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Effect of Vehicle Speed and Weight on Raveling of Chip Seal Constructed Using Mineral and Tire Derived Aggregate

Alireza Pourhassan[1,2], Ahmed A. Gheni[3], and Mohamed ElGawady[2]

Abstract

The characteristics of the load applied by traffic, namely, vehicle speed and load magnitude, play a critical role in the raveling performance of chip seal pavement, which is often overlooked in literature. Furthermore, a sustainable chip seal constructed out of tire derived aggregate (TDA) has been recently introduced. Unlike mineral aggregate, rubber is a time-dependent material, and its properties are greatly influenced by the magnitude and rate of loading. Introducing TDA in chip seal has increased the significance and need to investigate the effects of vehicle speed and load on chip seal. This study investigated the raveling performance of different chip seal specimens constructed out of mineral and TDA, as well as a hybrid tire derived–mineral aggregate, under various loading speeds and magnitudes using a small-wheel traffic simulation device. The findings revealed that both load and speed significantly affect the texture loss of conventional and TDA chip seals, but in opposite ways. Conventional chip seals experienced increased texture loss with higher load and speed, while TDA chip seals showed a decrease. The use of TDA as an aggregate in chip seal resulted in a 23% reduction in macrotexture loss under increased load and a 56% reduction in macrotexture loss under increased speed compared with conventional chip seal. This improved performance is attributed to the dynamic properties of TDA, such as internal hysteresis, time-dependent behavior, and load transmissibility.

Keywords

iChip seal, tire derived aggregate, vehicle load, traffic speed, raveling, traffic load simulation, crumb rubber

Chip sealing is a widely used pavement maintenance technique that is cost-effective and fast to implement. Chip seal can be degraded during its service life by traffic loads and climate effects. Raveling is one of the most common forms of distress in chip seal (*1*, *2*), and occurs when the bond between the aggregate and binder fails, causing the aggregate to separate from the binder. This results in the loss of skid resistance, as well as exposing the binder to abrasive traffic forces. Loose particles can dislodge, also posing a hazard to pedestrians, bicycles, and vehicles.

Chip seal raveling occurs in three stages: initial, early-stage, and late-stage (*3*). Initial raveling happens after construction as a result of inadequate design or construction. Early raveling is caused by insufficient bonding between binder and aggregate, influenced by site conditions, aggregate mineralogy, and binder characteristics. Late raveling, also known as in-service raveling, occurs as a result of long-term traffic effects and the degradation of the adhesive strength between the binder and aggregates at intermediate temperatures (*4*). Studies on late raveling focused on the factors that affect the binder-aggregate bond such as binder-aggregate compatibility, curing process, binder-aggregate interfacial bond strength, internal cohesive strength of the binder, binder stiffness, binder strain tolerance, moisture susceptibility

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of the binder-aggregate system, and binder oxidative aging (*4–10*).

Several tests including the ASTM standard sweep test (*11*), Pennsylvania aggregate retention test (*12*), and Vialit test (*13*) have been used to assess the binder-aggregate bond strength in chip seal as an indication for raveling potential. The sweep test (*11*) involves applying a force to the chip seal surface with a nylon brush using a mixer for 1 min and calculating the percentage mass loss. In the Pennsylvania test (*12*), a chip seal pan is placed upside down on top of five ½-in. sieves, and the entire assembly is subjected to shaking and tapping action in a Mary Ann Sieve Shaker for 5 min, with the percentage of knock-off determined as a result. In the Vialit test (*13*), an impact force is applied to an inverted plate containing the chip seal sample (100 graded aggregates embedded in the binder) by dropping a 2-in. diameter steel ball from a height of 18 in., with the results recorded as a percentage of aggregate retention. Other tests such as binder rheological tests and asphalt binder bond strength (BBS) (*14*), and pull-off tensile tests are also performed for potential raveling assessment (*4–10*).

Raveling performance of chip seal can be quantified using different methods. Two commonly used approaches include calculating the percentage of aggregate weight loss after testing (*15*, *16*), and measuring macrotexture loss. Macrotexture loss is considered to be the most relevant indicator for evaluating raveling in chip seal. It refers to the loss of surface texture over time, which can result in decreased skid resistance and increased risk of accidents. By identifying areas that require maintenance or repair using these methods, road engineers can ensure the safety and longevity of the road network (*3*, *17–19*).

Tire derived aggregate (TDA) has been used as a replacement for mineral aggregate in chip seal representing a more sustainable practice (*3*, *20–29*). Those studies indicated that there is a weaker bond between the bitumen binder and TDA compared with mineral aggregate, given the hydrophobic surface of the TDA and 0% water absorption (*3*, *24*, *27*). However, field measurements and laboratory tests have shown that replacing up to 50% of the mineral aggregate with TDA did not significantly affect the raveling resistance of chip seal at ambient temperatures, regardless of the binder rate (*3*).

