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Surface rehabilitation of Portland cement concrete (PCC) pavements using single or double surface dressings with soft bitumen, conventional or modified emulsions

Iran Rocha Segundo [b], Leonel Silva [b], Carlos Palha [b], Elisabete Freitas [a], Hugo Silva [a],*

[a] ISISE, Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal
[b] Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal

HIGHLIGHTS

- Single surface dressings increased more the macrotexture of concrete pavements.
- Soft bitumen performed better than emulsions when pulling-off surface dressings.
- Vialit mechanical adhesion was similar for conventional and modified emulsions.
- Double surface dressings covered with diluted emulsion wear less in the prototype.
- Surface dressings are potential surface treatment alternatives for concrete pavements.

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ABSTRACT

Surface dressings are a sustainable maintenance alternative for pavements with surface distresses, due to the low amount of resources involved. This paper aims to analyze the viability of using twelve different surface dressing solutions, including three binders (conventional and modified emulsions, and a soft 160/220 bitumen) and a covering with diluted emulsion, for surface treatment of Portland cement concrete (PCC) pavements. Several test methods were used to evaluate the macrotexture, skid resistance, adhesion, and resistance to wearing on a large scale prototype. In general, single surface dressings increased further the macrotexture of the concrete pavement surface. The skid resistance of single and double surface dressings was similar. The best surface dressing in the pull-off test was that with the 160/220 bitumen. The conventional and modified emulsions presented similar mechanical adhesion in the Vialit plate test. Concerning the prototype wearing test, the best result was obtained for the double surface dressing with bitumen covered with diluted emulsion. Based on this work's results, the surface dressings are a potential surface rehabilitation alternative for concrete pavements.

1. Introduction

Portland Cement Concrete (PCC) has been applied in the surface layers of rigid pavements for highway and airport lanes, presenting high durability. However, continuous pavement material deterioration can cause cracking, reducing structural and functional capabilities. The asphalt overlay is one of the most common pavement rehabilitation methods with asphalt mixtures [1,2], but this technique can reflect the old pavement's cracking and maintain its surface problems. Thus, surface dressings (also called chip seals) can be used for early PCC pavement rehabilitation, i.e., for crack control, although this solution is most commonly used for the same purpose in asphalt pavements [3,4].

Surface dressings are not as durable as conventional asphalt pavement, but they increase the original pavement's durability by improving the impermeability with low initial costs and a fast and easy construction process [5,6]. They improve road surfaces' impermeability, extend the life-cycle of asphalt pavements, provide a secure top layer with enhanced smoothness and skid resistance, and protect the pavement structure mostly to weather [7].

Surface dressings are typically used as a coating on unbound granular layers without significant structural contributions on

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* Corresponding author.
E-mail addresses: iran_gomes@hotmail.com (I. Rocha Segundo), leonelvalerio@hotmail.com (L. Silva), cpalha@civil.uminho.pt (C. Palha), efreitas@civil.uminho.p (E. Freitas), hugo@civil.uminho.pt (H. Silva).

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light and medium volume traffic roads. However, this technique is also built for preventive and maintenance purposes in flexible pavements with asphalt mixtures [8]. One significant distress of the pavements built with surface dressings is ravelling (loss of aggregates) due to the reduction of aggregate–binder adhesion caused by traffic, weather agents, or low-quality materials. Thus, the performance of the surface dressings depends on the efficiency of the aggregate–binder adhesion. Another distress of surface dressings is bitumen bleeding or flushing, indicated by asphalt binder rise above the pavement surface [6,8,9].

In general, this technique is built in three steps: i) spraying the asphalt binder (e.g., emulsion), ii) spreading a layer of aggregates, and iii) compaction [10]. These steps should be continuous to ensure the best performance. Their composition consists of one, two, or three layers of binder and aggregates, resulting in single, double, and triple surface dressings, respectively [11]. The surface dressings' performance is significantly affected by the aggregates' properties, the type of asphalt binder, and their relative rates. The substrate conditions and environmental factors also influence the surface dressings' performance [8]. When this technique is applied in low-quality substrates, their performance and the pavement's corresponding life-cycle are decreased [7]. The performance of the surface dressings are affected by eight construction features: i) the difference between the application ratios of transverse and longitudinal material, ii) uniform application, iii) binder rate, iv) interval between the applications of binder and aggregate, iv) material varieties, v) compaction equipment and rolling times, vi) aggregate penetration, vii) weather and viii) time for traffic opening [8].

Polymer-modified binders are being progressively incorporated in asphalt mixtures to improve high traffic volume roads' mechanical performance. Likewise, surface dressings made with polymer-modified emulsions provide better results, improve service life, and allow their use for roads with a higher traffic volume than the conventional emulsions [12,13].

The skid resistance is strongly affected by the macrotexture and microtexture scales [14], for wavelengths of 0.5–50 mm and 0.001–0.5 mm, respectively. Often, surface dressings are measured and characterized by their macrotexture, determining possible bleeding problems and ravelling [5,15]. The macrotexture loss is the most critical deterioration factor for this solution, and the initial texture depth is significant for long-term performance [6,8]

This solution usually provides higher noise than a conventional top layer composed of asphalt mixtures due to their positive macrotexture. Thus, surface dressings cannot be used for noise mitigation, although they are cheaper than asphalt mixtures, varying from 1.00 to 2.50 €/m^2 depending on the materials used and thickness or number of layers [16].

Rigid pavements, which are composed of PCC as the top layer, have a higher service life, but their rehabilitation is more complicated than that of flexible pavements. There are three maintenance strategies for repairing: i) emergency; ii) medium-term; iii) long-term. For medium-term repairs, the surface dressing can be applied over rigid pavements to improve their functional characteristics [17].

Buss et al. showed that the surface dressing enhanced the micro and macrotextures in a field investigation while reducing the cracks and potholes' occurrence, mitigating the pavement distresses [7].

Gheni et al. investigated crumb rubber incorporation in surface dressings, by substituting the conventional mineral aggregates from 25% to 100%. They concluded that this material could be used as aggregates in chip seals, by improving the macro and microtexture and the high-temperature resistance. By replacing the mineral aggregates totally, the texture depth increases around 30% [10].

Modelling prediction has also been evaluated to estimate surface dressing life using minimum macrotexture criteria, considering several variables for the prediction function shown in Equation (1). The minimum macrotexture depth (MT) for rehabilitation depends on country regulations [5]. For example, in New Zealand, the MT value is 0.9 mm, and it is recommended that surface dressing under this value need to be rehabilitated or rebuild [6,18].

$$\begin{aligned} \mathrm{MT} = {} & 15.721 - 0.605 \times \ln(\mathrm{CEV}) - 0.019 \times \mathrm{V} \times \mathrm{D} - 9.858 \\ & \times \mathrm{Vf} - 0.052 \times \mathrm{Ed} - 0.062 \times \mathrm{T} \end{aligned} \tag{1}$$

MT is the macrotexture depth, CEV is the cumulative equivalent traffic volume, V is the Vialit test result, D is the aggregate dust content, Vf is the basic void factor, Ed is the embedment depth of aggregate after construction, and T is the average surface temperature.

Gürer et al. observed that larger aggregates with a modified bitumen should provide better performance for single surface dressings on unbound granular base. The compaction at high temperatures results in excessive aggregate embedment, increasing macrotexture loss, and bleeding problems. Besides, they recommend that the application of the surface dressings should not be made below 30 °C or above 43.5 °C [8].

The use of polymer modified emulsions in surface dressings improves adhesion, reduces aggregate loss over a range of curing times, needs short curing times, facilitates the traffic opening, and improves safety by mitigating the friction deterioration ravelling. This material also enhances aggregate fixation below 25 °C, extending the life for cold temperatures [12]. Supported by Vialit test results for field evaluation, Karasahin et al. concluded that surface dressings with modified emulsion exhibit better performance when compared with a 100/150 bitumen [2].

Lee and Kim concluded that the higher the rolling passes, the lower the aggregate loss. Their study found that the best number of rolling passes is three, considering the aggregate retention performance and the cost-efficiency for single and double surface dressings [19].

In this paper, new solutions for the rehabilitation of PCC pavements were evaluated by applying single and double surface dressings over concrete slabs. These were composed of three different binders, sometimes covered with a diluted emulsion. The performance of the different surface dressings was evaluated through a series of tests, as presented in the next sections.

2. Materials and methods

2.1. Materials

2.1.1. Asphalt materials

A conventional emulsion (CE) type C69B2 and a modified emulsion (ME) type C69BP2, as well as a soft bitumen (B) 160/220, were provided by CEPSA® to be used in this work. The emulsions were dried for 24 h at room temperature (31 °C), and then at 60 °C for 24 h, for evaluation of the residual bitumen, according to standard EN 13074. The binders were characterized (Table 1) by the residual bitumen (retained mass) of the emulsions (EN 13074), penetration (EN 1426), softening point (EN 1427), resilience (EN 13880–3) and elastic recovery (EN 13398) and also by rheology (EN 14770) and dynamic viscosity (EN 13302).

The properties presented in Table 1 were intercepted and compared with the standard European limits presented in EN 13,808 for emulsions (CE and ME) and EN 12,591 for paving bitumen (B). All limits presented in those standards were fulfilled for binder B, while emulsions CE and ME were classified in the expected performance classes.

Table 1
Properties of the binders.

