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Road markings: important aspects related to retroreflectivity performance and the use of 3-D printing for dosage

Demarcação viária: importantes aspectos atinentes ao seu desempenho retrorrefletivo e o emprego de impressão 3-D em sua dosagem

Deividi da Silva Pereira[1], **Eduardo Martins Renz**[2], **Lucas Dotto Bueno**[3], **Luciano Pivoto Specht**[4], **Lucio Salles de Salles**[5]

[1]Federal University of Santa Maria, Rio Grande do Sul – Brazil, dsp@ufsm.br
[2]Sulclean, Rio Grande do Sul – Brazil, eduardo.renz@gmail.com
[3]Federal University of Santa Maria, Rio Grande do Sul – Brazil, lucas.bueno@ufsm.br
[4]Federal University of Santa Maria, Rio Grande do Sul – Brazil, luspecht@ufsm.br
[5]University of Pittsburgh, Pennsylvania – United States, lus49@pitt.edu

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ABSTRACT
Road markings are continuously present on the path taken by users, making it essential that they present adequate retroreflectivity. In this context, the present paper sought to evaluate factors related to the retroreflectivity of road markings, using field evaluations. In addition, the study used three-dimensional printed plates to identify the effect of macrotexture on retroreflectivity. The results indicate that the geometry of the retroreflectometer (15 and 30 m), the color of the markings (white and yellow) and the periodic cleaning of the markings significantly affect retroreflectivity. Furthermore, the study aimed to find a correlation between the marking's retroreflectivity performance and its microtopography (surface micro and macro textures). Pearson's correlation coefficients indicated a moderate association between the microtopography parameters and retroreflectivity. For macrotexture, the results from the 3D printing plates showed a significant relationship between macrotexture and retroreflectivity, with higher values of retroreflectivity for smaller mean texture depth. Results also indicated that the ideal application rate of drop-on glass beads is inconstant and varies depending on the macrotexture.

RESUMO
A sinalização horizontal está continuamente presente no trajeto percorrido pelos usuários, o que torna fundamental que as demarcações viárias apresentem adequada retrorrefletividade. Neste contexto, o presente trabalho buscou avaliar fatores relacionados à retrorrefletividade da sinalização horizontal, mediante avaliações de campo, além do emprego de placas tridimensionais impressas para identificar o efeito da macrotextura sobre a retrorrefletividade. Os resultados obtidos indicam que a geometria do retrorrefletômetro (15 e 30m), a coloração da demarcação (branca e amarela) e a limpeza periódica da sinalização impactam significativamente na retrorrefletividade. Ainda, procurou-se buscar correlação entre desempenho da retrorrefletividade e a microtopografia do substrato (microtextura e macrotextura superficial do revestimento). Os coeficientes de correlação indicaram moderada associação entre os parâmetros supracitados e a retrorrefletividade. Para o caso especial da macrotextura, a impressão tridimensional indicou significativa relação existente entre a macrotextura e a retrorrefletividade, com valores maiores de retrorrefletividade para alturas médias de areia menores. Ficou evidenciado que a taxa ideal de aplicação de microesferas do tipo *drop-on* não é constante e varia em função da macrotextura.

1. INTRODUCTION

Considering the elements that compose road signs, road markings play a fundamental role as it is in the center of the driver's field of vision. The driver does not need to look away to interpret the messages conveyed by the markings. In order to make this flow of information possible at night, the light coming from the vehicle's headlights is reflected by the markings and part of the incident light is retroreflected.

The retro-reflecting characteristic of road markings is conferred through the application of glass beads into the paint; these can be pre-mixed with paint (premix) and/or cast onto the newly applied marking material (drop-on). In Brazil, the current practice for drop-on glass beads application rate in in between 250 and 300 g/m^2, according to the recommendations by the DNIT (2017), Moreira and Menegon (2003) and the DNER (2000).

The equipment used to quantify markings retroreflectivity is the retroreflectometer. This equipment can differ, mainly, in relation to the geometry for analyzing the emitted and received retroreflective light. The most commonly available retroreflectometers simulate two distinct conditions of distance between the vehicle and the retroreflection point: 15 and 30 m. Retroreflectivity is represented by the measure of the retroreflected luminance coefficient (RL), expressed in candelas per square meter per lux (cd/m^2/lux). The unit commonly used in pavement markings, depending on the magnitude of their values, is milcandelas per square meter per lux (mcd/m^2/lux). In the USA and in the countries of the European Union, the regulatory agencies use as normative references and minimum required limits, the retroreflectivity measured by 30 m geometry retroreflectometers. However, in Brazil, specifications require a 15 m geometry retroreflectometer. (Salles et al, 2015)

At the national level, most restoration and maintenance contracts for road markings indicate that the retroreflectivity must be measured between 24 and 48 hours after construction. This measurement is called the initial retroreflectivity (Ri). Different regulatory agencies require different minimum acceptable initial values. The DAER-RS (2013), for example, stipulates at least 220 mcd/m^2/lux for white markings and 170 mcd/m^2/lux for yellow markings (15 m geometry). Regarding the minimum residual values, the road agency of RS requires a limit, for both colors, of 130 mcd/m^2/lux.

The DNIT, with the BR-LEGAL program (Process No. 50600.008728/2013-11), in its Technical Specifications, established the criteria to be followed throughout the national territory based on a proposal that brought together technicians and specialists of the sector for the construction of a standard model. The proposal englobed elaboration of projects and implementation of services, considering the Signaling Manuals of the National Traffic Council - CONTRAN, the DNIT Signaling Manuals, the Brazilian Traffic Code and its resolutions, the Technical Standards of the Brazilian Association of Technical Standards – ABNT and, above all, the physical and operational characteristics of Brazilian highways.

Thus, the BR-LEGAL Program, in a 2016 service instruction, stipulated initial retroreflective values of 250 and 150 mcd/m^2/lux (for white and yellow markings, respectively). For the final condition of use, the minimum residual retroreflectivity stipulated was 100 and 80 mcd/m^2/lux, respectively for white and yellow markings (DNIT, 2018).

Currently, however, there is a reference term for the bidding of the BR-LEGAL-2 Program in which the minimum residual values increased to 120 and 100 mcd/m^2/lux, respectively, for the same colors. This last document presents contradictions in terms of retroreflectometer geometry to be adopted, indicating some standards with 15 m geometry and another, more current, with 30 m.