While the impact of binder and aggregate characteristics on raveling has been well studied (*4–10*), the effect of traffic-related parameters, such as vehicle speed and weight, is not well understood. Furthermore, in the case of using TDA in chip seal traffic parameters become more pronounced as TDA is a time-dependent material, and its mechanical properties are significantly affected by the rate and magnitude of loading (*30*). The above-mentioned testing procedures cannot be used to investigate those parameters. Recently (*3*) it was shown that the small-wheel traffic simulator (SWTS) can be used to produce loading effects similar to those experienced by chip seal surfaces in the field. SWTS was able to accurately simulate the raveling performance and macrotexture loss of conventional and TDA chip seals (*3*). It was found that each wheel application on SWTS produces a similar amount of raveling damage as that produced by 2.75 passenger cars passing in the field. The trend and values of macrotexture loss measured with SWTS and in the field were found to be comparable (*3*). It is, therefore, important to examine the effect of traffic speed and load on both conventional and TDA chip sealing.

This study aims to bridge the gap in the existing literature and provide a better understanding of the raveling performance of chip seal under traffic loads. This paper presents the first-ever systematic study on the effects of traffic speed and weight on the raveling of chip seal constructed with mineral and TDA aggregates. To address the limitations of the above-mentioned testing procedures (sweep test [*11*], Pennsylvania aggregate retention test [*12*], Vialit test [*13*], and BBS [*14*]), this study employed the SWTS to investigate the raveling performance of chip seal. The chip seal specimens were constructed using mineral and TDA aggregates and partial replacements of mineral aggregate with TDA at 25% and 50% and were subjected to controlled traffic loads, in the number of vehicles, load, and speed using the SWTS. The raveling was assessed in the context of changes in macrotexture quantified using 3-D scanner. The study will also improve the understanding of using TDA in chip seal. The results of this study will provide a strong foundation for future implementation on using recycled tires as an aggregate in chip seal, which is crucial for natural resource preservation and environmental protection (*3*, *21*, *22*, *26*).

Experimental Program

The experimental program of this study consists of three phases (Table 1), using the SWTS device to investigate the raveling performance of chip seal pavement subjected to different loading conditions. Phase I included reference specimens that were tested under reference speed and load magnitudes. Phases II and III examined the effect of traffic load magnitude and speed, respectively. The raveling performance, the macrotexture of the specimens, was assessed using a 3-D scanning technique. The test specimens were labeled with the letters C (control), M (increased load magnitude), and S (increased speed), respectively, followed by a number representing the percentage of TDA used in each specimen. A statistical analysis was conducted to evaluate the significance of the parameters. This section discusses the experimental details, the materials

Table 1. Test Matrix

Test phase	Specimen ID	Number of specimens tested	Percentage of aggregate (by volume)		Normal load magnitude (lb)	Wheel travel speed (wpm)
			Mineral aggregate	TDA		
Phase I (Control)	C00	2	100	0	87	120
	C25	1	75	25		
	C50	1	50	50		
	C100	2	0	100		
Phase II (Increased load)	M00	2	100	0	172	120
	M25	1	75	25		
	M50	1	50	50		
	M100	2	0	100		
Phase III (Increased speed)	S00	2	100	0	87	180
	S25	1	75	25		
	S50	1	50	50		
	S100	2	0	100		

Note: TDA = tire derived aggregate; wpm = wheels per minute.

used, the macrotexture measurement method, and the statistical analysis used in this study.

SWTS Test Set-up

The SWTS device (Figure 1) includes three 8-in. diameter pneumatic tires with a width of 2½ in. attached to a circular plate with a 15¾ in. center-to-center diameter wheel tracking. A digital speed controller regulates the velocity of the driving system, enabling the application of varying speeds. The normal weight applied to the test specimens can be adjusted by adding weights to the circular plate. The same type of pneumatic tire is used throughout this study and is inflated to 290 psi under all loading conditions to maintain consistent tire–pavement contact areas. The tire pressure, wheel contact pressure, and wheel travel speed for control specimens were selected following the ASTM E660 for accelerated polishing of aggregate or pavement surfaces (*31*). Further details about the SWTS device can be found in (*3*, *21*).

Test Matrix

The specimens used in Phase I were previously prepared by the authors (*3*) and tested under a constant wheel travel speed of 120 wpm (wheels per minute) and applied weight of 87 lb. These test parameters have been shown to provide a long-term raveling effect for passenger cars comparable to those measured on a chip seal road section with a speed limit of 35 mph (*3*).