Binder	Residual Bitumen (%)		Penetration(10^{-1} mm)	Softening Point(°C)	Resilience(%)	ElasticRecovery(%)
	After 24 hat 31 °C	After 48 hat 60 °C				
CE	68	67	142	42	-*	-*
ME	67	65	100	49	11	55
B	-*	-*	160	40	-*	-*

*The material does not present the characteristic or does not allow the test

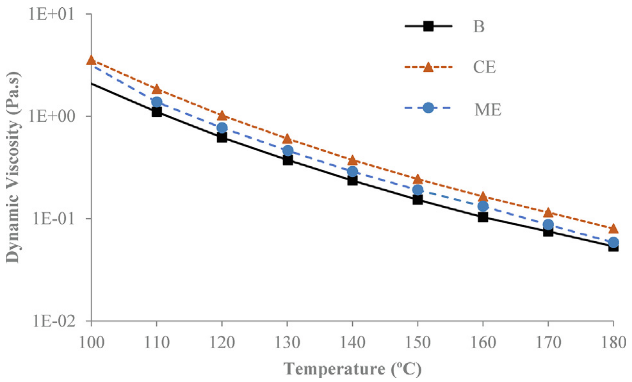


Fig. 1. Viscosity of binders.

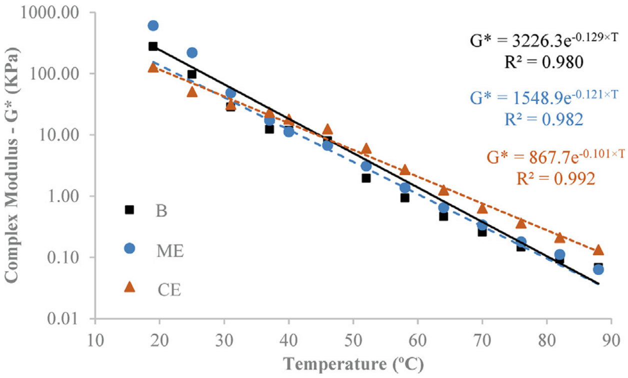


Fig. 2. Complex Modulus of binders.

After the first 24 h, almost all the water from both emulsions evaporated, with similar residual bitumen values when the drying process finished (nearly 66%). The characterization of the residual binder of the emulsions was made after concluding the previous process.

The less consistent binder in the penetration test was bitumen 160/220, followed by the conventional and the modified emulsions. Regarding the softening point, the binder with a higher softening temperature was the modified emulsion, which means that it will have fewer deformations. The resilience and elastic recovery tests are associated with polymer-modified asphalt binders, and these properties were only tested for the modified emulsion. Although the resilience was not very high (11%), the modified emulsion's elastic recovery presented a high value (55%) for this type of material. This test shows the ability of the modified emulsion to recover from tensile stresses. Thus, despite the high consistency of the modified emulsion, the polymers may contribute to a good fixation of the aggregates in the surface dressing.

Fig. 1 shows the variation of the three binders' dynamic viscosity as a function of temperature, as measured by the Brookfield rotational viscometer according to a lab-developed procedure [18]. The descending order of viscosity of the asphalt binders was CE, followed by ME, and finally, B. This test is essential to determine the spreading temperature of hot bitumen during the surface dressing application. At about 150 °C the viscosity of bitumen B is 0.15 Pa.s, which is sufficiently low for application of the bitumen in surface dressings.

Fig. 2 shows the characterization of the complex stiffness modulus (G*) of the binders in the rheology test. The rheological analysis mainly evaluates this property for a range of service temperatures ranging from 19 to 88 °C, closer to the surface dressings' service temperatures. In this solution, the aggregates are more easily removed for stiffer binders, especially at low temperatures.

Based on the results obtained, it is possible to notice that the most rigid binder at high temperatures was CE, followed by ME and B, confirming the order obtained in the viscosity test. However, at lower temperatures, the trend was different: the stiffer binder was ME, followed by B, and the softer binder was ME. The presence of polymers in ME may justify the stiffer behaviour observed at lower temperatures.

2.1.2. Aggregates

Three fractions (2/4, 4/6, and 6/10) of granitic aggregates were used to produce the surface dressings. Fraction 4/6 was used in single surface dressings, and fractions 2/4 and 6/10 were used in double surface dressings, according to Portuguese specifications [20].

2.1.3. Portland cement concrete slabs

The PC concrete slabs (CS) used as a base for the surface dressings were precast concrete for building paving, supplied with 60 × 40 × 4 cm^3. They were previously cut to apply the surface dressings in 2 slabs with 30 × 40 × 4 cm^3. The main properties of the slabs are presented in Table 2.

2.1.4. Specimens production

The binder and the aggregates were spread over each pair of concrete slabs to produce twelve different surface dressings: 1: Single with CE and aggregates 4/6; 2: Single with CE and aggregates 4/6 covered with diluted emulsion; 3: Double with CE and aggregates 6/10 and 2/4; 4: Double with CE and aggregates 6/10 and 2/4 covered with diluted emulsion; 5: Single with ME and aggregates 4/6; 6: Single with ME and aggregates 4/6 covered with diluted emulsion; 7: Double with ME and aggregates 6/10 and 2/4; 8: Double with ME and aggregates 6/10 and 2/4 covered with diluted emulsion; 9: Single with B and aggregates 4/6; 10: Single with B and aggregates 4/6 covered with diluted emulsion; 11: Double with B and aggregates 6/10 and 2/4; 12: Double with B and

Table 2
Concrete Slab Characterization.

Property	Compression Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)
CS	35.8	7.7	26.6

aggregates 6/10 and 2/4 covered with diluted emulsion. Thus four types of surface dressings were produced with each binder: Single (S), Single Covered with diluted emulsion (SC), Double (D), and Doubles Covered with diluted emulsion (DC). Table 3 shows the rates of aggregates and binders used for the surface dressings considering the Portuguese specifications [20], and Table 4 summarizes the composition of each of the surface dressings.

After applying the aggregates, each surface dressing was compacted using the Vialit plate's cylinder (25 kg) test with ten cycles. Six surface dressings were also composed with a 50/50 water-diluted asphalt emulsion carried out over the last layer of aggregates.

2.2. Methods

2.2.1. Macrotexture by the volumetric patch method

The macrotexture analysis by the volumetric patch is a method that assesses pavement surface macrotexture through the spreading of a volume of glass spheres onto the pavement surface. The material is distributed over a circular area, and the diameter of the circle is measured. The volume divided by the area of the circle is reported as the Mean Texture Depth (MTD), according to EN 13036–1.

2.2.2. Macrotexture by the Mean profile depth assessed with a laser table

Another test to assess the surfaces' macrotexture is carried out with a laser table, which accurately determines the surface profile. This equipment has better accuracy than the volumetric patch method because it enables recording ×, y, and z values of the continuous macrotexture. It also allows estimating the average texture depth for comparison with the results obtained in the volumetric patch method. The laser table used acquires longitudinal unevenness of the surface with horizontal increments of 0.2 mm for a vertical resolution up to 0.01 mm (Fig. 3).

Roughness and macrotexture are properties measurable through Equation (2) using the Mean Profile Depth (MPD) method [21–24]. With this test method, it is also possible to draw the surface on a 3D graph to perform qualitative analyzes.

$$MPD = \frac{1^{st}\ peak + 2^{nd}\ peak}{2} - average\ level \quad (2)$$

2.2.3. Skid resistance by British pendulum

The British pendulum test was carried out according to EN 13036–4. It indirectly evaluates the surface microtexture of asphalt mixtures through the coefficient of kinematic friction measured from friction energy. This property is one of the most critical functional features for pavements, related to safety. The test uses a piece of portable equipment (British pendulum). The friction coefficient is measured through the energy absorbed by friction expressed in PTV (Pendulum Test Value).

2.2.4. Pull-off test

The pull-off test used in this work aims to quantify the adhesion between the substrate and the surface dressing (Fig. 4). It is performed using equipment that applies a tensile load under a plate glued to the surface dressing using epoxy resin. The test, generally used for different coatings over cementitious materials, is specified for a constant displacement. The analysis was performed at a constant speed of 50 mm/min using a 38.5 mm diameter plate. It must be noted that bitumen behaviour is viscoelastic and can change with different loading speeds. Tests were carried out at room controlled temperature, which was set around 20 °C during these tests. The maximum strength and break time were recorded for each test. Three samples were taken in each coat to obtain the average result of the test.

2.2.5. Adhesion by Vialit plate

The Vialit adhesion test (EN 12272–3 standard) characterizes the adhesion and the stripping resistance between aggregates

Table 3
Application rates (kg/m^2) of the binders and aggregates for surface dressings.

Surface Dressing	1st application (1st layer)			2nd application (2nd layer)			Diluted emulsion
	Binder	Aggregate		Binder	Aggregate		
	Rate	Type	Rate	Rate	Type	Rate	Rate
1	0.9	4/6	6.5	–	–	–	–
2	0.9	4/6	6.5	–	–	–	0.3
3	0.7	6/10	7.5	0.9	2/4	4.5	–
4	0.7	6/10	7.5	0.9	2/4	4.5	0.5
5	0.9	4/6	6.5	–	–	–	–
6	0.9	4/6	6.5	–	–	–	0.3
7	0.7	6/10	7.5	0.9	2/4	4.5	–
8	0.7	6/10	7.5	0.9	2/4	4.5	0.5
9	0.9	4/6	6.5	–	–	–	–
10	0.9	4/6	6.5	–	–	–	0.3
11	0.7	6/10	7.5	0.9	2/4	4.5	–
12	0.7	6/10	7.5	0.9	2/4	4.5	0.5

Table 4
Surface Dressing Composition Scheme.

