Research Article
Assessing the Field Curing Behavior of Cold Recycled Asphalt Mixtures

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Abstract
Cold recycling techniques in road construction have been of rising interest because of huge environmental benefits in terms of energy saving, emission reduction, and preservation of natural resources. The improvement on selection and quality of the raw materials and binders as well as the enhancement of the knowledge on mixture performance are leading to the intensive use of cold recycling techniques in place of traditional ones. One of the main differences between cold and hot techniques is the evolutive development of performance, generally identified as curing process, due to the presence of water and hydraulic binders in the cold mixtures. Environmental-related factors such as temperature, humidity, wind, and rainfall significantly influence the curing process and, as consequence, the mixture properties over time. Several laboratory curing protocols have been developed by universities, research centers, and agencies, but a clear relationship between simulative procedures in laboratory and the field is still an open challenge. This paper aims at characterizing the short-term and midterm curing behavior of a cold recycled material (CRM) mixture. A CRM mixture was selected and characterized in laboratory, and the in-plant production procedure was validated. The CRM mixture was used to build the binder course of an instrumented pavement in the Republic of San Marino. Volumetric and mechanical testing on laboratory-produced specimens and cores were analyzed considering the temperature and moisture sensor measurements in field. Results address to a new insight for laboratory procedures and prediction models matching laboratory conditions and the real curing condition in field.

1. Introduction

In cold recycling of asphalt pavements, water (instead of heating) is used to promote the uniform distribution of the bituminous binder and enhance the densification of the mixtures [1–3]. Upon compaction, water-related phenomena, such as seepage, evaporation, suction, emulsion breaking, and cement hydration, normally lead to a reduction of moisture and an increase in stiffness and strength [4–8]. The development of the curing process is affected by the following:

(i) Material-related factors (dosage of bituminous and cementitious binders, initial water content)

(ii) Construction-related factors (drainage conditions, layer thickness, and compaction level)

(iii) Environmental-related factors (temperature, humidity, wind, and rainfall)

The environmental-related factors are extremely variable, and therefore their simulation in the laboratory for predicting the possible evolution of material properties in the field is extremely challenging [9, 10]. National specifications describe many different laboratory curing protocols, normally consisting in temperature and relative humidity conditions imposed to the specimens. Those protocols are used for mixture design and quality control to standardize the characterization of mixtures or to rank and to select mixtures [10–14]. Often the accelerated curing process does not fairly simulate the real curing process. Consequently, specimens subjected to accelerated curing process do not accurately allow to predict the short-
and long-term field performance. Moreover, actual measurements of gravimetric water content (GWC) and temperature of cold recycled layers during the field curing process have been rare.

Pioneering work was carried out by the University of Iowa (US) research group in several cold in-place recycling (CIR) projects with foamed bitumen and bitumen emulsion [15, 16]. The objective was to evaluate the short-term moisture of the mixtures and verify the local criteria for timing of overlay with hot-mix asphalt (HMA). After compaction, capacitance moisture sensors and temperature sensors were installed at about middepth of the CIR layers. During the monitored curing periods, about 30 days, the moisture measured by the sensors generally showed small daily fluctuations around a fairly constant project-dependent values. The moisture surged during rainfall events and decreased to the baseline value within a couple of days.

Capacitance moisture sensors and temperature sensors were also installed in a CIR project with Portland cement in Mississippi (US) [17]. The sensors were buried in trenches that were dug to the middepth of the CIR layer after the field mixing phase, but prior to compaction [18]. First, the raw signal reading was corrected to consider the biasing effect of temperature, and then the field GWC was calculated using a theoretical model based on the estimation of the dielectric constant of the CIR material. Overall, the evolution of GWC in the first 14 days of curing was similar to the one described above. Based on their measurements, the authors concluded that during compaction, the GWC of the layer reduced from 8.2% to about 6%, but they did not explain where that 2% water (about 8 kg/m²) was expelled.