In Phase II, the normal load magnitude was increased by about 100% from 87 lb to 172 lb while the wheel travel speed remained constant at 120 wpm. In Phase III, the wheel travel speed was increased by 50% from 120 wpm to 180 wpm while the normal load was kept constant at 87 lb. It is worth noting that while the SWTS results were correlated with field results for passenger cars at a speed limit of 35 mph (*3*), this does not ensure that the correlation between the SWTS results and field data will hold true for other weights and speeds. Rather, this study used the SWTS to compare the performance of chip seal specimens subjected to different loading conditions which improves the understanding of raveling of chip seal pavement.

Each test specimen underwent 100,000 wheel applications, which is equivalent to the impact of around 270,000 passenger cars for Phase I test parameters (*3*). Raveling measurements were performed at roughly every 20,000 cycles during testing. Severe raveling was observed in many specimens at 100,000 cycles, and continued testing would not have produced any significant results. Other test parameters such as temperature remained constant at 78 ± 4°F during testing.

Specimens Material and Preparation

Two different types of aggerate were used to construct the chip seal specimens: a trap rock, a common type of aggregate used in chip seal construction, and TDA. Both aggregate types had a similar gradation to neutralize the effect of size and gradation on comparisons (*3*, *23*). The aggregates had a similar nominal maximum size of 0.38 in. and a median particle size of 0.25 in. A commonly used (*8*), water-based, cationic, rapid-setting, high-viscosity, polymer-modified CRS-2P asphalt emulsion was used for the construction of the specimens.

Chip seal test specimens, measuring 2x2 ft, were constructed on a plywood base (Figure 2*a*) since foam or steel bases are too soft or hard for chip seal laboratory applications, respectively, leading to inaccurate results (*21*). The plywood was covered with an asphalt felt to simulate an existing asphalt layer (Figure 2*b*), as chip

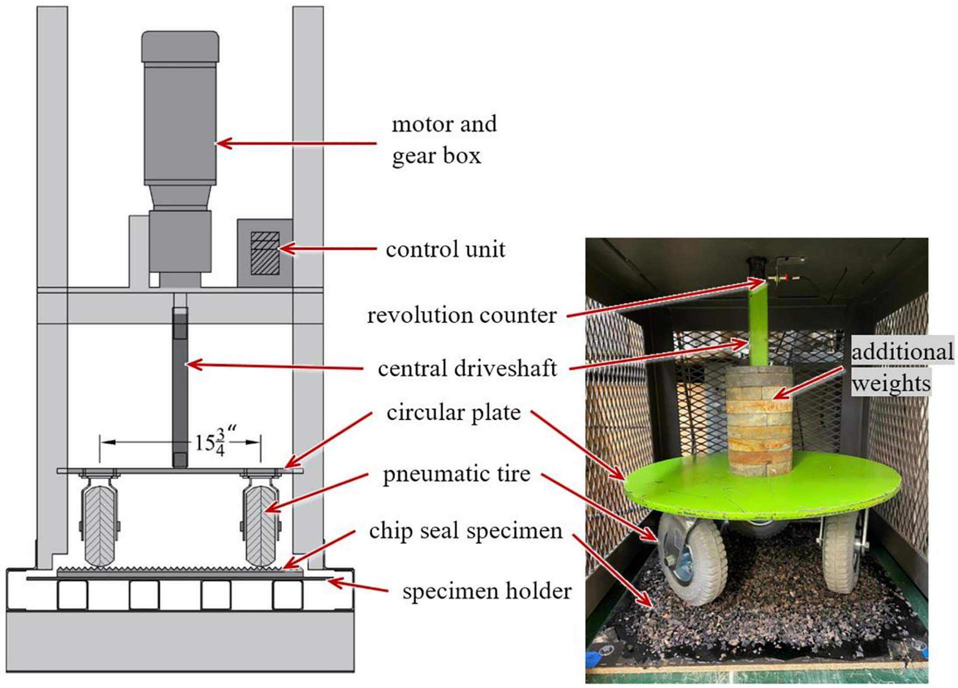

Figure 1. Small-wheel traffic simulation (SWTS) device.

seal is typically applied to existing asphalt. The laboratory chip seal specimens were prepared as follows. First, a measured amount of binder was preheated to 155°F and was poured on the asphalt felt and spread evenly with a metal rod (Figure 2*c*). A binder application rate of 0.5 gal/yd^2 was used for all specimens (*8*) providing sufficient embedment to avoid premature debonding (*3*). Then, a measured amount of aggregate, calculated using the McLeod method (*32*) and corresponding to an application rate of 7.11 lb/yd^2 for TDA and 18.72 lb/yd^2 for mineral aggregate, was spread manually on the binder (Figure 2*d*). Finally, the surface is compacted using a 220-lb steel roller for three passes (Figure 2*e*). The specimens were cured at an ambient temperature for over 40 days to eliminate the possible effect of early raveling. Before testing, the specimens were swept with a hand brush to remove loose aggregate particles (Figure 2*f*).