	Surface Dressing											
	1	2	3	4	5	6	7	8	9	10	11	12
CE	X	X	X	X								
ME					X	X	X	X				
B									X	X	X	X
Covered with diluted emulsion		X		X		X		X		X		X
Single (aggregates 4/6)	X	X			X	X			X	X		
Double (aggregates 6/10 and 2/4)			X	X			X	X			X	X

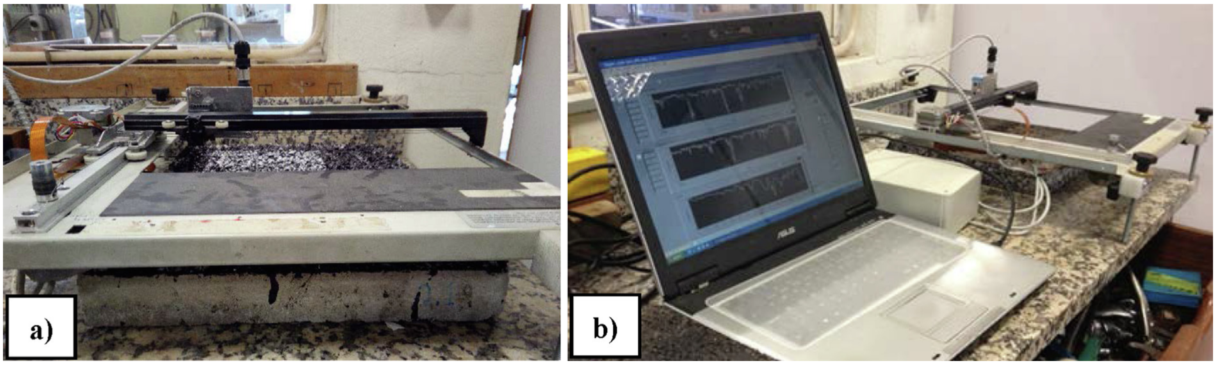


Fig. 3. a) Laser table used in this work and b) Acquisition of surface profiles.

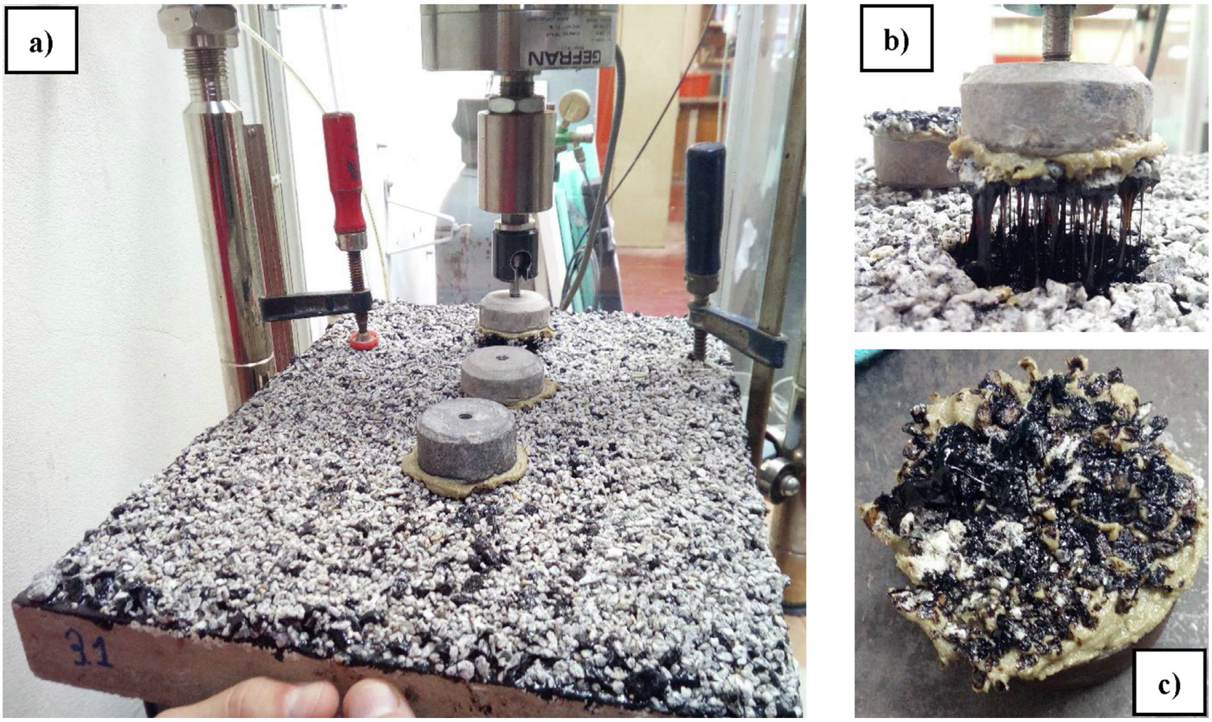


Fig. 4. Pull-off test: a) position of the plates; b) removal of the surface dressing; c) final aspect of the removed surface dressing.

and asphaltic binders of surface dressings through the use of the Vialit plate. The test is performed after applying 100 aggregates in a binder film previously deposited on metal plates with 20 × 20 cm^2. The test can be made for different aggregates and binders (e.g., emulsions and bitumen). The plate is placed horizontally and inverted on three supports, and a steel ball falls freely (0.5 m) three times, causing an impact. In the case of emulsions, the test can only be performed after the emulsion breaks. The test result is the number of loose stones, dirty or clean, and those remaining in the plate. This test evaluates the adhesion and stripping resistance of the surface dressing, i.e., the aggregate-binder adhesion, for dry and wet aggregates. The test aims to obtain four relevant results: i) mechanical adhesion; ii) active adhesivity; iii) wetting temperature; and iv) fragility temperature. The mechanical adhesion, fragility temperature, and wetting temperature were assessed in this work. The mechanical adhesion aims to evaluate the binder's adhesion to the aggregates, allowing classifying the binders about their mechanical adhesion. The aggregates were placed with the bitumen at 150 °C to obtain the mechanical adhesion. The wetting temperature test is performed to determine the lowest bitumen temperature guaranteeing the fixation of the aggregates. Finally, the fragility temperature test is performed to determine the lowest temperature at which the surface dressing can assure the fixation of asphalt emulsion or bitumen. In these tests, the binder application rates followed the values presented in Table 5.

2.2.6. Wearing test performed on a real scale wheel prototype

The wearing test in the prototype aims to evaluate the surface ravelling of the surface dressings. This prototype, called RARE, is a new piece of equipment that has been used to analyze rolling resistance [25], ravelling, and pavement noise, as demonstrated in this video: https://www.youtube.com/watch?v=ibYUoOY32Sk.

Table 5
Application rates of the binders (kg/m^2) in the Vialit plate tests.

Binder	Aggregate size (mm)	
	4/6	6/10
Bitumens	1.0	1.1
Emulsions	0.8	1.0

In general, the prototype consists of a central element that ensures the prototype's fixation on the test track. The equipment has two symmetrically arranged arms that are endowed with wheels. One of the wheels has coupled an electric motor, which guarantees the circular movement of the equipment. There is also a third arm, perpendicular to the latter two, with a laser for texture measurement. The prototype can simulate different loads up to 700 N in each wheel (using steel plates to increase the load). The prototype wheels can be tilted up to a maximum inclination of 5° to increase the pavement damage.

A cut with $30 \times 40 \times 4\ \mathrm{cm}^3$ was made on the existing pavement, in the test lane, where the testing slabs were placed. Tires 195/50 R 15 82 V were used in the test. Each wearing test corresponded to applying 1000 cycles in the prototype, each cycle being a complete revolution of the prototype for a running speed of 10 km/h without wheel tilt (Fig. 5). Tests were carried out at room-controlled temperature (set around 20 to 25 °C).

At the end of the test in the prototype, the following characterization was performed in order to compare the surface dressings before and after wearing (Fig. 6): i) macrotexture by laser table (calculation of MPD and its variation); (ii) British pendulum friction (calculation of PTV, and its variation); iii) the loss of surface dressing mass. The mass loss calculation of each surface dressing was performed by weighting the different slabs tested before and after the wearing process. Fig. 7 shows the schematic representation of this research.

3. Results and discussions

3.1. Macrotexture

3.1.1. Volumetric patch method

The results of the macrotexture by the volumetric patch method are shown in Fig. 8.

Regarding the texture depth, the concrete slabs (CS) used as support for the various surface dressings presented a value of 0.2 mm, being classified as a very thin or very closed texture.

As expected, the application of the surface dressings on the concrete slab increased the texture depth, which, on average, became 18.5 times higher. The surface dressings' texture depths were between 3.6 and 4.6 mm, which corresponds to a very coarse or open texture.

In general, single surface dressings had higher values than double ones, except for surface dressing 7 (double surface dressing with ME) that presented a high texture, possibly due to the ME binder's higher viscosity. The single surface dressings with emulsions increased their texture when covered with diluted emulsion, and the opposite occurred when bitumen was used. Regarding the double surface dressings, the influence of applying the diluted emulsion on the texture depth is not evident. The use of the different binders did not have a clear impact on this parameter. Nevertheless, the application of surface dressings in concrete pavements increases the macrotexture of the surface considerably, providing more significant drainage of water, and avoiding aquaplaning problems.

