Bonding Evaluation of Asphalt Emulsions used as Tack Coats through Shear Testing

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Received: 21 March 2019; Accepted: 23 April 2019; Published: 26 April 2019

Featured Application: Evaluation of bond strength between pavement layers.

Abstract: A poor bond between the layers constituting an asphalt pavement can cause structural problems such as slippage, delamination, and top-down cracking. These are consequences of the pavement being unable to act as a continuous element and to properly transmit the effects of the traffic to underlying layers. The aim of this research was to characterize an asphalt emulsion with low asphalt content using the Mexican standard and to evaluate its performance through the Laboratorio de Caminos de Barcelona (LCB) shear testing. Cationic slow setting (SS) and cationic rapid setting (RS) asphalt emulsions were tested by varying the asphalt contents, dosages, and cure times. The slow set emulsions presented a greater fracture energy than did the rapid set emulsions; a dose of 0.3 L/m² provided the same level of resistance as a 0.5 L/m² dose; and a 55% asphalt content provided greater resistance than the 60% asphalt content.

Keywords: asphalt emulsion; tack coat; bonding; asphalt pavement; LCB shear test; dose; asphalt content

1. Introduction

Asphalt pavements are widely used due to their characteristics, advantages, and versatility [1]. In fact, as a way of making pavements more economical, less polluting, and with less energy consumption, emulsions can be used; these are dispersed systems made up of two immiscible liquids [2] united by an emulsifier. Additive components such as stabilizers, adhesion enhancers, coating enhancers, or breakage control agents could also be part of these [3]. Emulsions are classified according to the emulsifier and type of setting [4]. If the emulsifier has a negative charge, it is anionic, while a cationic emulsifier has a positive charge. There are rapid setting (RS) emulsions, designed to react quickly with the aggregate [3,5]; these are used for irrigation as they are highly viscous to prevent runoff [2]. On the other hand, those with slow setting (SS) properties are designed to achieve stable mixtures, using closed granulometries with a high percentage of fines [3,5]; these are commonly used for pavement priming [2]. An emulsion’s viscosity and stability depend on several variables. Viscosity is controlled by the water/oil ratio, droplet size, and surfactant, where the water/oil ratio is very important, i.e., when the water/oil ratio decreases (at higher asphalt concentrations), the viscosity increases [6]. Schuster [7] affirmed that an emulsion was more stable when the droplet coalescence rate was slower. On the other hand, asphalt–solid adhesion depends on the electrical charge of the emulsion (anionic or cationic) and the pH of the aggregate; for example, if an anionic emulsion is mixed with an alkaline aggregate, it can produce a reaction that improves adhesion. In contrast, if
the anionic emulsion is mixed with an acid aggregate, the adhesion is compromised. On the other hand, cationic emulsions have improved adhesion when mixed with either alkaline or acid aggregates, so they have been preferred [6].