Time domain reflectometer (TDR) sensors and thermistors were installed in a full-depth reclamation (FDR) project near the city of Ancona (Italy) [19]. During the project two types of FDR, mixtures were produced: a cement-treated material (CTM) and a cement-bitumen treated material (CBTM). Before installation, the TDR sensors were calibrated in the laboratory using the same material that was placed around the probes during installation in the field. The TDR and thermistors were installed after compaction, at about middepth of the FDR layer. In addition, a bitumen emulsion tack coat was sprayed to simulate a sealed curing condition in one half of the section. O— the GWC was monitored for 90 days revealing that the curing process of the CTM and CBTM mixtures was comparable in terms of both initial rate and long-term value of moisture value. Preventing water evaporation with a bitumen emulsion membrane resulted in marked reduction of the initial water loss rate.

The objective of this research was to characterize the short-term and midterm curing behavior of a cold recycled material (CRM) mixture produced with the cold central-plant recycling (CCPR) technique and containing both bitumen emulsion and Portland cement. To this aim, an instrumented pavement section was built in the Republic of San Marino including a CRM binder layer. During construction, temperature and moisture sensors were installed within the layer. Moreover, a laboratory testing plan was implemented to characterize the physical and mechanical properties of the binder layer, and their evolution during the first year of service life. Physical characteristics of lab-produced specimens, cores and moisture, and temperature sensor measurements were analyzed to match the CRM properties with the real curing condition in field.

2. Instrumented Pavement Section

2.1. General Information and Design. The instrumented section was built along the main connector road between the historic center of San Marino and Rimini (Italy) on the Adriatic coast; a four-lane divided highway with an annual average daily traffic of about 4,000 vehicles per day and 10% heavy vehicles (Figure 1). The existing pavement consisted in an asphalt concrete course (wearing and binder layers) with a total thickness of 12 cm over an unbound granular base. The maintenance works were carried out on the right lane (San Marino direction), where the pavement was characterized by high-severity fatigue cracking and localized depressions due to permanent deformations in the granular base (subsection 1) and by medium-severity fatigue cracking (subsection 2).

Following the project-level assessment [20], the maintenance activities on both subsections were identified according to the guidelines of the San Marino national road administration. Figure 2 shows the structural design for subsections 1 and 2. It is highlighted that the CRM binder layer is enclosed within two impermeable bituminous membranes (the tack coat and the prime coat) and that a new CTM base course was built in subsection 1. Even if cold recycled mixtures are generally used for deeper layers, similar pavement structures were also used by other authors [5, 21].

The maintenance works produced 226 t of milled HMA and 160 t of milled unbound aggregates that were hauled to a mix plant 15 km far from the working site. The CTM base and CRM binder were manufactured at the same mix plant, recycling 85 t of unbound aggregates and 184 t of reclaimed asphalt and using just 12 t of virgin aggregates. 75 t of AC wearing course using virgin aggregates was instead produced in another mix plant 73 km far from the working site.

The sensors for monitoring the evolution of temperature and moisture content were installed in subsection 1 (Figure 1) at the mean depth of the binder course in cold recycled mixture, whereas the other sampling and field-testing activities were carried out on both subsections 1 and 2. Additional details can be found in Graziani et al. [22].

3. Materials and Mixtures

3.1. Aggregates. For a better control of the mixture gradation, two RA fractions, RA 0/10 and RA 8/20, were selected through crushing and sieving operations. A sand 0/1 and a filler were used to improve the bituminous mastic consistency and to meet the design grading envelope. Table 1 reports the main properties of the aggregates and filler used, while Figure 3(a) shows the particle size distribution of the sand, RA fractions ("black curve") and RA extracted aggregate ("white curve").
The design grading was close to midband gradation (Figure 3(b)) and was obtained by blending 92% of RA aggregate (48% of RA 0/10 and 44% of RA 8/20), 4% of sand 0/1, and 4% of filler.

3.2. Binders. The cationic bitumen emulsion had 60% of residual bitumen and was modified by adding SBR latex. According to EN 13808, the emulsion was designated as C60BP10, that is, overstable emulsion.

