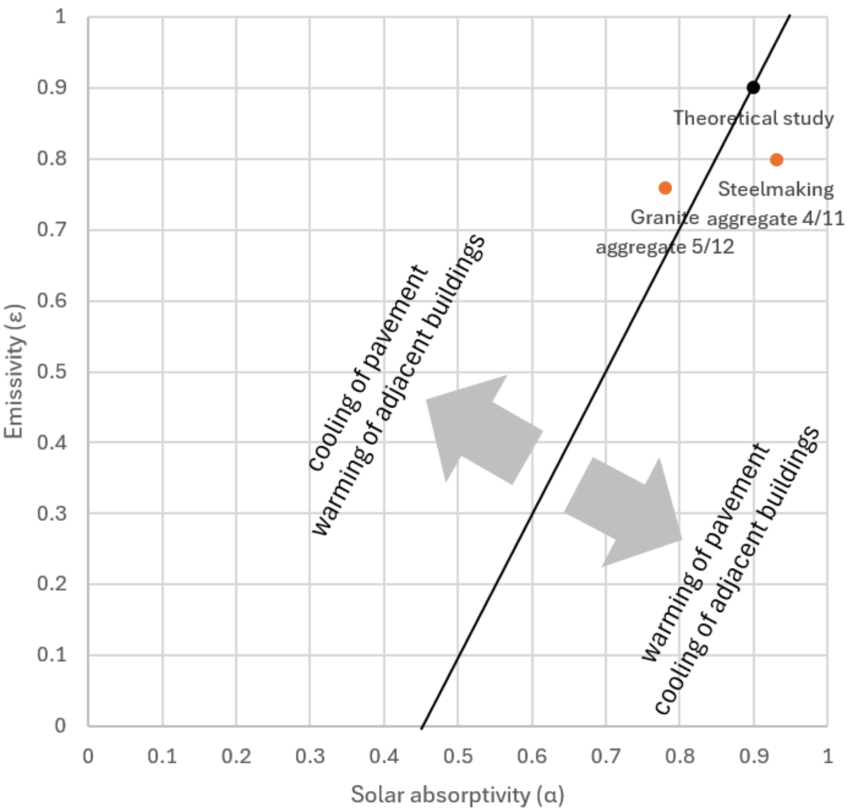


Figure 36. Relationship between solar absorptance (α) and emissivity (ε) of the experimental values of different aggregates analyzed. Source: COMSA, TECNALIA

The orange dots represent the experimental values of the aggregates analyzed. The graph shows how, depending on the combination of optical properties, materials can contribute to cool the pavement itself or adjacent buildings, depending on their position related to the theoretical equilibrium line. As it can be seen, the 4/11 steel aggregate appears to be better in terms of cooling capacity for pedestrians and buildings than the theoretical or tested aggregate, and another laboratory sample of tested granite aggregate.

BOF (Basic Oxygen Furnace) slag, which was considered promising according to an article cited above, was also tested. This material is not available in Barcelona area, but it was sent by Tecnalia from Bilbao. In any case, according to the tests carried out, the steel slag found in Barcelona appears to be better:

	CONVECTION COEFFICIENT	SAMPLE 1	SAMPLE 2	SAMPLE 3
	wind speed (m/s)	Granitic arid 5/12	Steel slag 4/11	Steel slag BOF 5/11
Solar reflectance index SRI	5	9	0	8
	12	14	0	9
	30	18	0	10

Solar absorptance	0,78	0,93	0,87	we seek higher absorptance
Solar reflectance	0,22	0,07	0,13	
Thermal emissivity	0,76	0,8	0,87	we seek lower emissivity

Table 7. Results of tests carried out by COMSA on steel slag aggregates. Source: COMSA

In short, the initial proposal to replace aggregate with recycled glass showed a positive but limited effect. Additionally, the modelling helped improve the understanding of pavement thermal behaviour related to the physical phenomenon under study. The results revealed certain inconsistencies in common approaches used in cities with high solar exposure, such as the use of reflective pavements. These pavements may not effectively improve comfort for pedestrians and nearby residents when installed at ground level.

It is essential to emphasize that the validated thermal model may suggest an expected range of variation in a thermal property to be achieved in a given layer of the pavement to improve the solution, but then there must be a recycled component that can provide those properties, and for the intervention to be environmentally effective and make sense in terms of the use of recycled materials, it should be a waste product that is available in the area. Consequently, we wanted to analyze the use of waste materials available in the area, such as steel slag aggregate, and, based on justified models and without ruling out the option of glass aggregates initially proposed in the project, we propose an alternative mixture.