Macrotexture Loss Comparison

This study used a non-contact handheld 3-D scanner, with a vertical accuracy of 0.04 to 0.1 mm and a resolution of 0.2 mm, to digitize the surface and determine the macrotexture of the specimens. This technique provides a comprehensive measurement of the macrotexture as it considers the texture of the entire wheel path (*25*) and yields a more accurate measurement compared with other conventional techniques such as sand patch (*33*, *34*). Furthermore, the sand patch method (*31*) was not feasible in this study because of the limited width of the wheel path, and using sand or glass particles would have contaminated the surface and made further testing impossible.

The digitized surface was processed using the Digital Surf's MountainsMap® software (*35*). The volumetric technique proposed by Pourhassan et al. (*25*) was applied to measure the macrotexture. The technique is based on the ISO 25178 (*36*) Abbott-Firestone volume of core material with bearing ratio thresholds of $p = 0$ and $q = 100$, indicated as $V_{mc(0-100)}$ in the original study (*25*) and referred to as volumetric macrotexture (V_m) in this study. V_m has been shown to provide accurate predictions of mean texture depth (MTD) with a significant correlation ($R^2 = 0.97$), high repeatability ($R^2 = 0.98$), and a very high prediction confidence level (*25*).

The calculation of V_m loss enables a fair comparison of the specimens considering that their initial macrotexture may vary given the random orientation of aggregates during sample preparation. The V_m loss was calculated by dividing the final V_m value of a specimen, obtained after 100,000 wheel applications, by its initial V_m value. The resulting value of loss in macrotexture on the wheel path provides a means to evaluate the performance of the different specimens.

Figure 2. Specimen preparation procedure: (*a*) plywood base; (*b*) plywood covered with asphalt felt; (*c*) pouring and spreading the binder; (*d*) spreading the aggregate; (e) compaction; and (*f*) hand brushing before testing.

Statistical Analysis (t-Test)

The t-test is a statistical hypothesis test that compares the means of two groups to determine if there is a significant difference between them. In this study, a t-test was conducted to compare the results from Phase I (control phase) with Phases II and III. The aim was to assess whether the increase in load and speed had a statistically significant effect on the texture loss of conventional and TDA chip seals.

The results of the t-test provided a measure of the difference between the means of the two groups in the number of standard deviations, allowing for an assessment of the likelihood that the difference was a result of random variation in the data. The results of the t-test gave important insights into the differences between the control phase and the phases with increased load and speed, helping to answer the research questions posed in the study.

It is important to note that only the specimens with 0% TDA (conventional chip seal) and 100% TDA were tested with multiple specimens in each phase. Therefore, only these specimens were compared using the t-test.

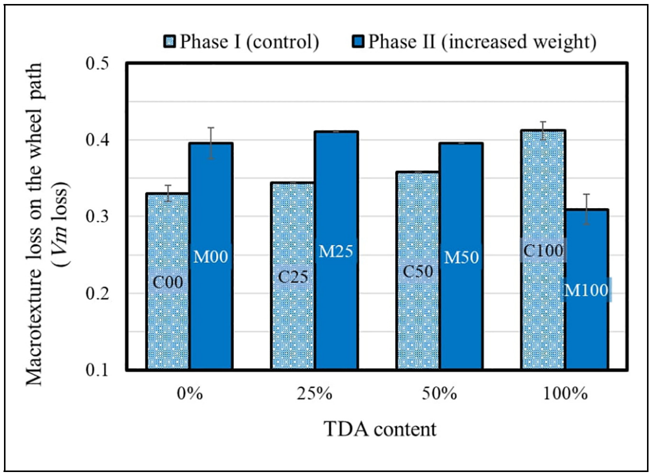

Figure 3. Macrotexture loss for chip seal specimens under different load magnitudes at the end of testing (error bars indicate standard deviation of multiple measurements).
Note: TDA = tire derived aggregate.

Results and Discussion

The results from Phases II and III were compared first with those from Phase I to evaluate the effect of traffic load magnitude and speed on the raveling performance of chip seals constructed with mineral and TDA. Then, the significance of the effect of traffic load parameters on raveling performance was statistically analyzed and presented. It is noteworthy that a thorough performance assessment of Phase I specimens and a comparison to field results was previously reported in (*3*).

Effect of Traffic Load Magnitude

Figure 3 compares the macrotexture loss between Phase II and Phase I corresponding test specimens. With an increase in the load magnitude, the V_m loss for specimens with 0%, 25%, and 50% TDA content increased by 21%, 21%, and 11%, respectively. This indicates that while increasing the TDA content in Phase I specimens led to a slight increase in the macrotexture loss, specimens in Phase II having TDA content up to 50% displayed approximately the same macrotexture loss. In contrast, for the chip seal with 100% TDA, the V_m loss was reduced by 24% with an increase in the load magnitude. Furthermore, comparing the texture loss of M100 and M00 indicates a 23% decrease in macrotexture loss. These results showed that replacing mineral aggregate with TDA has improved the raveling resistance of the test samples under increased load.