Because pavements are formed of multiple layers subjected to combinations of traffic load and climatic changes [1], they are subject to distress as a consequence of inadequate selection of materials. It has been interesting to analyze the principal types of distress, such as slippage, delamination, and top-down cracking, due to the asphalt emulsion quality and its capacity to bond two layers [8]. When the adhesion between coats is low, the binder of bearings tends to crack early with increased rutting due to the internal energy consumption of the material, resulting in fatigue problems and top-down cracks [9]. Rutting is a permanent deformation due to traffic and is more important at high temperatures, while fatigue manifests itself at medium and low temperatures, causing the evolution of micro-cracks and micro-voids [10]. Due to the above, several researchers have studied the behavior of asphalt mixtures through different tests; for example, Tajdini et al. [11] evaluated the geomechanical parameters of the asphalt concrete–sand interface using direct shear testing and a nonlinear analysis. Jahanbakhsh et al. [12] evaluated the behavior of low-temperature mixtures through bending beam rheometer (BBR), direct tension (DT), and semi-circular bending (SCB) fracture testing, in order to obtain the normalized tensile stress (NTS). Jahanbakhsh, Karimi, Jahangiri and Nejad [1] added carbon black (CB) as a conductive component to increase the electromagnetic sensibility of asphalt in order to accelerate the heating and healing of the material. They used indirect tensile (IDT), uniaxial compressive, and SCB testing. Karimi et al. [13] used activated carbon (AC) as a binder-based conductive additive to increase the electromagnetic radiation absorption of the asphalt binder; they used SCB and uniaxial testing. Finally, a study of adhesion using the LCB (Laboratorio de Caminos de Barcelona) shear test was performed by Cruz Romero [14] to characterize adhesion in ultra-thin whitetopping reinforcements, while Delbono [15] and Delbono, Fensel and Cepeda [9] analyzed the adhesion of an asphalt concrete–geosynthetic interface. Based on previous works, reducing those structural conditions [16,17] affirmed that one of the most influential factors in the service life and maintenance of pavements was appropriate bonding between layers, which is obtained by the correct application and surveillance of asphalt emulsion procedures during road construction. This process allows the pavement to act as one element to properly distribute strains, thus reducing the presence of cracks and deformations. This research is focused on complementing the idea that a low-viscosity asphalt emulsion can perform better than a normal emulsion because it can cover the entire surface and fill imperfections in the layers we are bonding. This process results in an improved interlock between layers (as sustained in reference [18]) and seeks to reinforce the perception of asphalt emulsions. Because emulsions are most commonly used for bonding layers due to their low-temperature application capability and low asphalt content, their use is a sustainable method. For this reason, in this article, the adherence of asphalt emulsions was evaluated and used as tack coats through LCB Shear Testing.

Tschegg et al. [19] maintain that during recent years, the study of tack coats in pavements has gained importance in Europe; as a consequence, many researchers have studied the behavior of bonding layers through the analysis of torque, tensile, and shear tests, where some factors with high relevance for asphalt emulsion performance, such as the dosage, asphalt content, type of asphalt mix, contact surface characteristics, compaction load, and application temperature, have been identified [20]. Considering the methodology of the Leutner test model, Sholar et al. [21] performed complementary studies to analyze the bonding layers. However, the asphalt emulsion behavior over time has only been studied in a limited way. Canestrari et al. [22] concluded in their experiments that the bonding improved after a period of days; additionally, the investigation by Raab and Partl [8] showed the long-term performance interactions between asphalt layers and the tack coat. The asphalt emulsion effectiveness when applied as a tack coat between pavement layers was analyzed in terms of the dose and setting time [20]. Considering the dose and setting time of the asphalt emulsion, Deysharkar [23] demonstrated that the best performance was achieved when using doses of 0.45 L/m\(^2\) instead of 0.18 L/m\(^2\) and when using a setting time of 30 to 60 min before compaction of the asphalt layer.
Therefore, the objective of this research was to evaluate the mechanical behavior (fracture energy and maximum load) of cationic slow (SS) and rapid (RS) setting asphalt emulsions with different asphalt contents, dosages, and cure times through LCB shear testing at a temperature of 25 °C. These tests produced displacement-load curves of the asphalt mix specimens. Furthermore, the relationships between the emulsion dosage, asphalt content, and curing time and the maximum applied load and fracture energy were found.

2. Background

As stated by Dar Hao [24], the application of a tack coat is considered a simple and cheap procedure during pavement construction; however, it should be seen as a requisite to guarantee the correct performance of the pavement. As stated in Johnson, et al. [25], the tack coat achieves its principal purpose by bonding a previous surface with the new layer to prevent deterioration, as mentioned before. We proposed that tack coats are not sufficiently taken into consideration in most pavement procedures, and acceptable bonding is not always achieved, as affirmed in reference [26]. Thus, slippage between layers appears to reduce the service life and shear distress becomes excessive at some particular points of the road where the horizontal loads increase. This process can occur in curves, intersections, and zones with ascendant or descendant gradients, causing surface distress.

Currently, the Mexican regulation for the quality control of asphalt emulsion consists basically of the procedures stated in N-CMT-4-05-001/05 [27]. However, as shown in Ontiveros [28], these tests presented by the Secretary of Communications and Transportation are only indicative of the quality of the material and do not describe the mechanical behavior of the binder performing as a tack coat when bonding the pavement top layers.