Several authors have studied possible factors influencing markings retroreflectivity. Abbound and Bowman (2002), Thamizharasan et al (2003), Stizabee, Hummer and Rasdorf (2009), Rasdorf et al (2009), Hummer Rasdorf and Zhang (2011), Mull and Stizabee (2012) were unanimous in their conclusions, pointing out that markings with higher initial retroreflectivity performed better over time. Thus, as perceived by the researchers, whenever the initial retroreflectivity was greater, the marking achieved greater performance for longer exposure to identical traffic conditions.

Other important aspects were found in the bibliographical research. According to Parker and Meja (2003), white markings present retroreflectivity, on average, 25% higher than yellow markings. Rasdorf et al (2009) mention that the direction of measurement also interfered in the results, with a tendency towards greater retroreflectivity when measured in the same direction as the application of the marking. Measuring geometry also creates variations in measured indices. For Salles et al (2015), devices with a geometry of 30 m measure retroreflectivity values 50% smaller than those measured with a geometry of 15 m, due to the greater retroreflection at a higher incidence angle, such as those obtained by the geometry that simulates the distance of the headlight of the distant vehicle 15 m from the road marking. In addition to these, the accumulated precipitation, traffic intensity, time since marking construction, rate of glass beads and the type of material used in the marking are also considered intervening factors in the retroreflectivity performance.

Another aspect that seems to be important is the microtopography of the marking, considered in this manuscript as the set of characteristics that associate parameters related to the micro and macro texture of the pavement surface. When evaluating different road segments in southern Brazil, the empirical experience has shown potentially different performances when the same material was applied over micro-surfacing surface treatment (MRAF) and asphalt concrete mixtures (CA). This empirically observed aspect was not mentioned in the national and international technical literature, a fact that motivated the development of the research by Renz (2018).

In this scenario, this paper aims to evaluate the influence of the microtopography pavement surface on the performance of markings retroreflectivity, given the absence of references on the subject. In addition, there is an interest in exploring the development of a method capable of subsidizing the dosage of materials used in road marking, such as, for example, the drop-on glass beads, using three-dimensionally printed plates. Currently, there is not a practical method reported in the technical literature for the dosage of materials used in road markings. There is only mention that the material must offer the initial retroreflectivity indicated by the contracting part (DNIT, 2018), regardless, for example, of the macro texture of the pavement surface layer.

2. MATERIALS AND METHODS

To achieve the proposed objectives, an experimental segment was constructed to evaluate the retroreflectivity of road markings on MRAF. The initial study designed planned to monitor the retroreflectivity in contrast with the traffic action and, whenever possible, to evaluate in parallel the aspects already listed in the literature and which could impact the marking efficiency, such as: the presence or not of dirt on the marking; rain; retroreflectometer geometry; and the direction of retroreflectivity measurements.

During the study, new experiments were included to improve the understanding and correlation between pavement aspects and retroreflectivity, especially those linked to surface macrotexture and application rate of drop-on glass beads.

2.1. Field Retroreflectivity

An experimental 100 m-long segment was designed and constructed on BR-287, in Santa Maria/RS. This segment had been the target of a pavement maintenance intervention with MRAF, giving the pavement a rougher macrotexture than that resulting from the CA. The bidirectional average daily traffic volume is 30,000 vehicles, with 15% of this volume composed of buses and trucks.

Following Brazilian regulations, the road marking were designed with a width of 0.15 m, with yellow markings used in for the center line and white markings on the edges of the road (simple lane with one lane in each direction). The markings construction was conducted by an automated truck, using water-based acrylic paint, for both colors, with a 0.6 mm film thickness. Type IB microspheres (premix) were used with a dilution of 200g/l were incorporated into the paint. Concomitantly with the paint by simple spraying, drop-on type II-C glass microspheres (equivalent to type III of the current DNIT specification - 100/2018-ES) were applied with a rate of 0.25 kg/m^2.

As shown in Figure 1, four hundred retroreflectivity analysis points were randomly defined with the limits of the retroreflectometer marked to ensure that, during the evaluations, the equipment was always positioned in the same place. The randomness of points coincided with the measurements of meter in meter of longitudinal distance. As each cross section had four lines of road markings (two on the edge – white and two at the center of the strip – yellow), each section corresponded to four independent analysis points. During the readings, the same operator always carried out the positioning of the equipment and the effective evaluation of the retroreflectivity.

Figure 1. Retroreflectivity reading points for retroreflectometer positioning

Initially, 60 stations (30 for each marking color) were chosen to have macro and micro texture evaluations confronted with marking retroreflectivity. The macrotexture was evaluated by ASTM E 965/2015, using the Sand Patch method. For the microtexture, the British Pendulum (ASTM E 303/1993) was used due to its availability, which, in practice, performs an indirect evaluation of the microtexture, measuring the resistance to skidding. Macrotexture evaluations were conducted on the day of the road marking and 60, 150, 240, 330, 420 and 720 days after. The microtexture evaluation started 150 days after painting. Initially, microtexture assessments were not planned; however, they were incorporated into the study because retroreflectivity oscillations were observed at some points, either increasing or decreasing its value, even with a certain constant texture depth. Therefore, it was decided to investigate whether such oscillations were occurring due to the "upwelling" of premix-type microspheres, which were initially submerged in the paint film, a fact that could indicate a variation in the microtexture of the marking.

For the evaluation of retroreflectivity, a dual geometry retroreflectometer (15 and 30 m) was used, with a reading area of 15,300 mm^2 (90 x 170 mm) and travel and observation angles of, respectively, 1.5° and 86.5° (15 m), and 1.05° and 88.76° (30 m), following the definitions of the Brazilian standard (NBR 15426/2013) and international agencies (ASTM E-1710/18 and EN 1436/18).

To assess the possible effect of the measurement direction, in between 60 and 300 days of the road marking, when the markings had already suffered the initial wear, surveys were carried out with the retroreflectometer positioned in opposite directions.

To verify the effect of cleaning the markings, another 20 points were chosen and, from the second month onwards, these locations received a monthly cleaning. The process consisted of measuring retroreflectivity as usual, and then cleaning these locations with water, a soft brush and neutral soap. After the surface had completely dried, the retroreflective measurements were repeated at exactly the same point. From the measurements conducted before and after cleaning, it was possible to determine the mean retroreflectivity difference.

2.2. 3-D plates for retroreflectivity evaluation

Even though the experimental section provided a pavement surface with different macrotextures, with a variation in the mean texture depth between 1.12 and 0.97 mm (yellow and white markings, respectively), and standard deviation between 0.19 and 0.11mm (in the same order of colors), there was little variation between macrotexture classes, with the texture of the analyzed points classified from "Very Open" to "Open". Only three points exhibited an "Medium" texture classification. The classification adopted was based on the criteria shown in Table 1.

