PERFORMANCE MONITORING OF PRESERVATION TREATMENTS IN HONOLULU

FINAL PROJECT REPORT

by

Adrián Ricardo Archilla
University of Hawaii at Manoa

Sponsorship
CHPP and University of Hawaii at Manoa

for

Center for Highway Pavement Preservation
(CHPP)

In cooperation with US Department of Transportation-Research and Innovative Technology Administration (RITA)

May 2019

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Technical Report Documentation Page			
1. Report No. CHPP Report-UH#1-2019	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle PERFORMANCE MONITORING OF PRESERVATION TREATMENTS IN HONOLULU		5. Report Date 05/29/2019	
		6. Performing Organization Code	
7. Author(s) Adrian Ricardo Archilla		8. Performing Organization Report No.	
9. Performing Organization Name and Address CHPP Center for Highway Pavement Preservation, Tier 1 University Transportation Center Michigan State University, 2857 Jolly Road, Okemos, MI 48864		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No.	
12. Sponsoring Organization Name and Address United States of America Department of Transportation Research and Innovative Technology Administration		13. Type of Report and Period Covered	
		14. Sponsoring Agency Code	
15. Supplementary Notes Report uploaded at http://www.chpp.egr.msu.edu/			
16. Abstract This study monitored the performance of pavement preservation (PP) treatments available in Hawaii. Several PP treatments were applied on a sample of sections. The treatments were monitored by observing their application and following the cracking progression and observing other issues such as wearing off the surface and aggregate loss. Two other efforts of this study included: 1) the measurement of temperatures with depth over time on a setup simulating a pavement structure, and 2) the development of an asphalt concrete specimen configuration for uniaxial fatigue testing that minimizes end breaks. Crack sealing was found to reduce the rate of cracking progression in straight sections. The results in cul-de-sacs were less conclusive but still consistent with a slight reduction. Sealants in routed cracks or in cracks wider than 10-mm (3/8 inch) were still effectively sealing cracks after 4.5 years. For thin cracks, the sealing was much less effective. All the seal coats evaluated, and the slurry seals were very effective at arresting the occurrence of raveling, but the durability of the seal coats varied. The cracking progression rates in all the sections treated with seal coats were higher than the rate on the corresponding control sections. The cracking progression rates in the two sections treated with a fog seal/rejuvenator were the lowest. The PP treatments studied could not prevent additional environmental cracking, but they can alter the progression rate. Significant aggregate loss was observed on some of the slurry seals. Pavement temperature profiles leading to high tensile and shear strain levels near the surface can easily occur on about 15% of the time and passing rains can cause sudden temperature drops of the order of 15ºC within short periods (15-min); because of these events occur frequently they may contribute to more cracking. The developed dog-bone shape configuration was effective at inducing mid-specimen breaks and avoiding undesirable strains concentrations. Several recommendations are provided for the programming of PP treatments in Hawaii and further research.			
17. Key Words		18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages 288	22. Price NA

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CHPP: Center of Highway Pavement Preservation
C&CH: City and County of Honolulu
HAPI: Hawaii Asphalt Paving Industry
HDOT: Hawaii Department of Transportation
MDOT: Michigan Department of Transportation

Acknowledgments

The author like would to thank the City and County of Honolulu and the Hawaii Asphalt Paving Industry (HAPI) for the invaluable help with this project. I would also like to thank Jon Young from HAPI and Kyle Oyasato from the City and County of Honolulu for helping with the coordination with the contractors, city permits, coordination with refuse trucks and the bus. Special thanks also go to Ross Sassamura for supporting this effort. I would also like to thank Alakona Corp., Crafco, Inc., Goldwings Supply Service, Inc., GP Roadway Solutions, Oahu Sealcoating and Paving LLC, and SealMaster Hawaii, and the large list of individuals from these companies that made this effort possible.

Executive Summary

This study monitored the performance of preservation treatments available in Hawaii to quantify their benefits and facilitate their adoption and use in pavement preservation programs. For this purpose, several preservation treatments were applied on a sample of sections to monitor their performance. The treatments included crack sealing, a fog seal, different proprietary seal coats (as used in Hawaii, which is a mix of emulsion with sand), and slurry seal.