To evaluate the mechanical behavior of a tack coat, researchers have considered shear, tensile, and torsion models to try to represent the stresses presented in the pavement during its service life. Some of the most representative models are the LCB (Laboratorio de Caminos de Barcelona) test implemented by the Polytechnic University of Cataluña, the ASTRA (Ancona Shear Testing Research and Analysis) [22] test from Polytechnic University of Marche, the SHSTM (Sapienza Horizontal Shear Testing Research and Analysis) test from Sapienza University of Rome, the FDOT (Florida Department Of Transportation) test, the UTEP Pull Off Test by the University of Texas El Paso, and the Torque Bond Test and LPDS (Layer-Parallel Direct Shear) [29].

Recasens, et al. [30] presented some of the research where the LCB shear test was implemented. As a necessity to study the performance of tack coats, a shear resistance test was developed by the Polytechnic University of Cataluña in Spain. This procedure is known as the LCB shear test, and a comparison between conventional, term-adherent, and modified emulsions was developed to evaluate the mechanical response of the tack coat.

![Force and stress diagram](image)

**Figure 1.** Force and stress diagram acting on the specimen in the LCB (Laboratorio de Caminos de Barcelona) shear test.
The LCB test was developed by the Laboratorio de Caminos de Barcelona with the objective of assessing the tangential stresses caused by the application of a shear force (Figure 1). The maximum load is the highest point of the load–displacement curve; therefore, higher resistance increases the adhesion between asphalt layers. On the other hand, the fracture energy is the area under the load–displacement curve, implying that the greater the area under the curve, the more energy that will be needed for disengaging between layers [31].

3. Methodology

To fulfill the objective of this research work, the behavior of asphalt mixtures manufactured with cationic asphalt emulsion was evaluated because they are preferred (Ronald and Luis [6]), are more stable (Schuster [7]), and are commonly used during asphalt pavement construction in Mexico. The asphalt emulsions are made with PG 64-22 asphalt binder under the quality control of N-CMT-4-05-004/08 [32]. The sample test mixtures were manufactured by combining slow (SS) and rapid (RS) setting cationic emulsions with different percentages of asphalt residue, using different emulsion dosages (tack coats), and using different curing times. Additionally, four samples of each asphalt mixture were manufactured and tested to obtain a statistical analysis. The methodology of the experiments is shown in Figure 2.
To perform the analysis, it was necessary to determine the asphalt binder content, emulsion dosage, and curing time. Thus, the methodological process of the tests was carried out according to the four steps shown in Figure 2.

3.1. Asphalt Binder Content

The percentage of asphalt residue used for this research, both for slow setting (SS) and fast setting (RS) asphalt emulsions (to obtain their mechanical behavior), was obtained in accordance with the manufacturer’s recommendations for the SS and RS asphalt emulsions. These percentages were 50%, 55%, and 60% of the binder content of asphalt residue. Hence, Table 1 summarizes the proportions of the incorporated emulsifier according to the recommended percentage of asphalt residue.

Table 1. Proportions of the emulsifiers.

| Emulsion Type    | Proportion of Emulsifier (kg/Ton) | % Asphalt Residue | Emulsifier Per 2 Liters of Asphalt Emulsion (g) |
|------------------|-----------------------------------|-------------------|-----------------------------------------------|
| Slow Setting     | 10.00                             | 50%               | 40.00                                         |
|                  |                                   | 55%               | 44.40                                         |
|                  |                                   | 60%               | 50.00                                         |
| Rapid Setting    | 3.00                              | 50%               | 12.00                                         |
|                  |                                   | 55%               | 13.33                                         |
|                  |                                   | 60%               | 15.00                                         |

3.2. Emulsion Dosage as A Function of The Tack Coat Rate and Curing Time

Dosages that are commonly used as tack coats during pavement construction were applied to the samples, resulting in the use of different dosages as a function of the tack coat rate. In addition, Table 2 summarizes the different dosages used for each asphalt emulsion at different tack coat rates of 0.3, 0.5, and 0.7 L/m². Additionally, the emulsion was heated with a water bath up to 60 °C to simulate the closest conditions to application in the field using a distributor truck.