For better visualization of the surface texture of the test specimens, Figure 4 shows both a picture and a topographic pseudo-color image for the test specimens. The dark blue color in the figures represents the points with the lowest elevation (no aggregate), and the red spots represent the highest elevation points on each surface. The wheel path is also outlined on the topographic surfaces. The M100 wheel path has very limited areas with dark blue color, indicating that the surface is covered by TDA and is still serviceable after the test, in contrast to conventional chip seal that experienced severe aggregate dislodging.

To investigate the difference in behavior between TDA and conventional chip seals under increased load magnitude, the trend of macrotexture loss was closely examined (Figure 5). The most extreme cases, with 0% TDA (conventional chip seal) and 100% TDA in both Phase I and II tests, were considered. Chip seal specimens constructed out of mineral aggregate only (M00) experienced more texture loss throughout the test compared with C00. Up to 40,000 wheel applications, M00 experienced 25% more texture loss compared with C00, and beyond that M00 experienced 20% more texture loss compared with C00. The higher load imposed by the tires of the SWTS increased the force transmitted to the aggregate-binder bond causing more failures during testing.

The trend is different for TDA chip seal (Figure 5). C100 experienced 11% more texture loss compared with M100 up to 40,000 wheel applications. Beyond that, M100 showed minimal texture loss with the graph almost plateauing, whereas C100 continued to lose texture, resulting in an increasing V_m loss trend with C100 experiencing 33% more texture loss compared with M100. A closer examination of the M100 and C100 macrotextures at 40,000 wheel applications reveals that V_m loss of 0.22 for M100 was a result of increased compaction of the surface under higher loads and not loss of TDA. Figure 6 indicates that the area without aggregate in C100 was 10.2% of the wheel path area, whereas for M100, it was only 8.4%.

These observations suggest that an increase in load magnitude improves the resistance to raveling for TDA chip seal. This can be attributed to the viscoelastic nature of TDA (*37–39*), which undergoes larger deformations with a significantly small Young's modulus and can dampen excess load. Conversely, hard materials like mineral aggregates, with a much higher Young's modulus than TDA, mainly exhibit plastic behavior and have limited hysteresis, resulting in a higher transfer of excess load to their bond with the binder. This ultimately leads to dislodgement of aggregates and increased raveling.

In conclusion, replacing mineral aggregate with TDA can be an effective solution to address the issue of raveling under high-magnitude traffic loads. This effect is more pronounced in chip seal with 100% TDA, as in the case of 25% and 50% TDA content, there is still a substantial amount of mineral aggregate with high stiffness that will take the excess load and cause raveling.