3.1.2. Mean profile depth assessed with a laser table

Fig. 9 shows the macrotexture results obtained using the laser equipment and calculating the MPD value. Compared with the previous volumetric patch method's results, the MPD values showed the same trend as the previews test, except for surface dressing 7. The application of surface dressings on concrete slabs increased 11.5 times the MPD. The average MPD values of the various surface dressings ranged between 3.4 and 3.9 mm. In general, single surface dressings had higher MPD values than the double ones. The single surface dressings with emulsions increased the MPD values when covered with diluted emulsion, in opposition to the surface dressings' results with bitumen. Regarding the double surface dressings, the diluted emulsion only increased the MPD values when ME and B binders were used. Furthermore, the different binders' use did not visibly impact the MPD value obtained with the laser table.

3.2. Skid resistance

Fig. 10 shows the British Pendulum results or PTV values before and after surface dressing's application over the concrete slab (CS).

The concrete slab had the lowest PTV value of 68. The application of surface dressings resulted in an average increase of the PTV to 71. All surfaces evaluated were classified as having very rough microtexture, including the base concrete. Single and double surface dressings showed similar PTV values. Regarding the single surface dressings, the application of diluted emulsion decreased the PTV values (71 to 69, 71 to 70 and 72 to 71, respectively, for surface dressings with CE, ME, and B). In opposition, the application of diluted emulsion on double surface dressings increased the PTV values (72 to 73, 68 to 72, and 71 to 73, respectively, for surface dressings with CE, ME, and B).

Although there are no significant differences between the different types of binders used, on average, the best surface dressings were those with B (average PTV of 72), followed by those with CE (average PTV of 71) and ME (average PTV of 70). In general, the best performance was that of double surface dressings covered with diluted emulsion, although the application of diluted emulsion was only beneficial for double surface dressings.

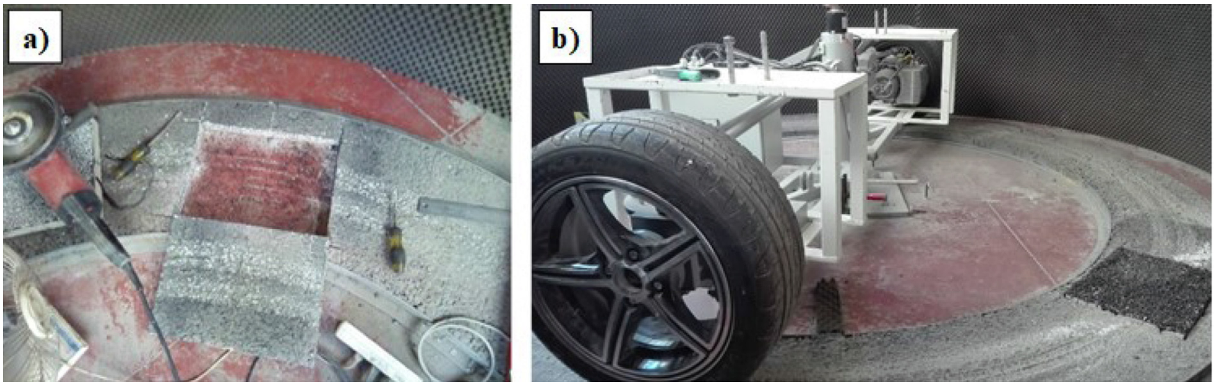


Fig. 5. Prototype: a) Pavement cut; b) Placement of the CS with the surface dressing.

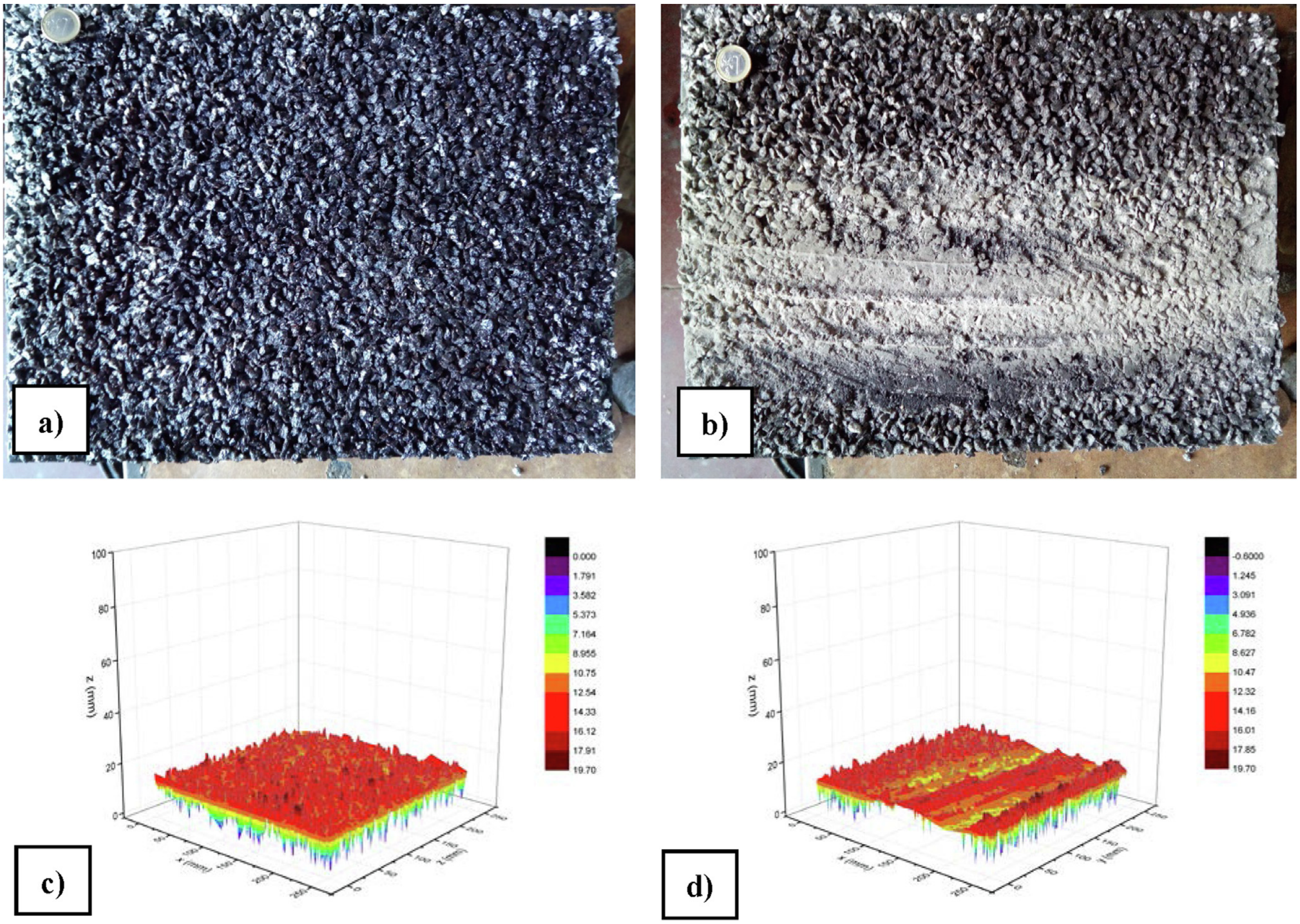


Fig. 6. Surface dressing: a) before wearing; b) after wearing. Macrotexture by laser table acquisition: c) before wearing; d) after wearing.

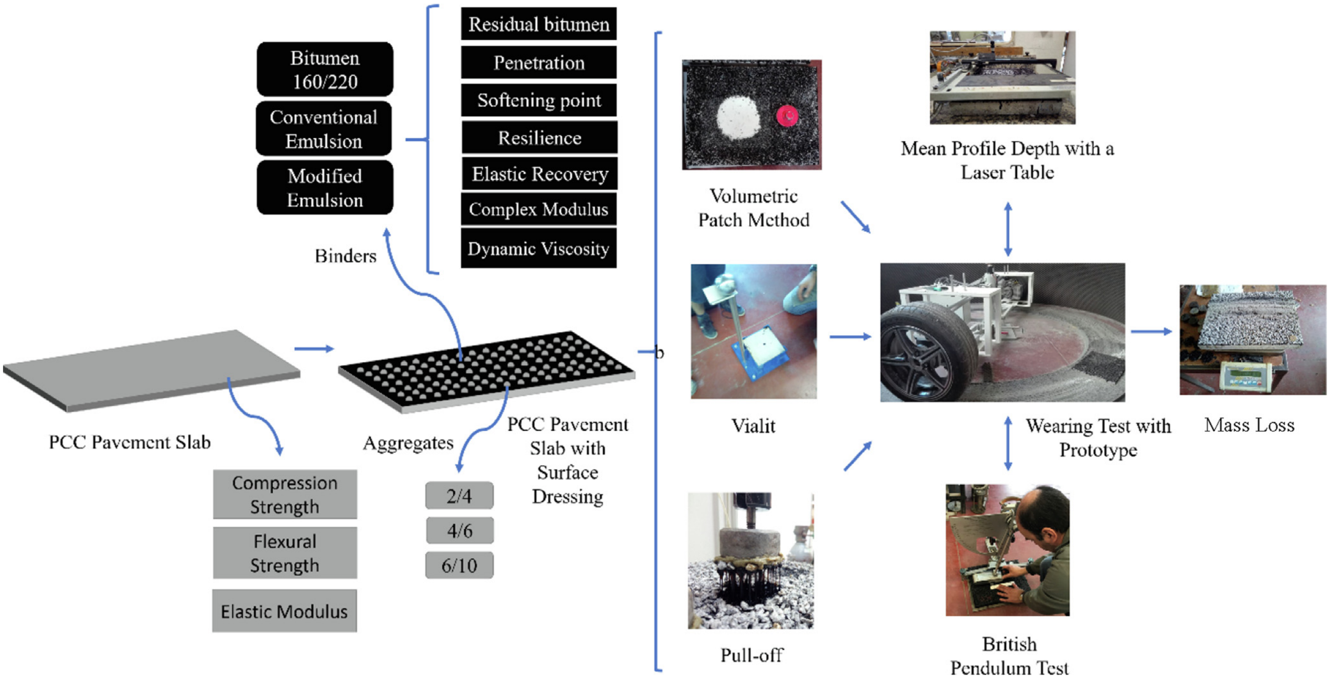


Fig. 7. Schematic representation of this research work.