Table 2. Proportions of the emulsifiers.

| Emulsion Type    | Sample Area (m²) | Application Temperature (°C) | Tack Coat Rate (L/m²) | Dosage for Each Sample (g) |
|------------------|------------------|-----------------------------|-----------------------|---------------------------|
| Slow Setting     | 0.008136         | 60.00                       | 0.30                  | 2.44                      |
|                  |                  |                             | 0.50                  | 4.02                      |
|                  |                  |                             | 0.70                  | 5.63                      |
|                  |                  |                             | 0.30                  | 2.44                      |
| Rapid Setting    | 0.008136         | 60.00                       | 0.50                  | 4.02                      |
|                  |                  |                             | 0.7                  | 5.63                      |

Three curing times were established in order to observe the mechanical behavior of the asphalt test samples. These curing times were 1, 3, and 5 days after the tack coat application at 25 °C.

3.3. Performance

In order to evaluate the performance of the asphalt test samples, the mechanical behavior of each sample was tested via LCB shear testing at 25 °C. For this testing, slow (SS) and rapid (RS) setting cationic asphalt emulsions were used, and these emulsions were made with PG 64-22 asphalt cement under the quality control of N-CMT-4-05-004/08 [32]. Following the NLT-382/08 standard, cylindrical specimens (101.6 mm diameter) of a hot mix asphalt were made using the Marshall procedure established in N-CMT-4-05-003/08 [33] and M-MMP-4-05-034 [34], combining the asphalt binder residue content and the dosages shown in Tables 1 and 2. Additionally, the asphalt test samples were cured for 1, 3, and 5 days and were then tested via LCB shear testing [30] using a loading press. The maximum load applied and the deformation until the softening load were recorded.
A total of 72 asphalt test samples were prepared and tested on LCB shear equipment, and the load–deformation charts were detailed to analyze the fracture energy from the calculated areas under the curves. The results of the SS and RS asphalt emulsions were compared in terms of the displacement–load graphs and the relationship between the emulsion dosage, asphalt residue content, and curing time and the maximum applied load and fracture energy.

3.4. Laboratorio de Caminos de Barcelona Shear Test

The LCB (Laboratorio de Caminos de Barcelona) test consists of measuring the resistance to the tangential stresses, caused by the application of a shear force, that are produced in the union of two asphalt layers, adhered or not by adherence irrigation. The deformation of one layer with respect to the other is also measured [14,15,31].

The force analysis is shown in the model shown in Figure 3. Part A (the part of the casing) is considered totally rigid and non-deformable, while Part B for a normal asphalt specimen represents the upper asphalt layer. There is pure shear stress and no bending stress [14].

![Figure 3. Schematic of forces and tensile stresses on the asphalt test samples: (A) specimen part into the casing and (B) upper specimen layer under pure shear stress.](image)

The test was performed at a feed rate of 1.27 mm/min at room temperature (approximately 22 ± 2 °C). Then, the equation which provided the value of the tangential stress (τ) on the bond joining both parts, if \( P \) was the maximum load and \( S \) was the surface of the transversal section, was [31]

\[
\tau = \frac{P}{2S} \quad (1)
\]

The test was devised with the intention of fulfilling the specifications of repeatability (when the same operator repeating the test following the same procedure and using the same materials and equipment obtains the same results) and reproducibility (when there is no difference in results when the test is performed with the same materials but by a different operator and with different equipment) [31].

4. Results and Discussion

To determine the necessary shear stress to separate two layers of the asphaltic mixtures with slow and fast emulsions, specimens were created with asphalt residue contents of 50%, 55%, and 60%. In addition, the specimens had different setting times and emulsion dosages according to the LCB test. The fracture energy was also determined from the area delimited above by the load–displacement curve obtained from the test.

Figure 4 shows a load–displacement curve obtained from LCB shear testing; this was representative of 72 tests. From Figure 4 it is evident that asphalt samples manufactured with slow setting emulsion had the highest resistance to applied loads but deformed more than those made with rapid setting emulsion. Therefore, more energy was required to fracture the samples, as can be seen in Figure 5.
The above shows that samples with slow setting emulsion were more tenacious, more ductile, and less fragile than mixtures made with rapid emulsion; therefore, again, more energy was required to fracture these samples.