Table 1 – Pavement macrotexture grades

Grade	Mean Texture Depth (mm)	Symbol
Very Closed	MTD ≤ 0.20	MF
Closed	0.20 < MTD ≤ 0.40	FE
Medium	0.40 < MTD ≤ 0.80	ME
Open or Coarse	0.80 < MTD ≤ 1.20	AB
Very Open or Very Coarse	MTD ≥ 1.20	MA

Source: Adapted from Bernucci et al (2010)

Given the low variability of macrotexture grade provided by the MRAF in the field, the markings retroreflectivity evaluations were conducted with very similar mean texture depth (MTD) grades. With this, it was necessary to format a new series of measurements in which it was possible to isolate the macrotexture, with more significant differences in MTD values. Thus, it would be possible to identify whether or not the surface texture affects retroreflectivity. In addition, the study sought to preliminarily evaluate a practical way of dosing the materials used in road markings, such as, the application rate of drop-on type glass beads.

Thus, a set of plates was designed with uniform microtopography compatible with significantly different mean texture depth (or macrotexture grades). For this purpose, a Dimension Elite 1200es 3D printer (Stratasys) was used. The printer has resolution of successive layers between 0.178 and 0.254 mm of industrial thermoplastic material for the plates manufacture (maximum dimensions: 203 x 203mm).

Three patterns of plates were digitally modeled: the first model had an mean texture depth (MTD) of 0.356 mm; the second of 0.712 mm; and the third of 1.246 mm (dimensions close to 0.35mm, 0.70mm and 1.30mm, corrected for the resolution of the 3-D printer), resulting in plates with closed, medium and very open macrotexture grades, respectively, according to Table 1. Five plates were printed for each macrotexture. It should be noted that the service specification DNIT 031-2006 ES recommends that the hot mix asphalt surface have MTD between 0.6 and 1.2 mm (medium to open).

The plates with different textures were placed in front of the paint truck in a conventional marking operation process (speed of 3 km/h). In the plates marking, only the yellow color paint was used. The material was a water-based acrylic paint and glass beads (premix) in a dosage similar to that used in the field. Each example of 3-D plates, molded for each of the proposed textures, was marked with drop-on glass beads application rates of 85 g/m², 160 g/m², 250 g/m², 325 g/m² and 460 g/m².

The marking process, as well as examples of the plates can be seen in Figure 2, with the adopted nomenclature referring to the macrotexture (FE-Closed; ME-Medium; MA-Very Open) and the drop-on application rate (in g/m²). Table 2 summarizes these combinations.

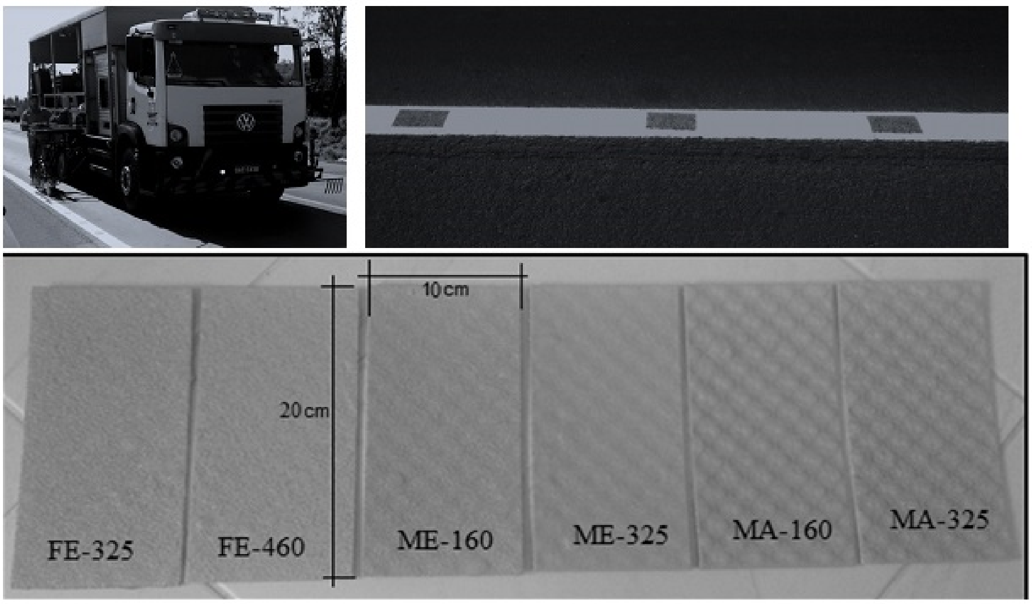

Figure 2. Marking process and plates samples after painting

Table 2 – Distribution of glass beads application rates and surface macrotexture

Plate	Macrotexture Grade	Mean Texture Depth (mm)	Application Rate (g/m²)
FE-085	Closed	0.356	85
ME-085	Medium	0.712	85
MA-085	Very Open	1.246	85
FE-160	Closed	0.356	160
ME-160	Medium	0.712	160
MA-160	Very Open	1.246	160
FE-250	Closed	0.356	250
ME-250	Medium	0.712	250
MA-250	Very Open	1.246	250
FE-325	Closed	0.356	325
ME-325	Medium	0.712	325
MA-325	Very Open	1.246	325
FE-460	Closed	0.356	460
ME-460	Medium	0.712	460
MA-460	Very Open	1.246	460

After the 3D plates were marked with paint (with premix) and drop-on, the plates were allowed to dry for 90 min until the complete drying of the paint was verified. Soon after, the plates were rotated so that the portion of non-anchored drop-on glass beads was removed, simulating what happens in the field from the effect of air displacement produced by the passage of vehicles near the road marking. After 24 hours, the initial retroreflectivity (Ri) of each specimen was computed based on the average of five measurements.

3. RESULTS AND ANALYSIS

All retroreflectivity surveys were performed with a dual geometry equipment. The behavior trend for both geometries was analogous, varying only in absolute values, with those for 15 m approximately equal to twice the retroreflectivity measured with the 30 m retroreflectometer (as shown in Figure 3). This trend has been reported in previous studies, such as those carried out by Salles et al (2016). The results and analyzes that will be presented in the sequence of this paper refer to the geometry adopted by the Brazilian standards (15 m).