The cement was a Portland-limestone CEM II/B-LL 32.5R according to EN 197–1 with a fineness of 4900 cm²/g (EN 196–6), setting time of 140 min (EN 196–3), and strength after 28 days of 42 MPa (EN 196–1).

3.3. CRM Mixture. The mix design of the CRM mixture for binder course was established on the basis of previous experimental study [23]. The dosage of SBR-modified bitumen emulsion was 4.5% (2.7% of residual bitumen), the dosage of
cement was 2.0%, and the total water content was 5.0% by aggregate mass (including water brought in by emulsion). The maximum density of the mixture was 2504 kg/m³, and the design value of the indirect tensile strength (ITS) at 25 °C after 3 days curing time at 40 °C in unsealed condition was 0.41 MPa complying with the road agency specification [24].

During construction, the CRM mixture was sampled at the mix plant and compacted by means of a gyratory compactor (GC) for quality control testing. The GC protocol provided a 150 mm diameter mold, a constant pressure of 600 kPa, a speed of 30 rpm, an angle of inclination of 1.25° (internal angle of 1.16°), a 2.8 kg sample (wet mass), and 100 gyrations. Specimens were divided into two series and cured at 40 °C for 72 hours following two curing conditions: unsealed (free evaporation) and sealed (wrapped in a plastic bag).

At the end of curing, the water loss values were 2.9 and 0.3% in unsealed and sealed condition, respectively, and the indirect tensile strength (ITS) values at 25 °C were 0.60 and 0.42 MPa, in unsealed and sealed condition, respectively (Figure 4). The results for both curing conditions satisfied the specification requirements.

3.4. Cement-Treated Recycled Material. The cement-treated recycled material (CTRM) base employed in subsection 1 was produced using 30% of RA aggregate and 70% of recycled aggregates (C&D products). The granular blend was characterized by nominal maximum size of 30 mm and a CBR value of 75 after 96 hours of immersion in water. The dosage of the Portland-limestone CEM II/B-LL 32.5R was 3.0% by aggregate mass, and the optimal water content was 4.95% by aggregate mass. The ITS and unconfined compressive strength after 7 days of curing at 25 °C in unsealed condition were 0.39 and 4.00 MPa, respectively.

3.5. Asphalt Concrete Wearing Course. The mix design of the asphalt concrete wearing course was obtained following the AASLP construction specifications. The AC mixture was characterized by a well-graded gradation containing 40% of

![Sieve size [mm] vs. Passing [%]](image1)

![Passing [%] at 40°C [%]](image2)

Figure 3: Grading distributions: (a) aggregate fractions; (b) design grading.

![Water loss vs. Indirect Tensile Strength [MPa]](image3)

Figure 4: Results of quality control tests on the CRM mixture: (a) water loss; (b) ITS.
natural basalt coarse aggregate with nominal maximum size of 12 mm and 5.55% by aggregate mass of SBS-modified bitumen. The ITS value at 25°C was 1.67 MPa.

3.6. Description and Calibration of the Sensors. Six Teros 12 capacitance moisture sensors, produced by Meter Group, were installed within the cold recycled binder layer and connected to a ZL6 datalogger (Figure 5) by means of 25 m custom cables. The sensors were designed to measure soil volumetric water content (VWC) temperature (thermistor) in a volume of about 1 dm³ surrounding the three stainless steel needles. The data logger, housed in a weather-resistant enclosure, includes built-in circuitry to charge nickel-metal hydride (NiMH) batteries using energy from two integrated solar panels. The logger has integrated GPS, temperature and barometric pressure measurement, and collected data are transmitted to a cloud server via cellular communication.

Teros 12 sensors come with calibration equations to convert the raw electrical measurement into a VWC value. These equations can be used for mineral soil types but not for CRM mixtures which contain a certain volume of bitumen. Therefore, a laboratory calibration procedure was developed for converting the VWC measured by the sensors to actual GWC of the mixture.