Figure 4. Representative load–displacement curves for all Laboratorio de Caminos de Barcelona shear tests.

The resistances of emulsion adherence for the two asphaltic layers are presented in a boxplot diagram which represents schematically the resistance distribution of the mixture adherence, with the slow and rapid setting emulsions, for the different asphalt test samples (Figure 6). The results show that the rapid setting emulsion with different dosages of asphalt and setting times presented less resistance to applied loads in comparison to the slow setting emulsion, with the exception of the 0.3 L/m² dosage with 5 days of curing.

Figure 5. Box and whisker chart of the specimen fracture energy.
Then, the parameters of the fracture energy were analyzed, which allowed us to evaluate the energy necessary to separate the two asphaltic layers. Figure 5 shows that the slow emulsion presented greater fracture energy over all the curing times and percentages of asphaltic residues. As a result, it was decided that the energy parameters for all the doses should be considered, including asphaltic contents, and curing times since the results from the fracture energy presented increased reliability with regard to the maximum resistance results of the specimens. The statistical summary results for all specimens are presented in Tables 3 and 4.

In Figure 7, the rapid setting emulsion is seen to have its highest fracture energy under a 0.3 L/m² dosage, a 3 day curing time, and an asphaltic content between 55% and 60%. The highest values reached were between 8 J/m² and 10 J/m². According to the mechanical properties, the use of a rapid setting emulsion combined with 60% of asphalt residue content and at a dosage of 0.3 L/m² with 3 days of curing proved to be the best option using this kind of emulsion. This was due to it having the best resisting loads and less deformation, thus requiring the highest possible fracture energy.
Table 3. Summary statistics for the fracture energy (J/m²) of the rapid setting asphalt emulsions for the three doses and cure times.

| Emulsion Dosage | 0.3 | 0.5 | 0.7 |
|------------------|-----|-----|-----|
| Asphalt Content  | 50  | 55  | 60  | 50  | 55  | 60  | 50  | 55  | 60  |
| Cure Time (Day)  | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. |
| 1                | 3.97 | 0.29 | 5.26 | 1.50 | 4.01 | 0.11 | 2.18 | 1.12 | 4.51 | 0.53 | 4.86 | 0.78 | 2.94 | 0.08 | 2.83 | 0.48 |
| 3                | 3.13 | 0.13 | 6.49 | 1.14 | 9.48 | 2.39 | 3.87 | 1.27 | 2.38 | 0.42 | 5.12 | 0.67 | 3.07 | 0.66 | 4.36 | 0.72 | 5.91 | 0.57 |
| 5                | 6.71 | 0.32 | 6.66 | 0.18 | 6.52 | 0.20 | 6.91 | 0.81 | 6.04 | 0.86 | 4.47 | 1.22 | 4.79 | 1.39 | 4.53 | 0.64 | 5.64 | 1.73 |

Table 4. Summary statistics for the fracture energy (J/m²) of the slow setting asphalt emulsions for the three doses and cure times.

| Emulsion Dosage | 0.3 | 0.5 | 0.7 |
|------------------|-----|-----|-----|
| Asphalt Content  | 50  | 55  | 60  | 50  | 55  | 60  | 50  | 55  | 60  |
| Cure Time (Day)  | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. |
| 1                | 5.42 | 5.42 | 5.42 | 5.46 | 5.93 | 1.83 | 5.17 | 0.15 | 7.28 | 2.12 | 7.67 | 0.96 | 5.65 | 0.32 | 9.99 | 2.25 | 16.74 | 1.54 |
| 3                | 7.98 | 1.75 | 15.05 | 0.16 | 9.68 | 2.50 | 9.53 | 0.13 | 9.37 | 0.47 | 9.57 | 3.23 | 5.26 | 0.61 | 7.95 | 0.91 | 8.28 | 0.37 |
| 5.00             | 7.30 | 0.16 | 12.30 | 0.16 | 14.31 | 1.48 | 13.40 | 1.10 | 11.28 | 0.90 | 17.09 | 0.25 | 10.04 | 2.11 | 13.83 | 0.42 | 8.30 | 0.16 |
In Figure 8, the slow emulsion is observed to have the highest fracture energy with a 0.5 L/m² dose, a 5 day curing time, and an asphaltic content of 60%. The highest values reached were between 16 J/m² and 17 J/m². However, most of the fracture energies were between 7 J/m² and 10 J/m². The foregoing evidence showed that the use of a slow setting emulsion combined with 60% asphalt residue content and at a dosage of 0.5 L/m² with 5 days of curing proved to be the best option using this kind of emulsion. This was due to it having the best resisting loads and less deformation, thus requiring the highest possible fracture energy.