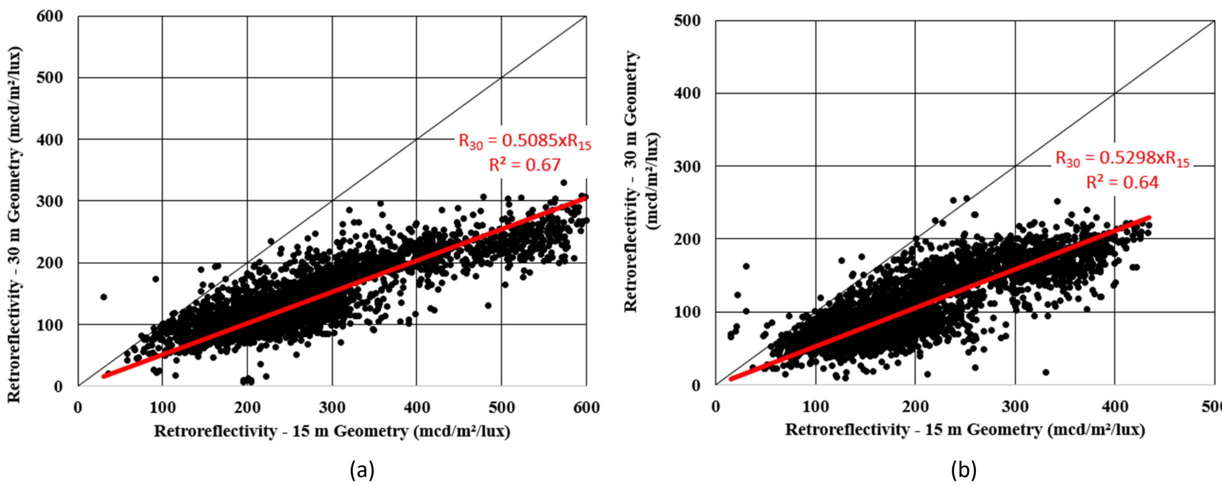

Figure 3. Correlations between measurements of different geometries (15 and 30 m) for white (a) and yellow (b) markings

3.1. Results from the field section

Over two years, the markings retroreflectivity was systematically evaluated, allowing the development of performance models as a function of the markings' time exposure to traffic, as illustrated in Figure 4. Table 3 presents the average data that allowed the construction of these models, as well as the standard deviation of each evaluation date.

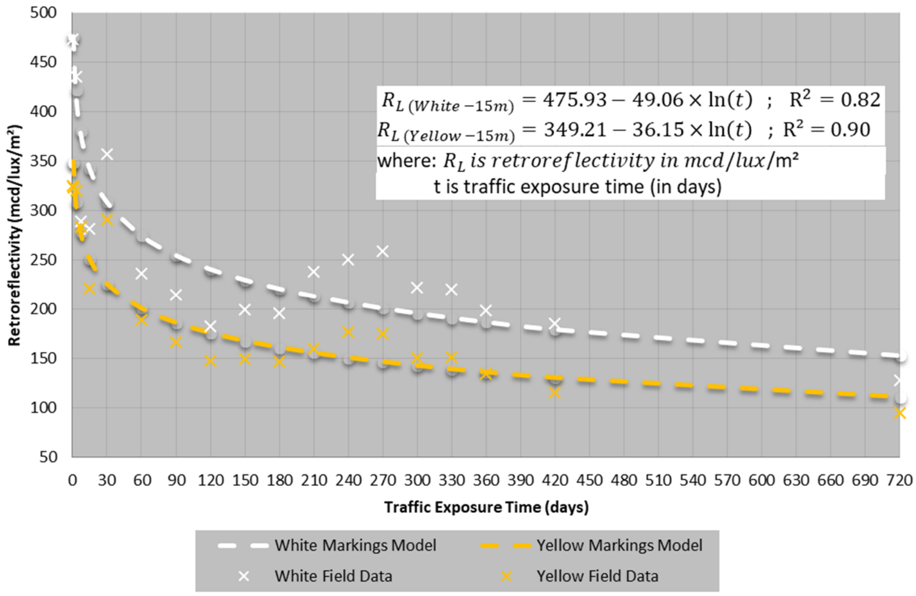

Figure 4. Retroreflectivity Performance Models for white and yellow markings

Table 3 – Model values, average retroreflectivity of field and standard deviation over exposure time

Time (Days)	White Markings (mcd/lux/m²)	Yellow Markings (mcd/lux/m²)	Field Data – White Markings: Average (mcd/lux/m²)	Field Data – White Markings: Standard Deviation	Field Data – Yellow Markings: Average (mcd/lux/m²)	Field Data – Yellow Markings: Standard Deviation
0	475.9	349.2	473.1	71.4	325.6	
1	475.9	349.2	524.5	37.1	323.5	36.2
3	422.0	309.5	435.5	55.0	320.2	34.7
7	380.5	278.9	289.8	34.8	284.0	13.8
15	343.1	251.3	282.2	23.3	221.2	22.4
30	309.1	226.3	356.9	18.7	291.4	27.8
60	275.1	201.2	236.4	22.6	189.3	24.9
90	255.2	186.5	215.0	21.9	166.8	25.0
120	241.1	176.1	182.5	31.3	147.5	19.3
150	230.1	168.1	199.7	22.3	149.7	19.0
180	221.2	161.5	196.2	23.6	147.4	16.3
210	213.6	155.9	238.1	28.0	159.7	18.3
240	207.0	151.1	251.0	34.8	176.6	16.7
270	201.3	146.8	258.9	40.2	174.9	16.7
300	196.1	143.0	222.0	36.4	151.0	15.9
330	191.4	139.6	220.9	35.9	151.2	16.2
360	187.2	136.4	199.2	23.8	134.9	13.5
420	179.6	130.9	186.0	21.6	116.0	10.8
720	153.2	111.4	128.0	19.3	95.0	7.1

The initial values of retroreflectivity, both those stipulated by the DNIT (250 and 150 mcd/lux/m^2, respectively for white and yellow markings) and by the DAER (220 and 170 mcd/lux/m^2, in the same order), were fully met. These initial values, according to the model, were 473 (white) and 325 (yellow) mcd/lux/m^2.

Regarding the influence of the marking's color, on average, the retroreflectivity measured for white markings is 38% higher than for yellow markings, considering the surveys carried out in the first year after construction. The results found in present study led to the same conclusions found by Parker and Meja (2003), but with an average retroreflectivity higher than the one mentioned by the authors (white color 25% higher than yellow). Some aspects can interfere in these differences, such as the color scale of the paints used, the coloration of the drop-on glass beads and the level of dirt presented in the markings. It is important to emphasize that, in this research, this comparison was carried out with cleaned markings.