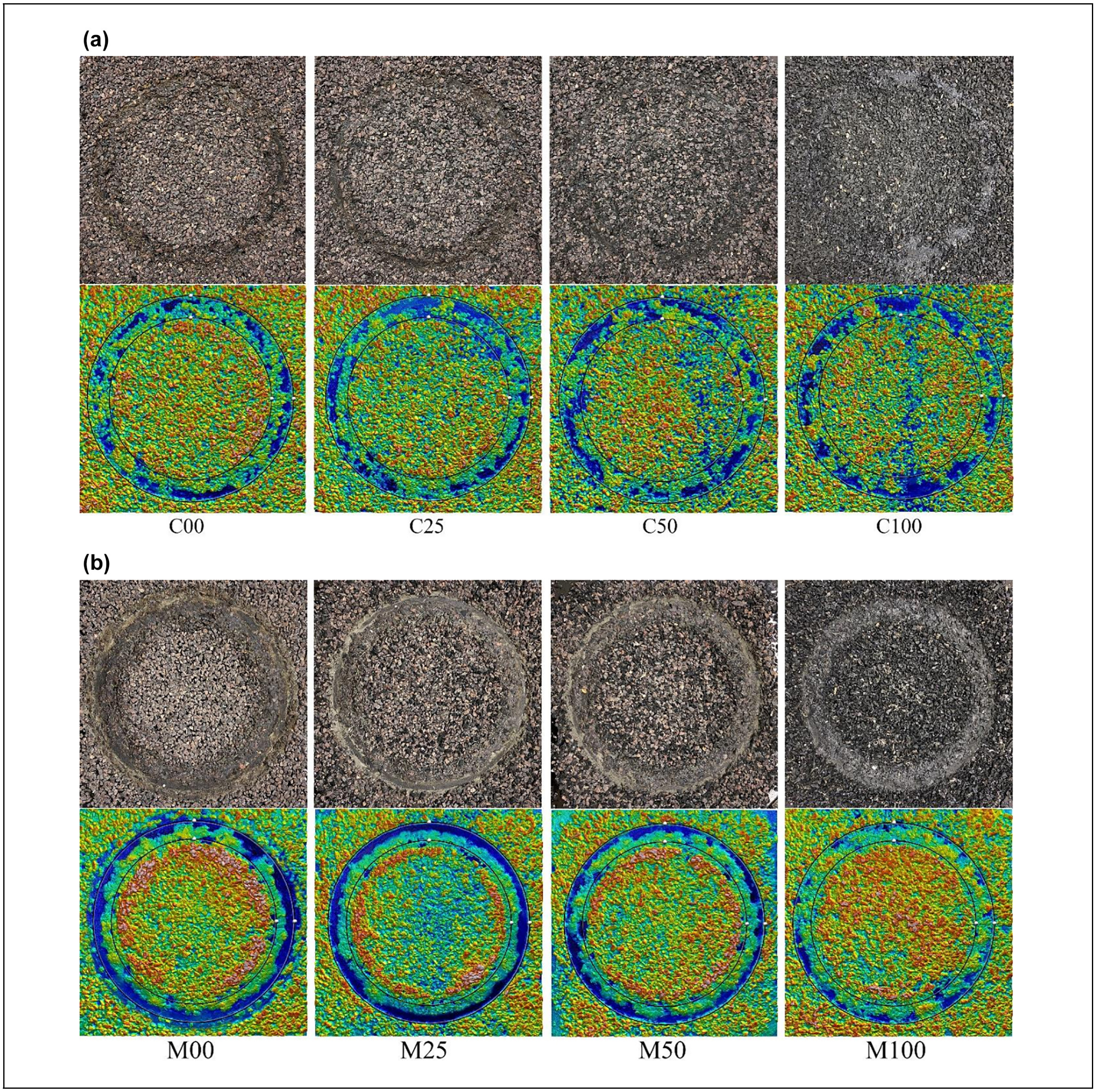

Figure 4. Pictures and topographic surface images showing the specimens after testing: (*a*) Phase I (control); and (*b*) Phase II (increased weight).

Effect of Traffic Speed

Figure 7 compares the macrotexture loss for specimens in Phase I and Phase III. With an increase in the TDA content, the macrotexture loss in Phase III specimens followed a completely opposite trend compared with Phase I specimens. Increasing the loading speed slightly affected the texture loss of chip seal made with 100% mineral aggregate, where the V_m loss increased by 9%. However, with increasing speed, the V_m loss for specimens with 25%, 50%, and 100% TDA content decreased by 9%, 33%, and 61%, respectively. Furthermore, comparing the texture loss of S100 and S00 indicates a 56% decrease in macrotexture loss. These results showed that under higher speeds, increasing the TDA content significantly improves the raveling resistance of chip seal.

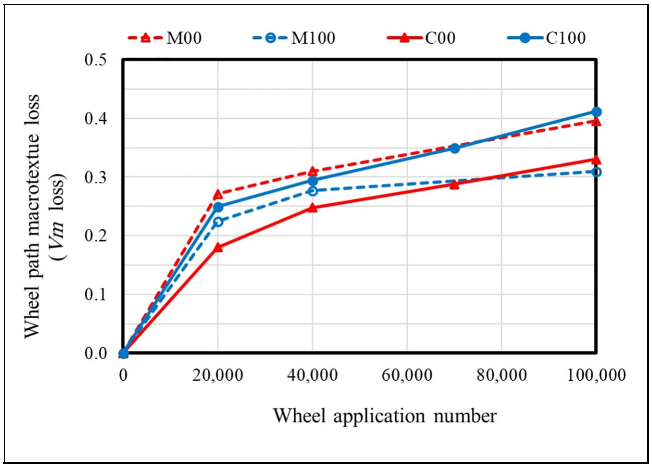

Figure 5. Volumetric macrotexture loss (V_m loss) versus wheel application number for 0% TDA and 100% TDA chip seal under control and increased load.
Note: TDA = tire-derived aggregate.

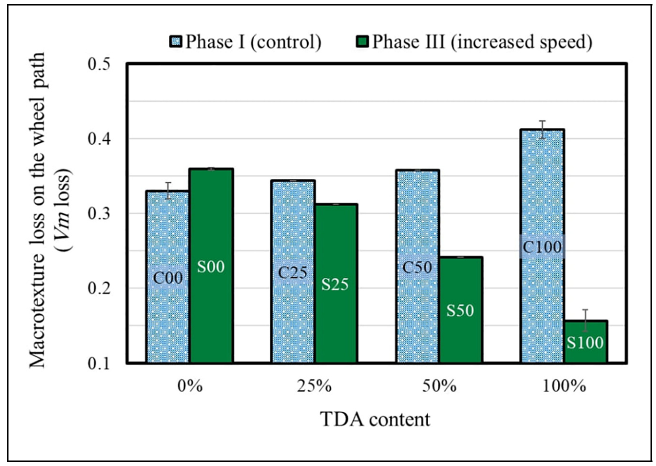

Figure 7. Macrotexture loss for chip seal specimens under different loading speeds at the end of testing (error bars indicate standard deviation of multiple measurements).
Note: TDA = tire derived aggregate.