First, it must be highlighted that the Teros 12 sensors are designed to be installed simply by pushing the needles inside the uncompacted soil. This procedure is not applicable with compacted CRM mixtures that offer a high resistance to the penetration of the needles due to their high density and to the presence of coarse aggregates. Originally, the plan was to drill three holes in the compacted CRM mixture for installing the sensors. However, the first attempt on a CRM mixture specimen failed because the presence of coarse aggregates did not allow the preparation of clean and straight holes. Therefore, calibration was carried out using CRM mortar specimens instead of CRM mixture specimens, and a specific field installation procedure was developed.

The CRM mortars were obtained by removing coarse RA aggregates (retained on the 2 mm sieve) from the mixture. Then, natural sand was added to obtain a volumetric composition of the mortar characterized by the same volume of bitumen as the CRM mixture used in the field (11%). Six mortar specimens were produced using three water dosages (3.0, 5.0, and 7.0% by aggregate mass) and two compaction energies (Standard and Modified Proctor).

Each sensor was installed in a different specimen for 24 hours and then removed and reinstalled in a specimen with a different water content. In this way, each sensor measured all the prefixed water dosages at least once. During the measurement, the specimens were placed in the laboratory at ambient temperature. At the end of the measurement, the specimens were broken, and their actual GWC was measured by oven drying.

Figure 6 shows the calibration curves developed to convert the VWC reading of the sensors, based on the default calibration curve, into the GWC of the CRM mixture. Figure 6(a) relates the VWC reading of the sensors (VWCsensors) and the actual VWC of the CRM specimens (VWC_{CRM}), whereas Figure 6(b) relates VWC_{CRM} to the GWC of the CRM mixture, based on its density (\( \rho_b \)).

4. Construction of the Instrumented Section

4.1. Pavement Construction. The instrumented section was built from 6 to 8 July 2020. During the first day, cold milling of the existing pavement was carried out in two phases: in the first phase, the milling machine reached the depth of 4 cm and in the second phase, the depth of 29 cm and 14 cm in subsections 1 and 2, respectively. Then, the existing subgrade was compacted by means of a vibratory steel roller. At the same time, a manhole was installed at the roadside for collecting and housing of the cables from the sensors.

The morning of the second day, the new CTRM base course for subsection 1 was laid through a paver and compacted using a vibratory steel roller and a pneumatic-
tired roller (Figure 7). The prime coat was applied immediately afterwards followed by the spread of limestone filler.

The afternoon of the second day, the CRM binder was laid in both subsections and compacted using both a vibratory steel roller and a pneumatic-tired roller (Figure 8(a)). More details on CRM production phase can be found in [23]. The sensors were installed immediately afterwards. To facilitate the initial water evaporation, the tack coat was spread in the morning of the third day, about 18 hours after the CRM binder layer construction. Finally, the AC wearing course was laid in subsections 1 and 2 and compacted using a vibratory steel roller (Figure 8(b)).

4.2. Installation of the Sensors. The six sensors were installed at the center of the right lane, at middepth of the CRM binder layer. Before installation, parallelepiped-shaped wood tablets (40 × 9 cm with a thickness of 3 cm) with three nails placed in the three sensors’ needles position were prepared (Figure 9(a)). Moreover, the sensors’ cables were protected with flexible metallic tubes to prevent damaging during installation (Figure 9(b)). The installation started
immediately after laying the CRM binder layer. The installation procedure was as follows:

(a) Small trenches were excavated into the uncompacted CRM binder layer, and the wood tablets were positioned where the sensors were to be installed. Steel bars were placed in trenches created in the position defined for cables (Figure 10(a)).

(b) The CRM binder layer was compacted to its final density, during the compaction, the wood tablets and the steel bars created trenches for placing the sensors and their cables. After compaction, the wood tablets and steel bars were carefully removed trying to limit the disturbance of the surrounding material (Figure 10(b)).

(c) The sensors were installed, and the cables were laid inside the trenches (Figure 10(c)).

(d) The sensor trenches were filled with a cold recycled mortar obtained by sieving the CRM mixture used for the layer on the 4 mm sieve to avoid the contact between sharp-angular aggregates and sensors. The mortar was compacted using a portable Marshall hammer (Figure 10(d)).