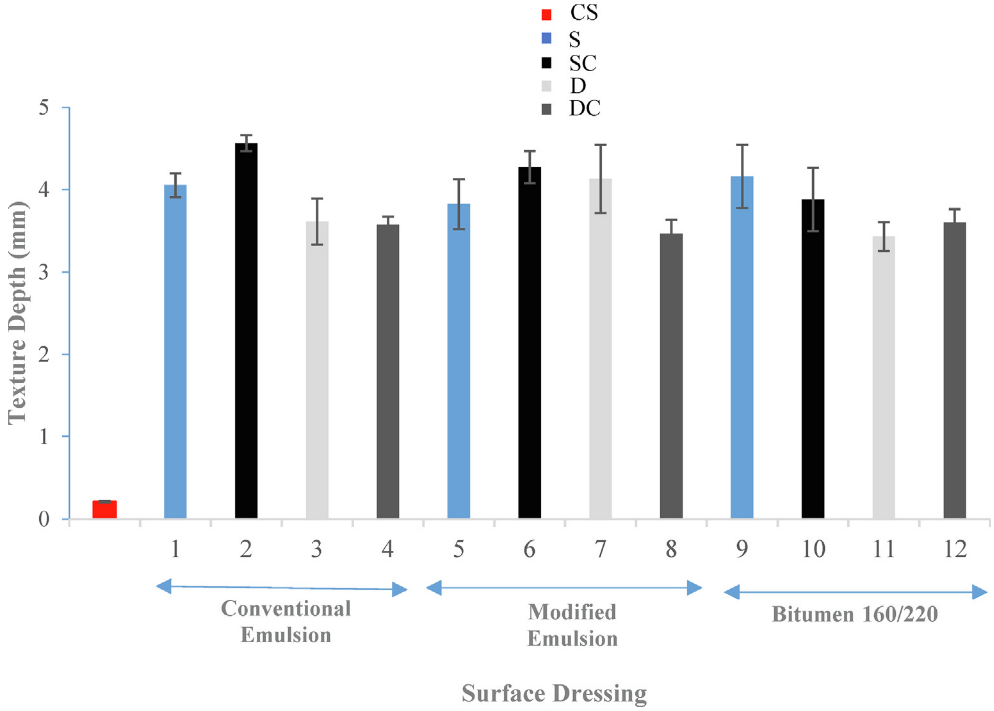


Fig. 8. Macrotexture by Volumetric Patch Method.

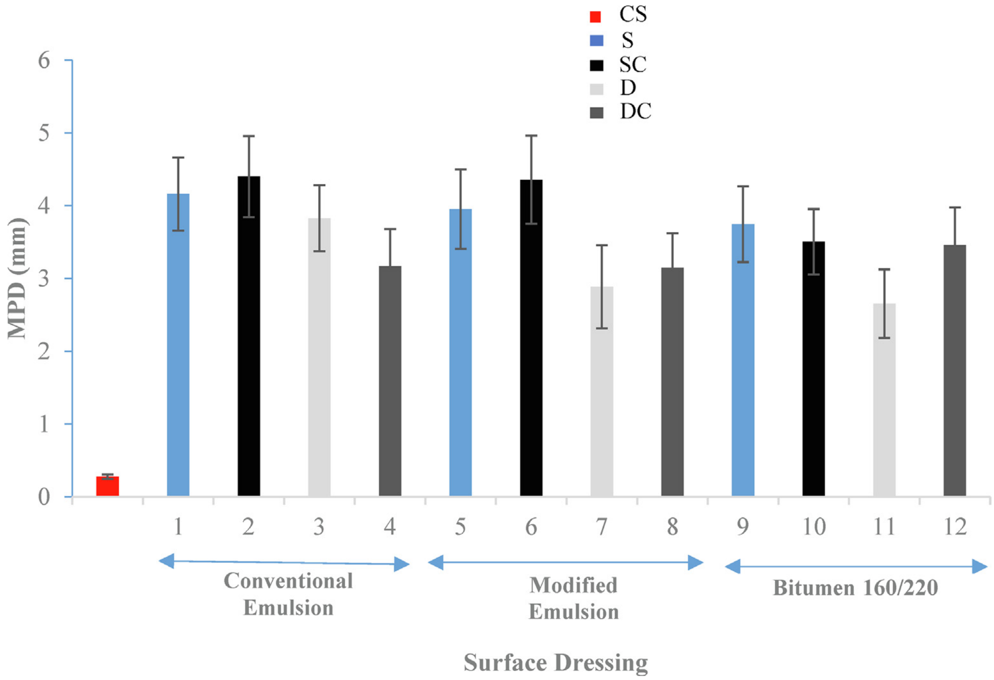


Fig. 9. MPD results obtained with a laser table.

3.3. Pull-off test

Table 6 presents the pull-off test results to evaluate the adhesion strength between the support surface (CS) and the surface dressings.

The results obtained in the pull-off test show that single surface dressings had average strength values (278 kN) about twice as high as double ones (139.8 kN). The pull-off maximum strength values of double surface dressings increased when covered with diluted emulsion, from 109.1 kN (non-covered) to 170.4 kN (covered coatings). On the other hand, using diluted emulsion in the single surface dressings resulted in an average decrease of the pull-off strength from 364.3 kN to 191.7 kN. Regarding the different types of binders used, the best results in this test were obtained for surface dressings with B (251.8 kN), as a consequence of their hot application, followed by ME (212.6 kN) and CE (169.8 kN). The type of binder used in the surface dressing has an evident influence on this test's results.

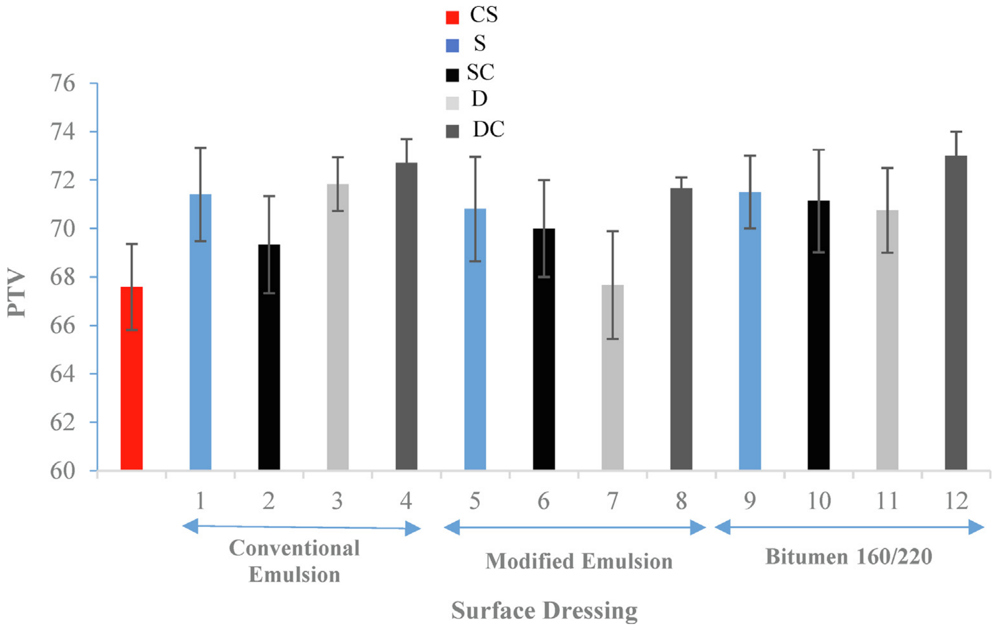


Fig. 10. Skid resistance results.

Table 6
Pull-off test results.

Surface Dressing	*Pull-off* rupture condition	
	Time (s)	Maximum force – F (kN)
1	2.7	281.5
2	2.2	217.0
3	2.0	57.5
4	2.0	123.1
5	2.0	416.2
6	2.5	182.6
7	2.7	74.7
8	2.3	146.8
9	1.9	395.1
10	3.6	175.6
11	3.4	195.3
12	3.4	241.2

In general, the pull-off time did not show a trend to increase proportionally to the force, which can be seen in Fig. 11. The surface dressings with the most extended pull-off times (of about 3.5 s) were 10, 11, and 12, composed of hot bitumen (B). Surface dressings 1, 6, and 7 showed intermediate pull-off times, around 2.6 s. The other surface dressings (2, 3, 4, 5, 8, and 9) had lower pull-off times, around 2.0 s.