The retroreflectivity performance models are parallel for both colors, and the difference between the models is given by the natural capacity of greater retroreflection of the white markings in relation to the yellow ones. In summary, the rate of retroreflectivity decrease over time is the same, since the dosage of the marking material was the same.

Concerning the measurement direction effect, there were no substantial differences between the values evaluated, regardless of the color of the road marking, as can be seen in Figure 5. This result contrasts with the observed by Rasdorf et al (2009) where measurements carried out in the same direction as the marking process had higher retroreflectivity values.

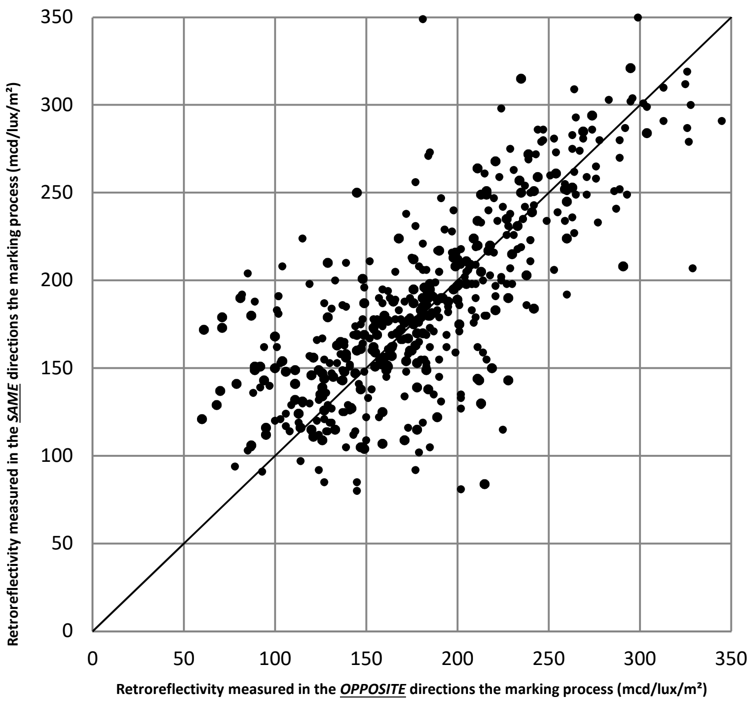

Figure 5. Retroreflectivity variation measured in opposite directions

At the end of the 720 days (24 months) of field evaluation, the mean (final) residual retroreflectivity measured were 128 mcd/lux/m^2 for white markings and 95 mcd/lux/m^2 for yellow markings, as shown in the Table 3. Regarding the minimum residual values stipulated by the DNIT (100 and 80 mcd/lux/m^2, respectively for white and yellow markings) and by the DAER (130 mcd/lux/m^2, regardless of color), the markings were considered acceptable for the DNIT, including for the BR-LEGAL program, and not adequate for the DAER, especially for the yellow color.

As for the minimum limits imposed for edge road markings, the English standard EN 1436 requires a minimum retroreflectivity of 100 mcd/m²/lux; while for the American Federal Highway Administration (FHWA, 2008), this value should be higher than 150 mcd/m²/lux. It is noteworthy that both minimum thresholds are referenced to the 30 m geometry retroreflectometer. In the present experiment, these minimum values would have been reached after 360 and 60 days, according to British and North American regulations, respectively. These data can be found in the study of Renz (2018). The international minimum requirements for the edge were not addressed due to the lack of color standardization of the markings for this position, which is also a function of the flow condition of vehicles on the road lane (double or single direction).

These observations related to the minimum requirements and the performance observed in the field reinforce the mismatch in terms of road safety required by Brazilian standards when compared to international ones, highlighting the need for a broad technical discussion in Brazil on this topic. It should be stressed that the performance found in the field was obtained considering the periodic cleaning of the markings, a very uncommon process in normal road conditions.

3.1.1. Effect of marking cleaning

Another aspect evaluated during the field experiment was the effect of cleaning the road markings as described in item 3.1. Figure 6 shows the retroreflectivity difference (before and after cleaning) for the two colors. On average, there was an increase in mean retroreflectivity after cleaning the white markings of 22%. For the yellow markings, the increase was 17%. Also, as the retroreflectivity performance drops, in the case under analysis after the first 240 or 270 days, there is a noticeable tendency to increase retroreflectivity after the cleaning process, especially for yellow markings. This tendency was not as expressive for white markings, possibly due to the presence of impregnated dirt, which gave a yellowish or grayish hue to the markings.

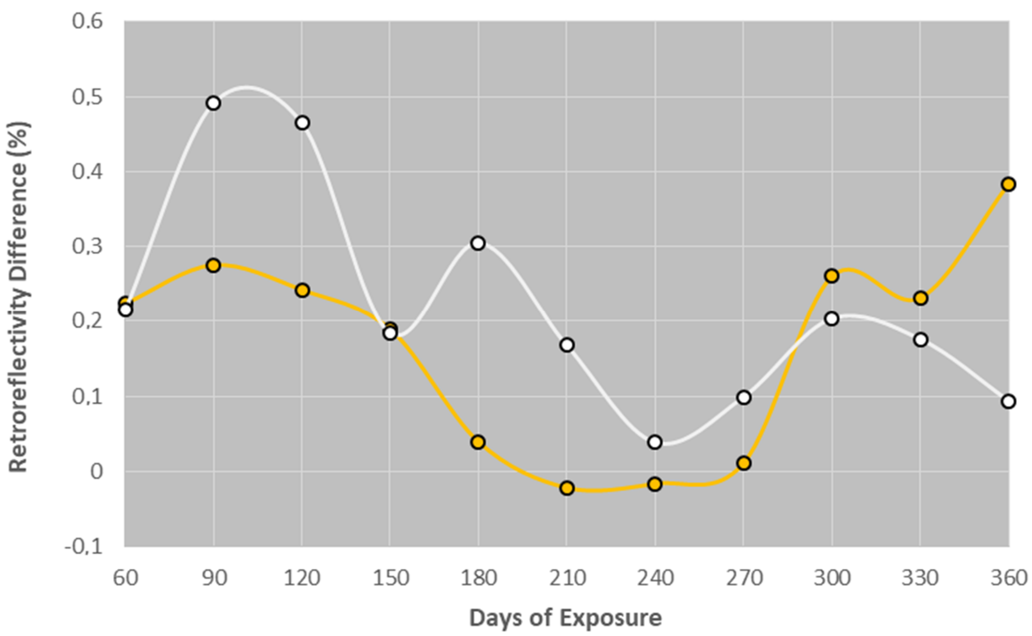

Figure 6. Percentage difference of mean retroreflectivity for white and yellow markings, before and after cleaning

When comparing the retroreflectivity of the points that were cleaned monthly in relation to the points that did not received any intervention in the first 12 months, the points that received cleaning showed 5% higher retroreflectivity for the white markings (edge line) and 53% higher for the yellow marking (center line). This detail is shown in Renz (2018). The low efficiency of the cleaning process for white markings was probably caused by the phenomenon described above, in which the color became yellowish or grayish.