(e) The cables trenches containing the metallic cables were sealed using a cementitious mortar (Figure 10(e)).

(f) The data logger was installed, and sensors were connected (Figure 10(f)).

The sensors measurements were recorded for one year after the construction of the demonstration site, and the sampling intervals were the following:

(i) 5 minutes, from 7 July 2020 (18:05) to 9 July 2020 (18:15)
(ii) 15 minutes, from 9 July 2020 (18:15) to 21 July 2020 (8:30)
(iii) 30 minutes, from to 21 July 2020 (8:30)

The rainfall data (accumulated rainfall every 30 minutes) measured by the San Marino weather station managed by the Agenzia Prevenzione Ambiente Energia Emilia-Romagna (ARPAE) were also collected.
5. Testing Programme

During construction, LFWD tests were carried out on the subgrade, the CTRM layer, and the CRM layer to evaluate the as-built stiffness. The CRM mixture was sampled and compacted in the field using a gyratory compactor (GC). GC specimens with diameter of 150 mm and height of 70 mm were cured at 10, 25, and 40°C and tested at 20°C to measure the indirect tensile stiffness modulus (ITSM) according to EN 12697–26 Annex C, at various curing times (Table 2). After construction, two series of cores were extracted along the middle of the right lane (outside the traffic wheelpaths): 7

![Figure 10: Installation of the sensors](image)

**Table 2: Testing programme.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Curing temperature (°C)</th>
<th>Curing time (days)</th>
<th>Test</th>
<th>Repetitions (no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimens</td>
<td>40</td>
<td>3, 7, 14, 28, 85</td>
<td>ITSM</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>308</td>
<td></td>
<td>Air voids</td>
<td>4</td>
</tr>
<tr>
<td>Specimens</td>
<td>25</td>
<td>3, 7, 14, 28, 85</td>
<td>ITSM</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>308</td>
<td></td>
<td>Air voids</td>
<td>4</td>
</tr>
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<td>Specimens</td>
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<td>ITSM</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>308</td>
<td></td>
<td>Air voids</td>
<td>4</td>
</tr>
<tr>
<td>Cores</td>
<td>Field condition and 25°C in lab</td>
<td>22 on site + 6, 63, 286 in lab.</td>
<td>ITSM</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Field condition and 25°C in lab</td>
<td>22 on site + 286 in lab.</td>
<td>Air voids</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Field condition and 25°C in lab</td>
<td>305 + 3 in lab.</td>
<td>ITSM</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Field condition and 25°C in lab</td>
<td>305 + 3 in lab.</td>
<td>Air voids</td>
<td>4</td>
</tr>
<tr>
<td>Subgrade layer</td>
<td>Field condition</td>
<td>0</td>
<td>LFWD</td>
<td>16</td>
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<tr>
<td>CTRM layer</td>
<td>Field condition</td>
<td>0</td>
<td>LFWD</td>
<td>16</td>
</tr>
<tr>
<td>CRM layer</td>
<td>Field condition</td>
<td>0</td>
<td>LFWD</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>18 hours over one year</td>
<td></td>
<td>Temperature moisture content</td>
<td>every 5 minutes</td>
</tr>
</tbody>
</table>
cores after 22 days and 4 cores after 305 days. Specimens including only the CRM layer were cut and continued their curing in a climatic chamber at 25 °C; their ITSM was measured at different curing times (Table 2). The air void content was measured on all the GC and CRM cores specimens according to EN 12697–8.

Table 2 summarizes the testing programme developed in laboratory and field.

6. Analysis of Results

6.1. Light Falling Weight Deflectometer. Figure 11 shows the values of the LFWD modulus measured during pavement construction on the subgrade (64 MPa), the CTRM base course right after construction (79 MPa), and the CRM binder course right after construction (137 MPa) and after 18 hours of curing, right before the tack coat application (218 MPa). The increase in stiffness of the CRM layer is an effect of both curing and temperature [25]. In fact, during the first measurement, the average layer temperature as recorded by the sensors was about 34 °C, whereas during the second measurement the average layer temperature was about 24 °C.