3.4. Vialit adhesion test

The Vialit test evaluates the adhesion of the aggregates to the binder for surface dressings. Table 7 shows the mechanical adhesion results obtained in this test.

According to the Vialit Standard, there is no specification for compaction time, although the mechanical adhesion results are better when slower compaction is performed. Higher values of

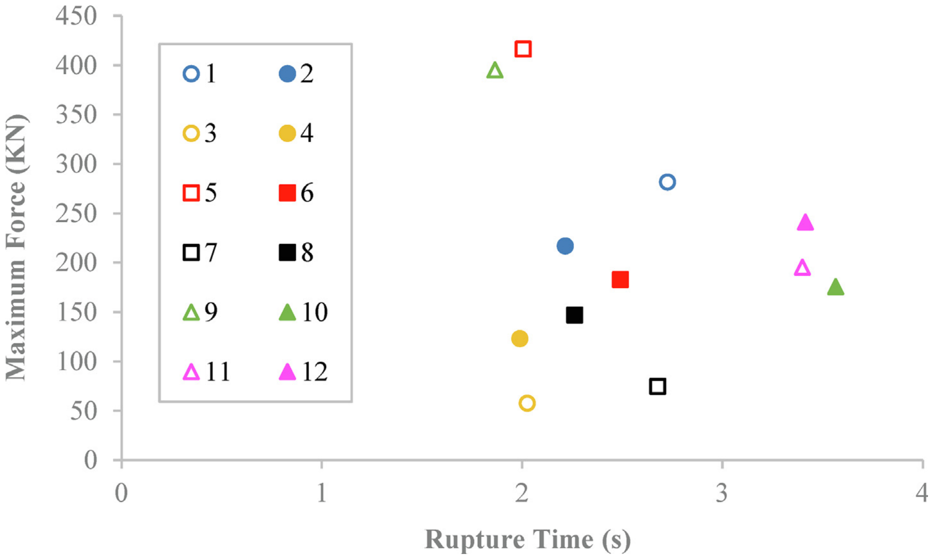


Fig. 11. Pull-off test results.

Table 7
Results of mechanical adhesion by the Vialit test.

Binder	Aggregates	Compaction	Fallen Aggregates		Remained Aggregates(c)	Mechanical adhesion (b + c)
			Unstained(a)	Stained(b)		
B	6/10	Fast *	46	24	30	54
B	6/10	Slow **	39	26	35	61
B	4/6	Fast *	20	4	76	80
B	4/6	Slow **	16	3	81	84
CE	6/10	–	1	0	99	99
CE	6/10	–	0	0	100	100
ME	4/6	–	0	0	100	100
ME	4/6	–	0	0	100	100

* 20 s
** 40 s

mechanical adhesion are also observed when smaller aggregates are used in the test.

Regarding the binders used, both emulsions behaved remarkably, although ME shows a slightly better mechanical adhesion than CE. Hot bitumen (B) had the worst results among the three binders studied, but the standard test conditions are different for this binder, influencing the results.

Table 8 and Fig. 12 present the values obtained when studying the fragility temperature of the emulsions. This test assesses the lowest surface dressing application temperature for each emulsion.

This test was initially performed at 5 °C, successively reducing the temperature wit steps of –5 °C until less than 90% of the aggregates remained in the plate. The fragility temperature is the lowest test temperature above that limit. According to the results obtained, the fragility temperature for the ME is −5 °C, while the fragility temperature for the CE is 0 °C. It can be concluded that the ME behaved better at low temperatures than the conventional emulsion due to the modification with polymers.

The wetting temperature evaluates the lowest temperature at which the aggregates can be successfully applied to the hot bitumen. This test starts at 5 °C, the temperature gradually increasing at steps of 5 °C until the mechanical adhesion of the aggregates is equal to or higher than 90%. Table 9 and Fig. 13 show the results of the hot bitumen (B) wetting temperature.

By increasing the conditioning temperature for aggregates' application, there was a trend to improve the mechanical adhesion, as expected. However, the wetting temperature of the bitumen 160/220 was only reached at 35 °C, for an adhesion value of 91.

In the Vialit test, it can be concluded that the ME presented the best performance, followed by the CE. Hot bitumen (B) behaved worse than the emulsions, due to the need for careful temperature control during application.

3.5. Characterization after the wearing test in the prototype

3.5.1. Mass loss

Table 10 shows the results obtained after the wearing test in the prototype regarding the mass loss. In general, double surface dressings have higher initial mass than single ones (since they have more material applied on the concrete slab), but they have lower mass loss values. The surface dressings covered with diluted emulsion presented a lower mass loss than those without that covering (except surface dressing 6, which showed a similar value). On average, the mass loss of the surface dressings with CE and C is similar, while the ME showed the best overall performance. The best overall solution was surface dressing 12 (double, with B, covered with diluted emulsion), with a mass loss below 10%. The worst results were obtained for single surface dressings 1, 9, and 10, with mass loss values higher than 20%.

Table 8
Results of fragility temperature by the Vialit test.

Binder	Aggregates	Conditioning temperature (°C)	Remained aggregates in the plate (%)
CE	6/10	5	99
CE	6/10	0	99
CE	6/10	−5	87
CE	6/10	−10	76
ME	6/10	5	100
ME	6/10	0	99
ME	6/10	−5	97
ME	6/10	−10	87

3.5.2. Macrotexture and skid resistance after wearing

According to Table 11, all surface dressings showed a decrease in MPD after wearing, which may be caused by layer compaction or disintegration. Surface dressings covered with diluted emulsion (even numbers) showed lower MPD reductions than those without emulsion covering (except surface dressing 12). Evaluating the average variation of MPD after wearing the surface dressings produced with the same binder, it was observed that the ME showed the best (lowest) result, followed by B and the CE. In general, the double surface dressings had lower MPD variation values (20%) than single surface dressings (40%). The surface dressings with the best performance (lower MPD variation after wearing) in descending order were 4, 7, 8, and 11, with an MPD reduction lower than 20%. The surface dressings with worst performance were 1, 2, 5, and 9, with an MPD reduction higher than 40%.

Then, Fig. 14 shows the values of the British pendulum after wearing. The best results obtained by the British pendulum after wearing were those of the double surface dressings covered with diluted emulsion. All surfaces evaluated were classified as having rough microtexture except specimens 3 and 4, classified as very rough. On average, single surface dressings had a lower British pendulum value (69) than double ones (72). Specimen 10 showed the best PTV for the single surface dressings. Regarding the different types of binders, on average, the best surface dressings were those composed with CE (PTV of 72), followed by ME (PTV of 70) and finally by B (with PTV of 69).

Fig. 15 shows the variation of PTV after wearing comparing to the initial PTV. The PTV was expected to be reduced by ravelling and compression, but this was not observed for all cases.

All the single surface dressings without diluted emulsion covering decreased their PTV value and were more sensitive to wear. The surface dressings composed with B were the ones with a higher variation of PTV after wearing. The worst result was that of surface dressing 12, with a PTV decrease of 11%. The PTV of surface dressings 2, 6, 8, and 11 were barely affected by wearing. Some surface dressings increased their PTV values after wearing, in particular, the double ones without diluted emulsion.

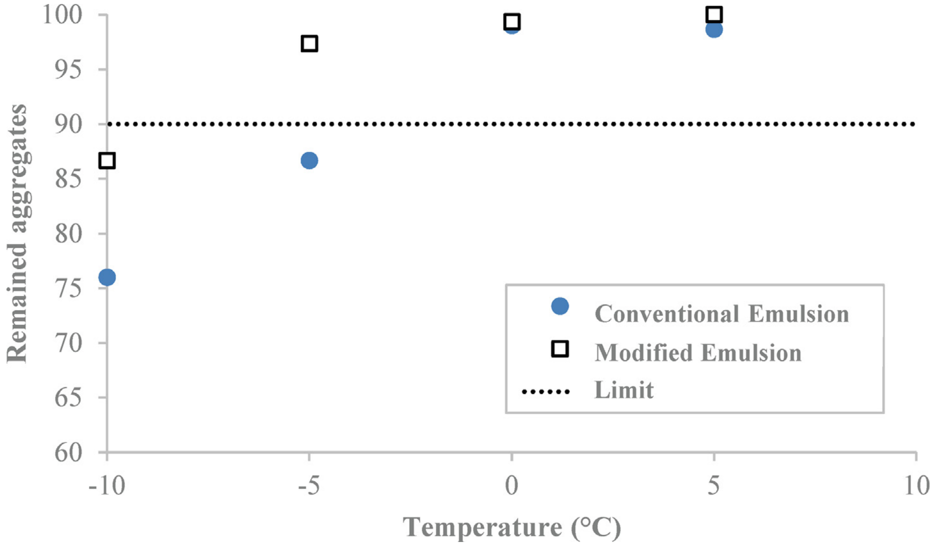


Fig. 12. Results of fragility temperature by the Vialit test.

Table 9
Results of wetting temperature by the Vialit test.