By the minimum criteria stipulated by DNIT/BR-LEGAL for residual retroreflectivity, all markings, white or yellow, with or without cleaning, would be above the imposed normative requirements. However, for the values imposed by the DAER, after one year, the yellow markings, without cleaning, would have surpassed the threshold value.

In the absence of markings cleaning, according to the minimum parameters imposed by the North American and British standards (30 m geometry, not presented in this work), there would be only 30 days and 300 days of satisfactory performance, respectively. These results reinforce the need for a better regulation of these limit parameters and an approach regarding the cleaning of road marking paints, both in terms of periodicity and process.

Moreover, the abrasive process of periodic cleaning of road markings did not accelerate the retroreflectivity decrease. In the technical literature, no reports were found on comparative studies of the performance of markings submitted to different cleaning processes.

3.1.2. Microtopography of the pavement and retroreflectivity

Figure 7 shows the mean values of MTD (mean texture depth) and VRD (skid resistance value) throughout the experiment.

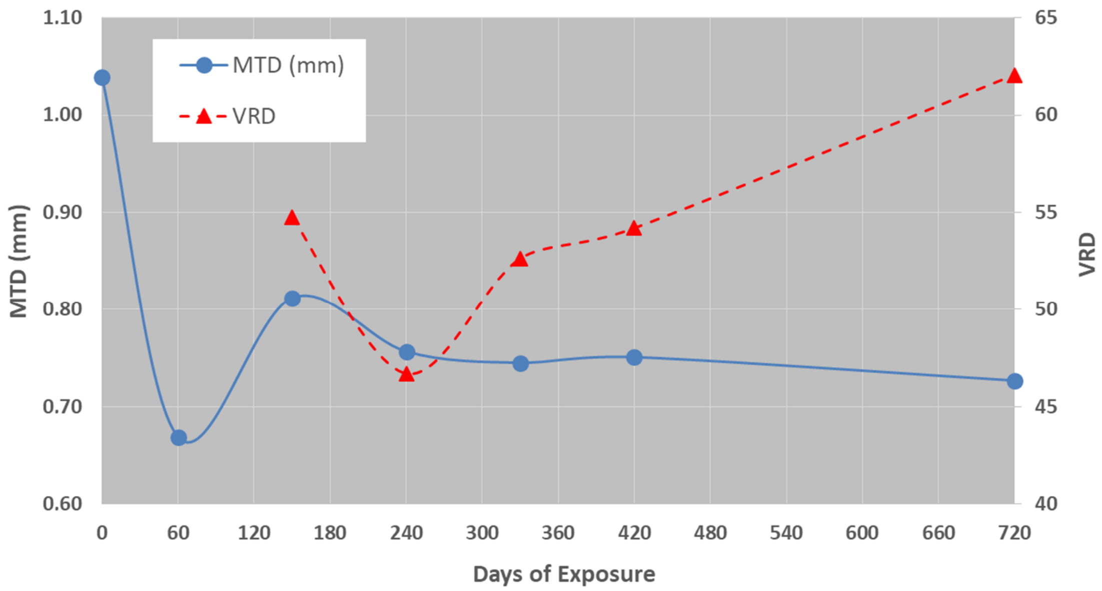

Figure 7. Evolution of macro and micro texture throughout the study (mean values of the 60 points evaluated)

The first point shown in Figure 7 represents macrotextures measurements performed before the section's marking where only the sand had filled the recesses of the MRAF microtopography. Thus, this point presents the initial condition of the pavement surface in relation to the macrotexture as recommended by ASTM (2008). However, after painting, in addition to the sand, the paint plus premix and drop-on began to partially occupy the spaces, reducing the free volume to be occupied by the sand, resulting in a smaller MTD. This reduced the MTD in the second round of macrotexture surveys, conducted at 60 days.

The increase in MTD occurring after 60 days can be correlated with the abrasive process of tire-pavement interaction, which pulls out the drop-on glass beads. Other reasons might be the paint wear (loss of paint thickness) and, even, an eventual removal of MRAF aggregates. These factors when combined would increase the irregularity in the pavement surface microtopography, increasing the MTD.

The microtexture evaluation (British Pendulum - VRD) started in the fifth month of the section's opening to traffic (150 days), presenting, until the end of the study, an unstable behavior. A possible explanation for this variation is related to the markings' paint film wear, which gradually exposes the premix-type microspheres as the film thins out.

Moreover, because the experimental section is composed of a single type of surface (MRAF), the intermediate values of MTD and VRD were disregarded. Only the MTD and VRD values corresponding to the 33% larger and 33% smaller points in each time exposure to traffic were considered, disregarding the middle third. The entire data tabulation is presented in Renz (2018).

Considering the results, there was no sense in analyzing the behavior of retroreflectivity against micro and macro texture throughout the field study period, since the natural process of degradation of the retroreflectivity characteristics (unrelated to the pavement microtopography) affects markings quality. Therefore, this study was unable to assess in isolation the effect of micro and macro texture on marking retroreflectivity over the 720 days of evaluation.

In view of this, it was decided to determine the Pearson correlation coefficients (bivariate association measure - strength - of the degree of relationship between two variables) for the exposure time of the pavement markings in which the micro and macro texture evaluations were performed, as shown in Table 4. The correlation measures the direction and degree of the linear relationship between two quantitative variables. According to Cohen (1988), Pearson correlation coefficients between 0.10 and 0.29 are considered small; between 0.30 and 0.49 are considered as averages; and between 0.50 and 1.0 can be interpreted as large. The sign of this correlation indicates the relationship direction between the investigated parameters.