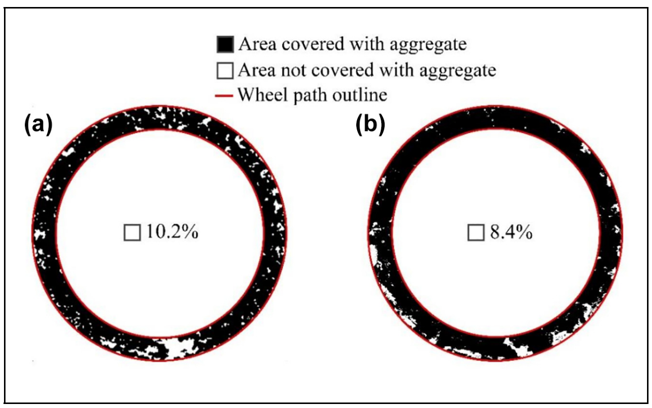

Figure 6. Areas that are not covered with aggregate (shown in white) after 40,000 wheel applications in the small-wheel traffic simulation (SWTS) test for: (*a*) C100; and (*b*) M100.

The surface condition of the Phase III test specimens at the end of the SWTS test is shown in Figure 8. By comparing Figure 8 to the Phase I specimens shown in Figure 4*a*, a significant difference in the surface condition of the Phase III TDA chip seal specimens can be observed. Considerably fewer spots with no aggregate remaining on the surface, indicated by dark blue color, can be seen on the wheel paths of S100, S50, and S25 compared with their corresponding specimens in Phase I, that is, C100, C50, and C25, respectively. Furthermore, spots with no aggregate are very limited on the wheel paths of S100 and S50 compared with other specimens. Both S100 and S50 were still covered with aggregate and were in very good condition with high macrotexture. In conclusion, the results from the Phase III test showed that using TDA in chip seal can significantly improve its resistance to raveling under high traffic speeds. This is likely a result of the dynamic properties of rubber particles (TDA), which have a force transmissibility smaller than 1.0, making them well-suited for use as shock absorbers (*37*). Force transmissibility is defined as the ratio of the magnitude of the force transmitted through the system to the support, and the applied force (*40*). In the context of this study, it refers to the magnitude of the force transmitted to the bond between the aggregate and binder, divided by the force imposed by the vehicle's wheels onto the surface of the aggregate.

As a viscoelastic material, the force transmissibility of rubber is dependent on the loading speed and frequency (*41–43*). Increasing the loading frequency (or travel speed in our study) beyond a certain speed decreases the dynamic modulus of rubber leading to lower transmissibility factor, reflecting increased resistance to molecular motion at high rates (*37*). Therefore, in general, as the loading frequency or rate increases, the force transmissibility in rubber decreases as a result of its time-dependent behavior and inherent damping properties (*30*, *42–44*). With a given applied force, a smaller transmissibility results in a smaller load transmitted to the aggregate-binder bond, leading to less bond failure and higher raveling resistance for the TDA chip seal. In contrast, rigid materials like mineral aggregate do not exhibit this behavior. It has been proven that for rocks, the effect of loading frequency on their properties is small compared with the load magnitude (*45–47*), as confirmed by the results obtained in Phase II (Figure 3). This also explains the slight increase in raveling of conventional chip seal when the loading frequency was increased in Phase III. Therefore, replacing mineral aggregate with TDA can be a solution to address raveling distress under high traffic speed.