Binder	Aggregates	Conditioning temperature (°C)	Fallen Aggregates		Remained Aggregates(c)	Adhesion(b + c)
			Unstained(a)	Stained(b)		
B	6/10	5	46	24	30	54
B	6/10	10	52	7	41	48
B	6/10	15	32	18	50	68
B	6/10	20	34	28	38	66
B	6/10	25	26	25	49	74
B	6/10	30	28	9	63	72
B	6/10	35	9	26	66	91

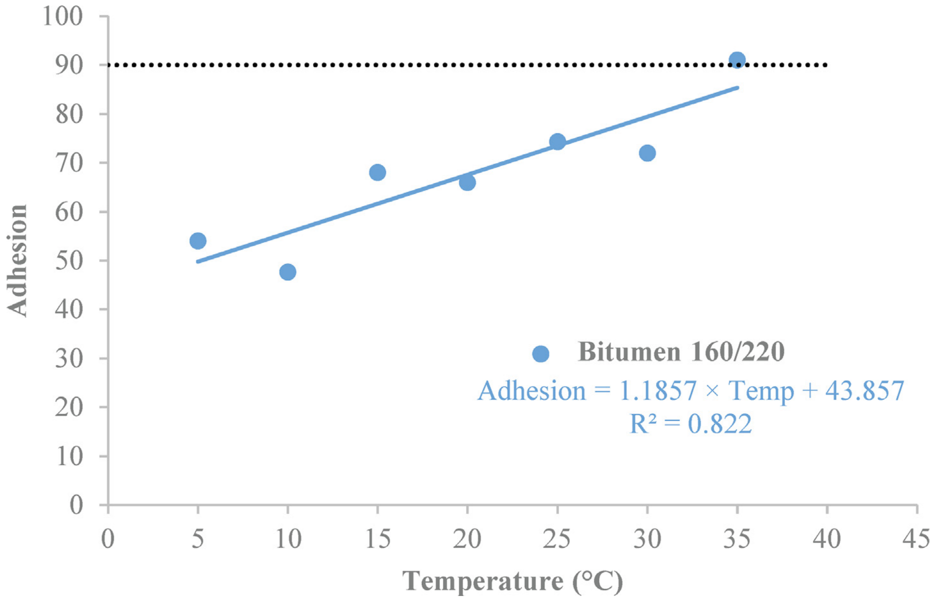


Fig. 13. Results of wetting temperature by the Vialit test.

3.5.3. Test results correlation

Fig. 16 shows the correlation between texture depth, PTV and MPD. The texture depth showed a decreasing trend with the increase of PTV with a low R^2 of 0.3932 (Fig. 16a). The trend presented shows that the smoother the macrotexture, the lower the friction of the surface dressings. There is no correlation between MPD and PTV, with an R^2 value of 0.0019 (Fig. 16b). As expected, the best correlation was MPD *versus* texture depth. There is a linear increase of texture depth with the increase of MPD with an R^2 of 0.4537 (Fig. 16c).

Table 10
Mass loss after the wearing test.

Surface Dressing	Initial Mass(g)	Mass after wearing(g)	Mass Loss(%)
1	798	590	26
2	807	702	13
3	1465	1264	14
4	1520	1324	13
5	739	650	12
6	779	661	15
7	1458	1246	15
8	1596	1425	11
9	661	486	26
10	997	786	21
11	1393	1241	11
12	1400	1298	7

After wearing, linear correlations were also studied: i) mass loss *versus* MPD variation; ii) MPD variation *versus* PTV after wearing; iii) mass loss *versus* rupture time; and iv) mass loss *versus* maximum force (Fig. 17). The MPD variation showed a slightly linear increase with the mass loss, presenting an R^2 of 0.3123 (Fig. 17a). This result indicates that the surface becomes smoother with the growing loss of aggregates. There is also some linear trend (R^2 of 0.3494) of MPD variation with PTV after wearing (Fig. 17b). The loss of mass does not correlate with rupture time (R^2 = 0.0126) and maximum pull-off force (R^2 = 0.1237), as presented in Fig. 17c and 17d. The effect of using each type of asphalt binder, single or double surface dressings, and using emulsion covering was different in each one of these tests, severely reducing the correlation coefficients.

The relationship between MPD and PTV values before and after wearing is presented in Fig. 18. There is no visible trend when comparing these parameters before and after wearing (R^2 of 0.0123 for MPD and 0.0002 for PTV). Surface dressing' wearing is a complex process, with different impact in each studied solution, changing the MPD and PTV values benchmark before and after wearing.

4. Conclusions

This paper aimed at evaluating single and double surface dressings with different binders, with and without diluted emulsion covering, which were applied on concrete slabs, thus classifying different materials and analyzing the possible rehabilitation of concrete pavements with these paving solutions. Twelve surface dressings were composed of conventional emulsion, a modified emulsion, and a 160/220 bitumen. The solutions were evaluated by testing their macrotexture, skid resistance, wearing resistance, adhesion to the support, and adhesion between binder and aggregates. The results obtained in this work showed that:

- In the volumetric patch method, the single surface dressings generally had higher texture values than the double ones. The use of the different binders had little impact on the texture height. The application of surface dressings in concrete pavements significantly increases their macrotexture, improving the drainage of water.
- MPD values obtained with the laser table increased 11.5 times after applying surface dressings on the concrete slab. In general, single surface dressings had higher MPD values than double ones. The single surface dressings with emulsions increased the MPD when covered with diluted emulsion, and the opposite is observed in surface dressings with bitumen. There is no evident trend on using diluted emulsion covering in the MDP values of double surface dressings.

Table 11
MPD variation before and after the wearing test.

Property	Surface Dressing											
	1	2	3	4	5	6	7	8	9	10	11	12
Initial MPD(mm)	4.1	4.4	3.8	3.1	3.9	4.3	2.8	3.1	3.7	3.5	2.6	3.4
MPD after wearing(mm)	2.2	2.6	2.6	2.8	2.2	2.7	2.3	2.7	2.1	2.3	2.2	2.4
MPD Variation(%)	−47	−40	−30	−11	−42	−37	−19	−14	−44	−33	−14	−30

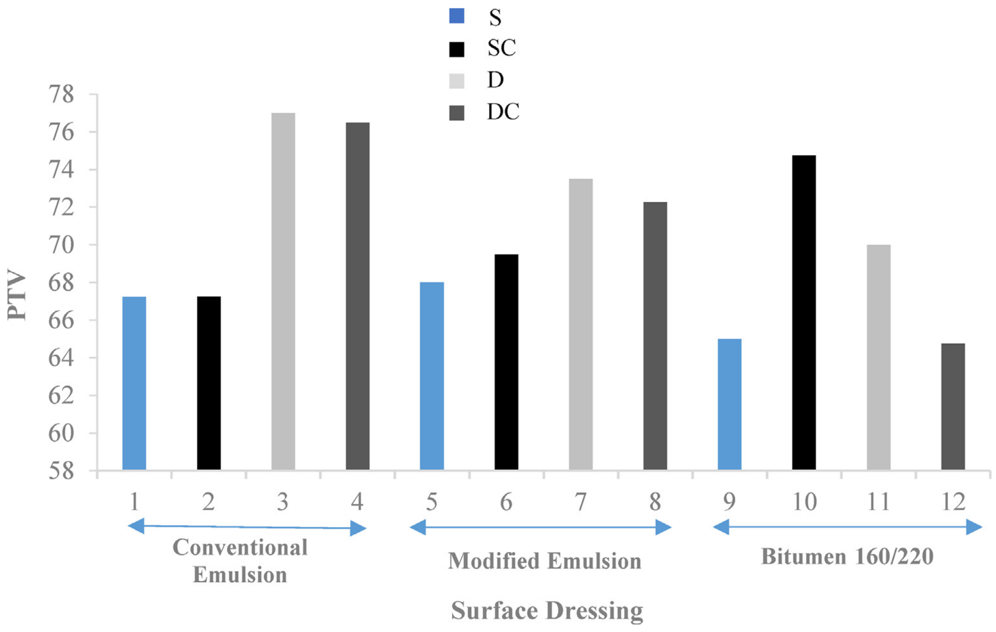


Fig. 14. PTV results after wearing.

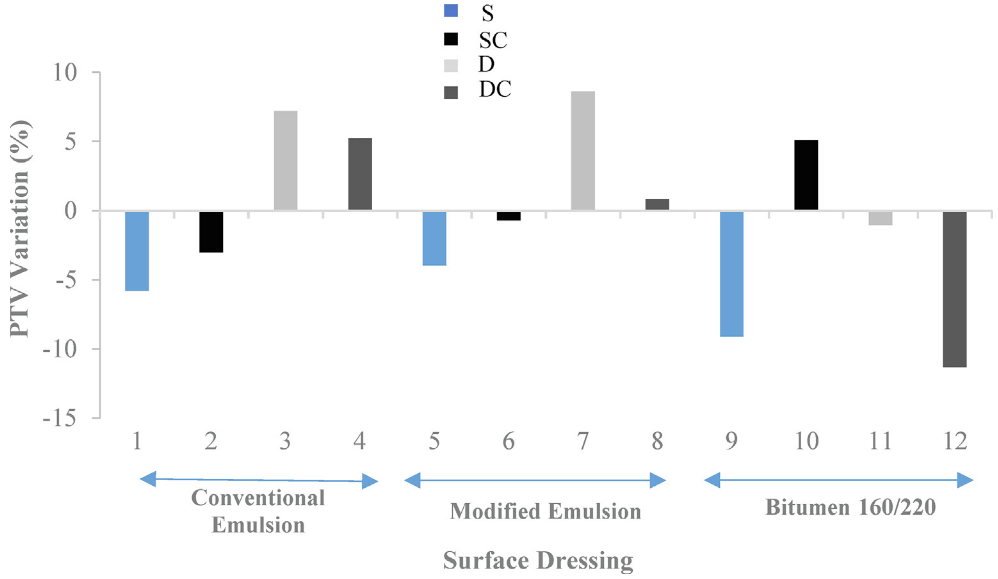


Fig. 15. PTV variation due to wearing.