Table 4 – Pearson correlation coefficients for macrotexture (MTD) and for microtexture (VRD) versus retroreflectivity

	Coef. Pearson (MTD x RI)		Coef. Pearson (VRD x RI)	
Days	**White Markings**	**Yellow Markings**	**White Markings**	**Yellow Markings**
1	-0.260	-0.249		
60	0.059	0.286		
150	-0.226	0.234	-0.418	-0.589
240	-0.240	-0.043	0.478	-0.175
330	-0.133	-0.245	0.182	0.121
420	0.268	-0.261	0.187	-0.260
720	-0.051	-0.049	0.570	-0.035

The white and yellow markings can be evaluated together. With regard to microtexture, there is a median relationship between this parameter and retroreflectivity, with higher VRD values correlated with lower retroreflectivity (in 50% of cases - according to Pearson's correlation coefficients), without a trend of priority behavior observed. Such behavior can be attributed to greater or lesser exposure of premix type microspheres, as the paint is worn down (losing film thickness) by the abrasive process of tire-pavement interaction.

In asphalt surfaces, such as the one evaluated in this study (MRAF), the results related to microtexture are exclusively influenced by the fine texture of the applied paint. As the microtexture were evaluated only after 150 days of exposure to traffic – at which time the drop-on type glass beads had possibly already been pulled out – it was more specifically associated with the presence of the premix glass beads on the marking surface.

Results clearly show a lack of trend towards the constancy of the VRD over the 720 days (Figure 7). As discussed, the association between VRD and retroreflectivity was empirically proven, and appears to be relatively significant. However, this condition should be investigated in future studies, since the present study sought to evaluate only the effect of the microtopography of the pavement and not of the material used in the markings.

With regard to the influence of macrotexture on retroreflectivity, there is an oscillation between Pearson's correlation coefficients. In 71% of the conditions evaluated, the mentioned coefficients had a negative sign, meaning a trend towards a reduction in retroreflectivity with the increase in MTD. The strength of this relationship ranged, depending on the case, from small to medium.

Based on the empirical results presented, a new method was developed to to fully identify the relationship between macrotexture and retrorefelctivity. The 3-D printing of plates with uniform macrotextures and different MTD was adopted, allowing the evaluation of this interdependence based exclusively on these two parameters. It was not possible to evaluate the microtexture due to the difficulty of performing the British Pendulum test on the three-dimensional plates in a reliable and accurate way. In addition, the microtexture would be evaluated only in the initial condition (with drop-on) ignoring the wear of the painting film exposing the premix glass bleads, a factor that proved to be relevant on the field.

To finalize the responses that can be analyzed in the field, the data presented in Table 5 provide information on the general retroreflectivity performance. Results are focused on the first day (opening to traffic) and the last survey (720 days of exposure), dividing them between points with larger and smaller macrotextures.

Table 5 – Retroreflective performance for different Macrotextures

		Traffic Opening		**720 days**		
		MTD (mm) Average	**R_i (mcd/m²/lux)**	**MTD (mm) Average**	**R_{final} (mcd/m²/lux)**	**Loss in Performance (%)**
White Markings	Larger MTD	1.1	538.9	0.6	136.2	74.7%
	Lower MTD	0.8	550.7	0.5	133.5	75.8%
Yellow Markings	Larger MTD	1.3	253.0	1.1	92.3	63.5%
	Lower MTD	0.9	282.3	0.6	106.0	62.5%

There was the same level of loss in retroreflectivity performance for the points with the largest and lowest MTD (macrotexture) – close to 75% for white markings and 63% for yellow markings. This means that in a long-term evaluation, the retroreflectivity decrease over time is independent of the macrotexture. In summary, at a given moment of exposure to traffic, macrotexture influences marking's retroreflectivity; however, the rate of retroreflectivity reduction was similar, regardless of macrotexture.

3.2. 3-D plates laboratory evaluation

Aiming to evaluate the relationship between pavement macrotexture and retroreflectivity, specifically in terms of initial values, a novel approach was used: three-dimensional printing of plates in plastic material that simulate different conditions of surface microtopography.

3.2.1 Macrotexture and retroreflectivity

Following the procedure presented in item 3.2, it was possible to isolate the macrotexture to assess its influence on the initial retroreflectivity. The results for the yellow markings are shown in Table 6.

The confection of the three-dimensional plates allowed to verify the interdependence between macrotexture and retroreflectivity. Assessing this relationship based on the Pearson correlation coefficient shows a negative correlation, indicating a reduction in retroreflectivity with an increase in MTD. This proves the suspicion generated by the practical experience over the years of assessments on Brazilian highway sections, i.e., macrotexture does influence marking retroreflectivity, which gave rise to the development of this research.

Table 6 – Effect of Macrotexture on Initial Retroreflectivity of 3-D Plates

Plate	Drop-on rate (g/m²)	Macroteture Grade	MTD (mm)	R_i (mcd/lux/m²)	Pearson's Coef. of Correlation
FE-085	85	Closed	0.356	173	
ME-085	85	Medium	0.712	161	-0.996
MA-085	85	Very Open	1.246	148	
FE-160	160	Closed	0.356	194	
ME-160	160	Medium	0.712	190	-0.984
MA-160	160	Very Open	1.246	177	
FE-250	250	Closed	0.356	209	
ME-250	250	Medium	0.712	206	-0.954
MA-250	250	Very Open	1.246	183	
FE-325	325	Closed	0.356	248	
ME-325	325	Medium	0.712	242	-0.974
MA-325	325	Very Open	1.246	238	
FE-460	460	Closed	0.356	221	
ME-460	460	Medium	0.712	205	-0.397
MA-460	460	Very Open	1.246	213	

One hypothesis for such behavior lies in the fact that the retro-reflection of light from vehicles is more easily enabled when the pavement is more flat (lower MTD). Furthermore, when the glass beads are applied on the marking, they can move into the microtopography valleys (mostly present on surfaces with greater mean texture depth), leaving the places where the light strikes devoid of drop-on glass beads.

The strength of the macrotexture/retroreflectivity relationship is not constant and depends on the application rate of drop-on glass beads. The relationship proved to be more significant for application rates up to 325g/m^2, a value generally higher than that used in Brazil, and moderate for the higher application rates.

3.2.2. Dosing proposal for drop-on glass beads

The use of three-dimensional plates has also shown to be promising in the development of protocols capable of indicating the best dosage for the materials used in the markings in view of the pavement's macrotexture.

As a way of exemplifying the potential use of 3-D plates, the ideal rate of application of drop-on glass beads for different macrotexture conditions was established, as shown in Figure 8.

There is a good correlation in the determination of the sampling points in the proposed second-order polynomial regression models. Using these models, the optimal drop-on rate (for the highest initial retroreflectivity value) was estimated. The values are 370 g/m², 340 g/m² and 385 g/m², respectively for the closed, medium and very open macrotextures. Schwab (1999) indicated an optimal rate between 237 and 295 g/m² (for a retroreflectometer geometry of 12m).