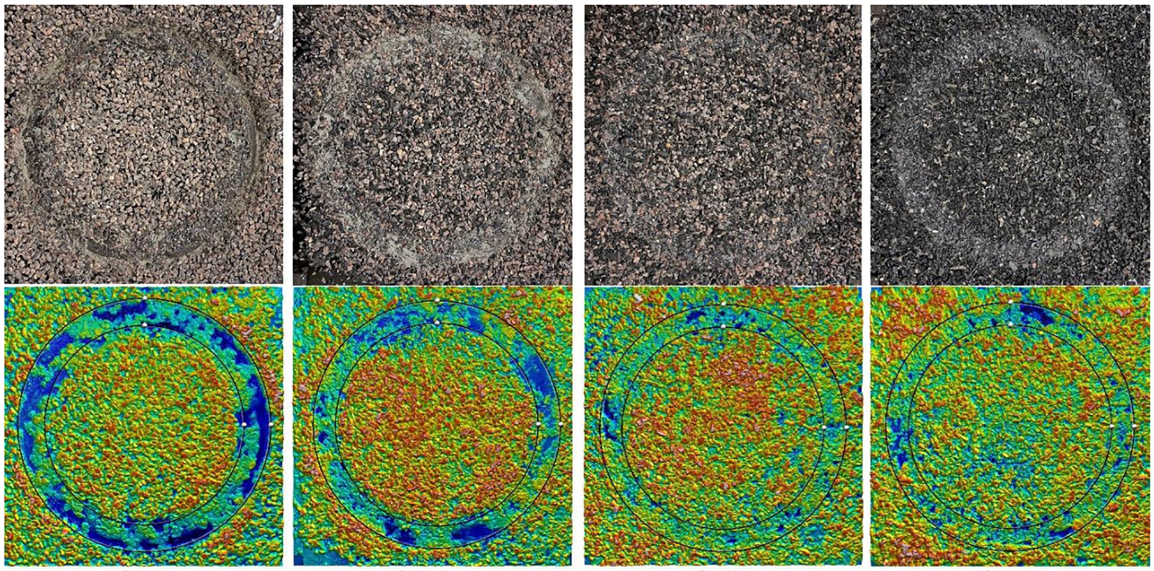

Figure 8. Pictures and topographic surface images showing the specimens after testing in Phase III (increased speed).

t-Test Results

The comparisons between Phase I and Phase II and between Phase I and Phase III were conducted to determine the effect of increased load and speed on the texture loss of both conventional and TDA chip seals. The results from the t-tests showed a statistically significant difference in the texture loss between samples with 0% and 100% TDA when the load and speed were increased with a p-value of 0.044 for 0% TDA samples and 0.025 for 100% TDA samples in the comparison of Phase I with Phase II as well as a p-value of 0.003 for 100% TDA samples and 0.098 for 0% TDA samples. The lower p-values for the 100% TDA samples compared with the 0% TDA samples indicates a more pronounced impact of both increased speed and load on the texture loss of TDA chip seal compared with conventional chip seal. Additionally, comparing the p-values for the 100% TDA chip seal in Phase II and Phase III reveals that the effect of increased speed was more significant than the effect of increased load. These findings are important for the design and maintenance of chip seal roadways as they emphasize the significance of considering the influence of loading and speed conditions on road surface performance.

Conclusions

This research used a small-wheel traffic simulation device (SWTS) to investigate the effect of traffic-related parameters, namely, vehicle speed and load magnitude on the raveling of chip seal. The specimens were constructed out of mineral aggregate, TDA, as well as a hybrid 25% to 50% TDA and mineral aggregates. It was concluded that replacing mineral aggregate with TDA can enhance the raveling resistance of chip seal under both heavier and faster traffic loads. The specific findings were as follows:

- Under increased load, using TDA significantly improved the raveling resistance of the chip seal. Chip seal made entirely of TDA experienced 23% less macrotexture loss compared with conventional chip seal, given the viscoelastic properties of TDA that allow it to undergo larger deformations and damp excess loads. In addition, the surface of TDA chip seal was deemed serviceable after the test, unlike the conventional chip seal, which experienced severe aggregate dislodgement.
- As the load magnitude increased, the raveling resistance of conventional chip seal (made from mineral aggregate) was impaired. A 21% increase in the macrotexture loss was experienced when the imposed load was doubled, as the larger imposed load from tires transmitted a larger load to the aggregate-binder bond through the rigid mineral aggregates, causing more failures.
- Under increased speed, using TDA significantly improved the raveling resistance of the chip seal. Chip seal made with TDA experienced 56% less macrotexture loss and negligible aggregate

dislodgement compared with conventional chip seal, given the dynamic properties of TDA, which exhibit lower load transmissibility under higher load frequencies, leading to less bond failure with increased speed.

- As the loading speed increased, the raveling resistance of chip seal made from mineral aggregate was slightly impaired. Only a 9% increase in macrotexture loss was experienced when the loading rate was increased by 50%, as the effect of loading frequency on rock properties is small compared with the effect of load magnitude.
- The results of the t-tests statistical analysis indicated that increased load and speed have a significant impact on the texture loss of both conventional and TDA chip seals. The results suggest that TDA chip seals are more affected by the increased speed and load compared with conventional chip seals, with the effect of increased speed being more pronounced than the effect of increased load.

In conclusion, this paper provides new insights into the performance of conventional and TDA chip seal under different traffic characteristics. Nevertheless, it is crucial to factor in the dynamic response of the underlying surfaces, such as hot mixed asphalt or previous chip seal layers, in future assessments to have a more thorough understanding of chip seal performance. Further investigation in this area is still required as some of the presented results and conclusions are based on relatively small numbers of samples.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: A. Pourhassan, A.A. Gheni, M.A. ElGawady; data collection: A. Pourhassan; analysis and interpretation of results: A. Pourhassan, M.A. ElGawady; draft manuscript preparation: A. Pourhassan, A.A. Gheni, M.A. ElGawady. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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