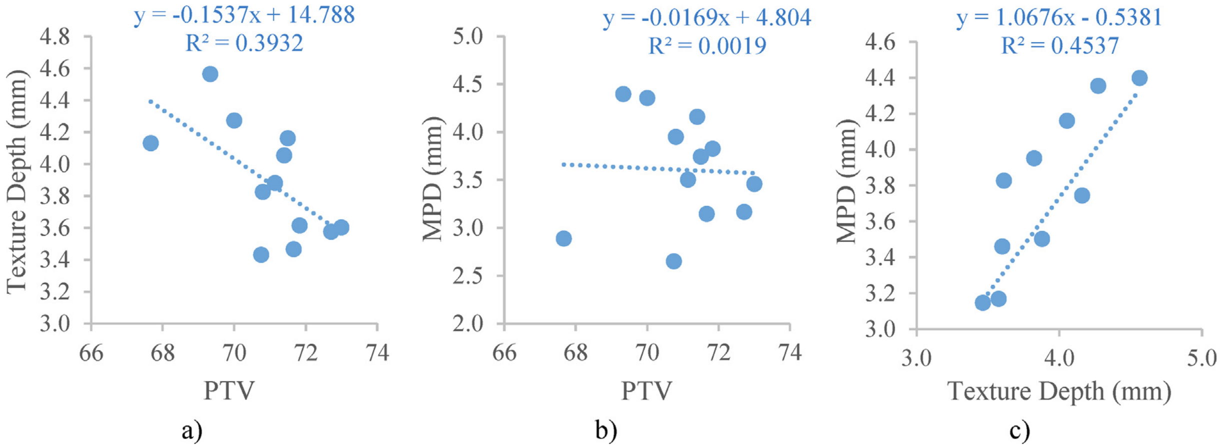


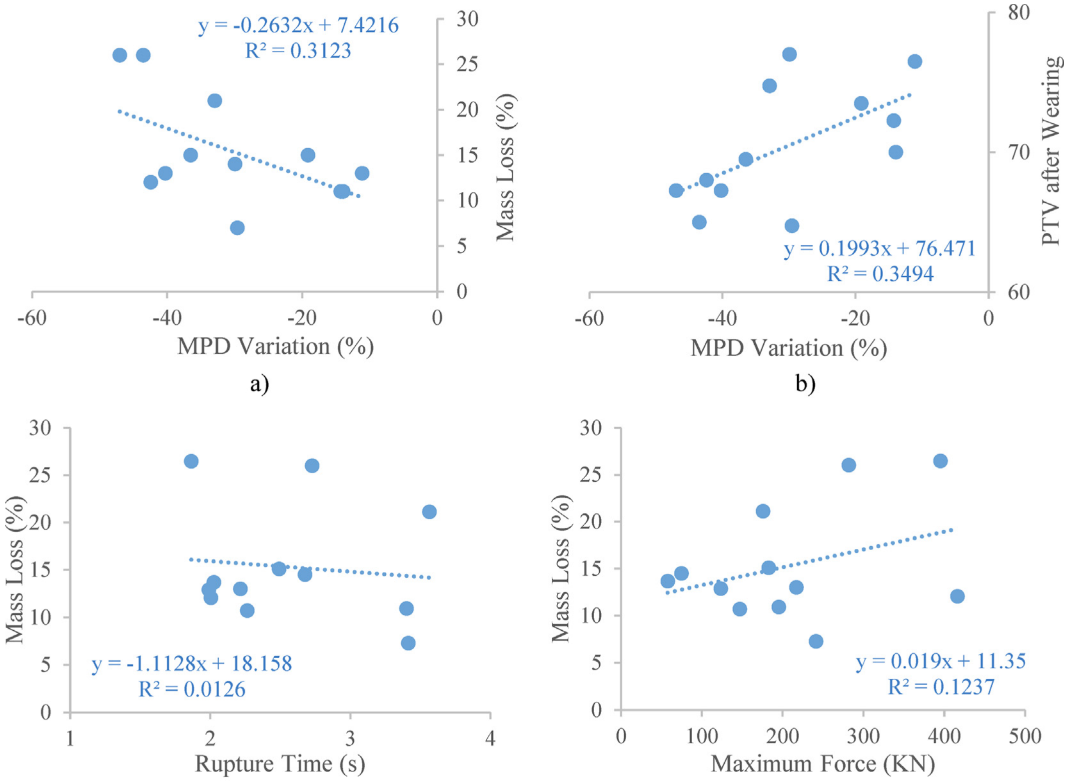
Fig. 16. a) Texture Depth *vs.* PTV, b) MPD *vs.* PTV, c) MPD *vs.* Texture Depth.

- All surfaces evaluated were classified as having very rough microtextures in the British Pendulum test. The single and double surface dressings showed similar PTV. The best solutions were the double surface dressings covered with diluted emulsion. The diluted emulsion application was beneficial for the double surface dressings, but detrimental for the single ones, taking into account the skid resistance results.
- The single surface dressings presented about two times higher resistance values in the pull-off test than the double surface dressings. The diluted emulsion covering increased the double surface dressings' pull-off resistance, while having the opposite effect on the single surface dressings. The binder that provides a better adherence of the surface dressing to the concrete support was the hot bitumen, followed by the modified emulsion and the conventional emulsion.
- The Vialit plate test results showed that the conventional and modified emulsions provide a similar and excellent mechanical adhesion to the aggregates. The modified emulsion behaved better at low temperatures, presenting a fragility temperature of −5 °C against the 0 °C of the conventional emulsion. The wetting temperature obtained in the test with hot bitumen was 35 °C, and this solution needs a careful temperature control during application.
- Regarding the prototype's wearing process, it can be concluded that the double surface dressings covered with diluted emulsion generally presented lower mass loss. On average, the mass loss of the surface dressings composed of conventional emulsion or hot bitumen is similar, but the modified emulsion presented the lowest mass loss. The best results in the wearing test were obtained for double surface dressing with bitumen covered with diluted emulsion, with wearing values lower than 10%.

In conclusion, surface dressings are a viable rehabilitation alternative for pavements with adequate bearing capacity but with some surface problems. The best results were obtained for surface dressings with hot bitumen in this work, although they need strict temperature control during application. Thus, in cold-weather countries, the use of modified emulsion is the best solution for surface dressings.

CRediT authorship contribution statement

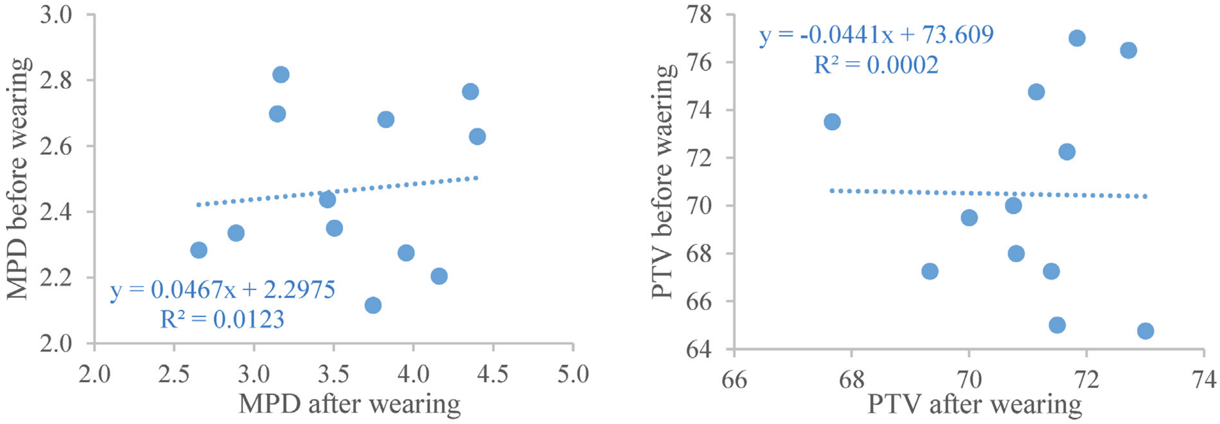
Iran Rocha Segundo: Investigation, Formal analysis, Writing - original draft. **Leonel Silva:** Investigation, Resources. **Carlos Palha:** Methodology, Software. **Elisabete Freitas:** Funding acquisition.



a) b)

c) d)

Fig. 17. a) Mass loss *vs.* MPD variation; b) MPD variation *vs.* PTV after wearing; c) Mass loss *vs.* rupture time; and d) Mass loss *vs.* maximum force.



a) b)

Fig. 18. a) MPD before *vs.* after wearing; b) PTV before *vs.* after wearing.

Hugo Silva: Conceptualization, Methodology, Validation, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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