In Brazil, the current practice uses drop-on rates of the order of 250 g/m² (as in the field experiment reported in this research), well below, therefore, what would be recommended by the present study. This can help explain the low retroreflectivity performance of the markings when compared to the more restrictive international standards. For the limits imposed by the FHWA (30 m geometry), the experimental section markings on the edge would have failed after 60 days of traffic exposure. Work by Abbound and Bowman (2002), Thamizharasan et al (2003), Stizabee et al (2009), Rasdorf et al (2009), Hummer et al (2011) and Mull and Stizabee (2012) corroborate the previous conclusion, as they indicate that markings that present higher initial retroreflectivity have a longer service life.

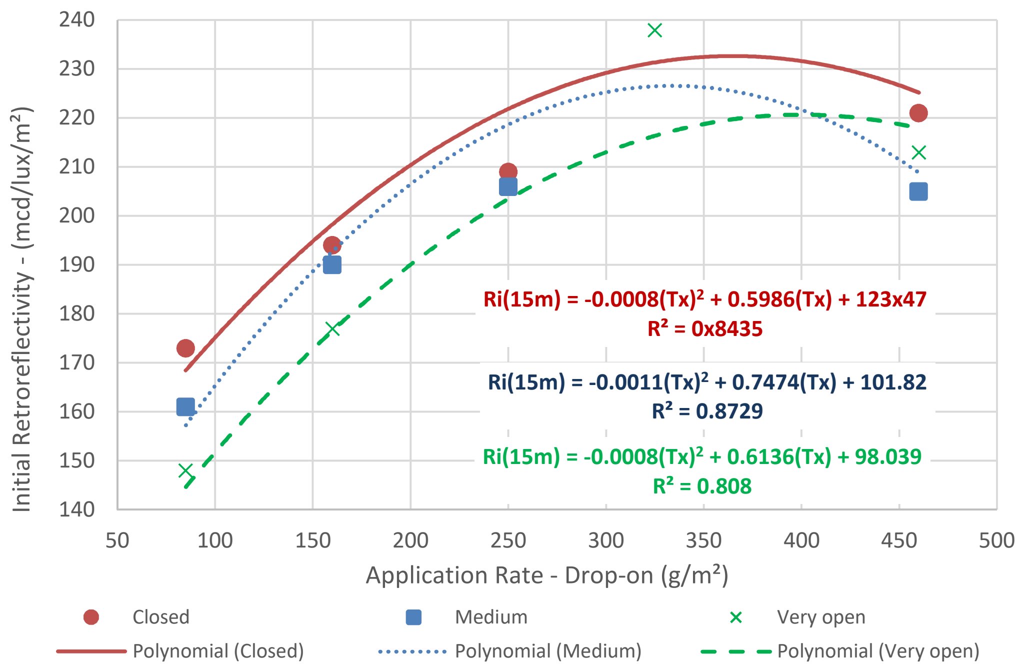

Figure 8. Initial retroreflectivity versus Drop-on Application Rate for Different Macrotextures

Also, as seen in Figure 8, the optimal drop-on application rate varied according to the macrotexture, with a greater quantity of these glass beads required for the very open macrotexture. This can help explain the poor performance of road markings on MRAF in Brazil, since the drop-on amount currently used in Brazil is well below that which would generate the greatest initial retroreflectivity and, consequently, better performance over time for coarser textures. Thus, in the present study, for markings on MRAF, a drop-on glass bead application rate of 385 g/m² would be recommended; 54% higher than the national practice (250 g/m²), as established in the Works Reference Cost System (SICRO/DNIT).

Finally, another important aspect observed from Figure 8 refers to the shape of the curve that correlates retroreflectivity with the drop-on rate. After the optimum glass bead content is reached, increasing the amount of these elements reduces the retroreflectivity; such behavior had already been empirically observed by Salles et al (2015), attributed to a more diffuse light reflection due to the excess of glass beads.

4. CONCLUSIONS

The experimental protocol used in this study made it possible to prove that measuring pavement markings retroreflectivity using a 15 m geometry retroreflectometer results in retroreflectivity values on average 50% higher than those obtained using a 30 m-geometry device. The color of the marking was also an important aspect; white and clean demarcations reached levels of retroreflectivity 38% higher than the yellow ones.

Furthermore, the retroreflectivity performance over the 24 months evaluation period was similar (absolute values were higher for white markings) for both colors. However, given the problems reported, especially due to the low rate of applied drop-on glass beads (250 g/m^2) and the effect of the pavement's open macrotexture, the performance observed in the field was unsatisfactory considering the retroreflectivity thresholds recommended by the FHWA. For Brazilian regulatory agencies, the markings performance would have been considered satisfactory, demonstrating the lack of more in-depth discussions about the quality required for pavement markings in Brazil.

The markings monthly cleaning proved to be effective, being responsible for a retroreflectivity increase of between 17 and 22% considering measurements conducted before and after cleaning, depending on the marking’s color. When comparing the points that received recurrently cleaning with those that did not, the differences were even more significant, reaching an average retroreflectivity 53% higher for the clean yellow markings compared to the same color markings without cleaning. On the other hand, the direction of retroreflectivity measurements was found to not influence overall retroreflectivity.

The pavement surface microtexture proved to be influential for markings retroreflectivity, which can be attributed to the gradual exposure of premix glass beads. In the same way, the surface macrotexture showed significant influence in retroreflectivity levels. The trend indicated by the empirical data was a reduction in retroreflectivity for coarser surfaces. This was confirmed by the three-dimensional printing of plastic plates with uniform macrotextures and different mean texture depth grades.

The making of 3-D plates also showed potential for developing a method for dosage of pavement markings materials. The ideal rate for drop-on glass beads is not constant, varying depending on the macrotexture, with a higher rate for the very open macrotexture (385 g/m^2). The application rates recommended by this novel methodology were higher than those currently used in Brazilian markings, answering, in part, for the markings poor performance observed in the field. Interestingly, the use of drop-on above the ideal rate incurs in a substantial reduction in retroreflectivity, probably due to a diffuse reflection of light.

Finally, the data presented in this study demonstrate the need to define a procedure capable of dosing, among other parameters, the application rate of drop-on glass beads, including as input the texture of the pavement. Moreover, a deeper reflection on the normative processes for evaluating pavement marking retroreflectivity, equipment geometry, restrictive minimum residual values and conservation of markings was shown to be necessary.

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