Based on the analyses carried out and the results obtained with the steel slag aggregates studied, an alternative mixture design has been defined using 100% steel slag from electric arc furnace from Barcelona area. The proposed mix meets the AC-16 granulometric envelope specifications, as shown by the resulting particle size distribution curve, which remains within the limits of the corresponding grading band.

FRACTION SIZE (MM)	% BY WEIGHT
0/5	48%
4/11	36%
10/20	13%
Filler	5%
Total	102%

Table 8. Aggregate Composition and Gradation Curve (Steel Slag – Alternative Mix Design). Source: COMSA

SIEVE SIZE (MM)	22	16	8	4	2	0.5	0.25
Envelope (% Passing)	100	90–100	64–79	44–59	31–46	16–27	11–20
Resulting Curve (%)	102	98	80	51.6	38.9	14.4	11

Table 9. Grading envelope AC 16. Source: COMSA

The asphalt binder content for this mix design was set at 4.8% by weight of the mixture. It should be noted that this is the curve obtained with cold aggregates, and adjustments will be required based on hot bin analysis during production.

Both could be installed in the demo, with the aim of evaluating whether they can contribute, together with the vegetation provided by the bioswales, to reduce the impact of the heat island effect in cities, based on the premise that all these solutions are compatible with the constraints of the site and the city itself, which, as mentioned above, cannot be ignored in the search for adaptation and progressive improvement of a metropolis of this size. There is no ideal solution, but rather a sum of contributions, to which the developments presented can contribute.

6.2. M#7 BIO-RETENTION SWALE

Through the work carried out and the construction of bioswale prototypes, their functionality was successfully demonstrated, even in a practical case involving the replacement of a gutter at the edge of a parking area that was frequently flooded, as well as their ease of construction. These results allow the work to continue during the following year, focusing on a long-term study of the monitored variables. At the same time, additional analyses will be carried out, either through hydraulic simulations or real installations, to evaluate their possible contribution in urban contexts such as Superilles, which already incorporate vegetation and are currently started to be evaluated using the instrumentation provided at the request of Barcelona City Council.

The bioswales were constructed, except for management and provisions, in a simple manner, have proven contaminant filtration capabilities, to be evaluated in the longer term, and are capable of developing vegetation without maintenance and infiltrating and controlling stormwater (demonstrated in a real intervention).

Therefore, given that the hydraulic and thermal behaviour of bioswales is less complex than that of pavements, the current prototypes are considered mature enough to advance to the next phase in their present design. Nevertheless, some enhancements could be progressively integrated in future iterations, without altering the core concept proposed, with the experience gained in the longer term within the project.

6.3. RAM Approach for the Monitoring System

In terms of the RAM (reliability, availability, and maintainability) of the monitoring system, the monitoring system architecture implemented, previously designed in task 3.2, is capable of:

- Sending alerts when a user-defined threshold is exceeded.
- Send alerts when data transmission stops. The system is modular and can integrate any type of sensor capable of sending or adapting to data transmission (it does not depend on hardware). This is a great help for short- and long-term maintenance of the monitoring system and the monitored assed as well.
- It is remotely accessible, displays contextualized information (Digital Twin), and is flexible or open to different formats for data exchange via download or for communication between platforms (sending data packets in real time or according to the transmission latency determined by the communication network and the consumption of each sensor). It can integrate equipment connected to the power supply, as well as sensors with long-life batteries that use low-power, high-availability 0G networks. All of this guarantees availability through remote access and energy sufficiency (powered devices could have safety UPSs if necessary, and IoT nodes have replaceable batteries and/or solar panels).

Implement AI algorithms for anomaly detection when long-term data is available on demo sites. These types of alerts, which will be implemented within the project, can indicate or anticipate unseen phenomena, or discover problems with equipment that needs calibration. This has an impact on reliability. Moreover, the actual reliability of the system can be evaluated based on the accuracy of the testing and evaluation phase of the algorithms (by standard metrics when deployed in a real long-term case). Finally, these contextualized algorithms (in BIM environments, drone captures, etc., as shown) support the maintenance of the solutions developed and the infrastructures where they are installed.

Co-funded by the European Union

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Co-funded by
the European Union

Co-funded by the European Union