**Figure 8.** Fracture energy diagram of the slow setting asphalt emulsions for different dosages and cure times.

In summary, the slow emulsion had a higher fracture energy than the fast emulsion for all the doses, curing times, and asphaltic contents tested. This outcome reflected a better bond between the asphaltic layers and resulted in longer durability and greater resistance overall.

5. Conclusions

The aim of this work was to evaluate the mechanical behavior (fracture energy and maximum load) of cationic slow (SS) and rapid (RS) setting asphalt emulsions with different asphalt contents, dosages, and curing times through LCB shear testing at a temperature of 25 °C. The asphalt test samples were made using the Marshall procedure, combining the asphalt binder residue content and the dosages. The mechanical behavior (load–displacement, fracture energy, and applied load) was determined using the LCB shear test.

Some interesting facts were observed from the analysis of the laboratory results. First, the performance of both asphalt emulsions (SS and RS) improved over time, indicating that the tack coat still worked over time. If we applied this analysis to field conditions, the shear resistance for a road open to transit 15 days after construction would be higher than the resistance of a road that was newly constructed. Traffic driving immediately on the road would compact the asphalt layer and densify the pavement structure. Second, the asphalt emulsions with low binder content (50% and 55%) presented similar shear resistances to the 60% asphalt emulsions. In some cases, higher resistances were seen, which suggested that these particular low-binder-content asphalt emulsions could be used as tack coats without drawbacks in pavement procedures.

For the dosages derived from the tack coat rates used during the experimentation, it was observed from the application of the emulsion in each sample that the 0.3 L/m² rate seemed to be insufficient to serve as a proper tack coat in comparison with the 0.5 L/m² rate, which always seemed to perfectly coat the bond surface. However, the results from the LCB shear test showed that the former of these rates resulted in better performances, and it could be applied and reproduced in the field as an option for tack coating during pavement construction.

From the LCB shear test results, we concluded that we could use the N-CMT-4-05-004/08 [18] regulation and support the application of asphalt emulsions with low binder content as a viable option for the construction of a sustainable asphalt pavement. This will save resources during the production process while still meeting quality control standards.
During the analysis of the fracture energy for both the SS and RS asphalt emulsions, it was observed first during the LCB shear testing that the specimens constructed with an SS tack coat had a gradual and more prolonged failure compared with the RS tack coat, where the failure was considerably abrupt. This result can be explained by analysis of the load–displacement chart, where it was observed that the fracture energy for an SS asphalt emulsion was nearly double the RS fracture energy.

**Author Contributions:** Conceptualization, D.A.C., P.L.C., J.R.G.-G.; Methodology, D.A.C., P.L.C., J.R.G.-G. and M.Z.P.; Software, D.A.C., J.R.G.-G. and M.Z.P.; Validation, P.L.C., J.R.G.-G. and M.Z.P.; Investigation, D.A.C., P.L.C., J.R.G.-G. and M.Z.P.; Resources, D.A.C. and J.R.G.-G.; Data Curation, P.L.C., J.R.G.-G. and M.Z.P.; Writing—Original Draft Preparation, P.L.C., D.A.C. and J.R.G.-G.; Writing—Review & Editing, P.L.C., D.A.C., J.R.G.-G. and M.Z.P.; Supervision, M.Z.P. and J.R.G.-G.; Project Administration, P.L.C. and D.A.C.

**Funding:** This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**Acknowledgments:** The authors would like to acknowledge the administrative support from the César O. Monzón to head of the Engineering Division of the University of Guadalajara.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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