6.2. Volumetric Properties. Figure 12 shows the values of the voids measured on the specimens and cores as defined in [1]. As it can be observed, the air voids of the gyratory specimens were significantly lower than the field cores. This confirms the findings of a previous field investigation [26] and suggests that the number of gyrations requested by the specifications (n = 100) overestimates the actual compaction energy applied in the field with the available rollers [27]. Slightly lower voids were measured on the cores extracted from subsection 1, with respect to subsection 2. This was probably related to the higher stiffness of the underlying CTRM base layer, which led to a better compaction of the CRM layer.

6.3. Mechanical Properties. Figure 13 shows the ITSM evolution of the GC specimens and CRM cores confirming another previous study [23]. The GC specimens had a similar evolution, and after 3 days, the ITSM was always higher than 3000 MPa complying with the specification [24], regardless of the curing temperature. After 28 curing days of curing at 40, 25, and 10 °C, the average stiffness was 6385, 5894, and 4996 MPa, respectively. Stiffness continued increasing after 28 days, the average increase of ITSM from 28 to 85 days was 22%.

The cores extracted 22 days after construction showed lower stiffness than the GC specimens. After 28 days (22 days of in-field curing and 7 days of laboratory curing at 25 °C), the cores extracted from subsections 1 and 2 had average ITSM values of 3323 and 2789 MPa, respectively. After 308 days (22 days of in-field curing and 286 days of laboratory curing), the average ITSM reached 4825 and 4431 MPa, for subsections 1 and 2, respectively.

The average stiffness of the cores sampled 305 days after construction was 4013 MPa. This value is comparable to that of the cores sampled after 22 days and cured in laboratory up to the same specimen age. This confirms that the curing temperature mainly influences the initial curing rate, whereas its effect on the long-term properties is lower.

The difference in stiffness between the GC specimens and the field cores may be explained by the different compaction levels (Figure 12). Ferrotti et al. [26] observed that the stiffness could be directly related to the air voids
regardless of the curing conditions. In particular, testing a material having the same composition as the one considered in the present investigation, they found that a 1% increase in air voids led to an ITSM reduction of about 900 MPa. By applying this correction to the ITSM of the cores, a value comparable to those obtained on the GC specimen would be obtained.

Figure 14 shows the temperature and VWC CRM data measured in the first 3 days after the installation of the sensors. Initially, the temperature of the CRM layer decreased from about of 35 °C to about 18 °C. In this time interval, water evaporation was free from the top surface of the layer and the sensors recorded fairly constant VWC CRM values ranging between 6.5 and 8.5%. Then, the tack coat was applied followed by the laydown and compaction of the AC wearing course. Although the thickness of the wearing course was only 4 cm, all sensors survived and measured a sudden increase of both moisture (about 2%, probably due to the emulsion water), and temperature (up to a maximum value of 67.2°C). In addition, sealed curing condition started. Figure 14 also shows that, in the middle of the day, a temporary decrease in temperature was measured by sensors 2 and 3. This was a local effect due to the shadow occurring on the pavement in the position where those sensors were installed (Figure 10(b)).

The average air and CRM layer temperatures in the first three days were 26.9 and 37.0°C, respectively, while the average VWC CRM and GWC CRM values of the CRM layer were 9.2 and 4.4%, respectively.

Figure 15 shows the average daily values of temperature and VWC CRM data measured in the first year of pavement monitoring. It is highlighted that sensors 4 and 6 stopped working on 18 August 2020 because their cables were damaged during maintenance operations carried out along the road margin.

Considering the full year, the median value of the average daily temperature of CRM layer was 16.7°C, with 67% of the days showing values below 25°C. On a monthly base, the average temperature varied between 33.4°C in July 2020 and 4.5°C in January 2021. On the other hand, the absolute maximum and minimum temperatures were 53.1 °C, measured by sensor 4 on 29 July 2020 at 16:30, and −0.7 °C measured by sensor 2 on 13 January 2021 at 6:30. The air temperature measured by the logger was generally lower than the temperature of the CRM layer, except from November 2020 to February 2021, when the two temperatures were practically the same.

The VWC CRM readings showed higher variability than temperature readings. Specifically, the measurements of sensors 1, 3, and 6 showed huge peaks, related to rainfall events. The peaks were characterized by a sharp daily increase of VWC CRM, followed by a slower decrease, lasting from a few days to some weeks. Although the peaks appear to be similar to those shown in Woods et al. [16] and Cox and Howard [17], their cause is different. In those cases, the CIR layer had not been overlaid and the moisture increase could be related to the direct infiltration of the rainfall water. In the present case, the peaks that were not registered by all the sensors cannot be due to direct infiltration because the CRM binder layer was below the AC layer and sealed by two bituminous interlayers (Figure 2). Instead, they were likely due to the infiltration of water from the roadside or manhole through the trenches excavated for the cables, or directly through the corrugated tubes that were used to protect the cables (Figure 10). The peak shown by the measurements of
sensor 5 has a lower increasing rate but was likely due to a similar cause (infiltration of water from the road margin). Therefore, those VWC_{CRM} peaks can be considered a local effect that cannot be extended to the whole pavement similarly to the effect of the shade on the temperature recordings.

Figure 16 relates the daily average values of VWC_{CRM} and temperature, for sensors 1, 2, and 5 (peaks were removed). As it can be observed, VWC_{CRM} was comprised between 7 and 10%, with the values measured in July 2021 being about 1.5% higher than those measured in July 2020. The VWC_{CRM} values can be converted into GWC_{CRM} values using the densities of the cores extracted from subsection 1 that were comprised between 2081 and 2122 kg/m³. Therefore, we can estimate that during the first year of service life, the GWC_{CRM} increased from about 4.0% to about 4.5%. The observed long-scale variation probably reflects the gradual transition toward equilibrium conditions with the moisture of the soil surrounding the pavement. This hypothesis could be validated by the joint measurements of temperature and GWC_{CRM} that will be carried out in next years.

7. Conclusion

Temperature and moisture sensors were successfully installed as part of cold central-plant recycling project in the Republic of San Marino. A CRM mixture including 4.5% of SBR-modified bitumen emulsion, and 2.0% of cement was used to build a 10 cm binder layer that was sealed between two bituminous interlayers (a prime coat at the bottom and a tack coat on the top). Overall, the rehabilitation of the pavement section, from the milling of the existing pavement until re-opening to traffic, had a duration of less than 3 days.

By comparing the volumetric properties of GC specimens compacted during construction and cores extracted from the pavement during the first year of service life, it was found that the latter had higher voids. This indicates that the compaction energy specified by the construction specifications (100 gyrations) overestimated the actual compaction energy applied in the field by steel and a pneumatic-tired rollers. As a consequence of the higher voids, the cores were also characterized by lower long-term stiffness values.

The volumetric water content of the CRM binder layer had an increase of about 2% after the application of the emulsion tack coat application on its surface and its temperature exceeded 65°C during the construction of the AC wearing course. However, the average values of VWC_{CRM}, GWC_{CRM}, and CRM binder layer temperature in the first three days were 9.2, 4.4, and 37.0°C, respectively. Taking into account the quality control procedure and the monitoring of moisture loss, it can be affirmed that three days curing time at 40°C in sealed condition adequately simulates the in-field condition recorded (sealed CRM binder layer, average air temperature of 26.9°C, no rain).

During the first year, the average daily temperature of the CRM layer ranged between 4.5°C (January 2021) and 33.4°C (July 2020), with a median value of 16.7°C. During the same period, the volumetric water content of the CRM layer remained almost constant until January 2021 and then slightly increased reaching a value of about 10% (corresponding to a gravimetric water content of 4.5%). This behavior can be explained considering that the upper and lower surfaces of the CRM layer were sealed and that, in the long-term, the moisture of the pavement must reach an equilibrium with the surrounding soil.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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