The treatments were monitored by observing their application and following the cracking progression of the treated section and untreated control sections over time and observing any other issues such as wearing off the surface, delamination, and aggregate loss. Cracking lengths and other issues were monitored for about three years, but another visual inspection was performed after 4.5 years.

In addition, two other efforts of this study included: 1) the measurement of pavement temperatures with depth over time using a test configuration aimed at simulating a thick pavement, and 2) the development of an asphalt concrete specimen configuration for uniaxial fatigue testing that avoids or minimizes end breaks. Both efforts were directed at addressing the common occurrence of the top-down fatigue cracking in Hawaii. The following text lists the main findings within each of the three main areas studied.

Pavement Preservation Treatment Performance:

- In straight sections, crack sealing was found to reduce the rate of cracking progression with respect to the untreated control section even when the cracking was clearly mostly environmentally induced. The results in cul-de-sacs were less conclusive because of factors that could not be controlled but they were still consistent with a slight reduction in the rate of the cracking progression.
- In general, the sealants in routed cracks or in cracks wider than about 10 mm (3/8) were effectively sealing the cracks after 4.5 years.
- For thinner cracks, the performance ranged from providing mostly a short-lived temporary bridge that was quickly broken because of the high strains created by the crack movement, to cracks where the sealant and the crack wall separated on one side.
- All the seal coats evaluated, and the slurry seals were very effective at arresting the occurrence of raveling, but the durability of the seal coats varied.
- The cracking progression rates in all the sections treated with seal coats were higher than the rate on the corresponding control sections. This happened for both, straight sections and sections in cul-de-sacs. This was a surprising result that deserves further study.
- The cracking progression rates in the two sections treated with a fog seal/rejuvenator were lower than the rates on the corresponding untreated control sections.
- None of the preservation treatments studied could prevent the additional environmental cracking that would eventually had occur without the treatment. The fog seal is the only treatment that decreased the cracking progression rate. The results for the slurry seals did not appear alter it much but the seal coats appear to consistently increase it.
- Significant aggregate loss was observed on some of the slurry seals.

Measurements of pavement temperatures:

- The measured pavement temperatures near the surface were rarely below 20ºC (68ºF), so given the relatively uniform temperatures in Hawaii (within most locations of interest for pavement performance), top-down fatigue cracking must necessarily be occuring at higher temperatures.
- Pavement temperature profiles leading to inverted moduli profiles that create high tensile and shear strain levels near the surface occur often. The results depend on frequency of loading and binder aging, but they can easily occur on about 15% of the time.
- Passing raines can cause sudden temperature drops of the order of 15ºC within short periods (15-min). For Hawaii, this happens quite often.

Uniaxial fatigue cracking test configuration (dog-bone shape) to avoid end breaks

- The dog-bone shape configuration, combined with epoxy smoothing and the use of aluminum foil shims to reduce the effects of load eccentricity, was effective at inducing mid-specimen breaks and avoiding undesirable strains concentrations.

The following are the main recommendations of the study:

Conservative lives for programming pavement preservation work on low volume city streets are:

- Standard seal coats with 2 lb. of sand: 4 years,
- Liquid Road (proprietary seal coat with 4 lb. of sand): 5 years,
- Slurry Seal: 6 years.

An interval ranging from 2 to 3 years is also recommended to revisit sections that were previously crack sealed to seal new cracks and resealed any previously sealed cracks that have reopened. This recommendation includes sections previously treated with seal coats, since in this study they were found to crack at a faster rate than the untreated control sections.

The application of a seal coat shortly after the application of the slurry seal should be considered as an alternative to minimize the loss of aggregate in slurry seals.

Pavement design should be considered an important component of an effective pavement preservation program. Thus, pavement thicknesses of reconstructed pavement sections should be looked at carefully to avoid failures where PP can be of limited help.

Further laboratory research should be conducted to understand the increase in the cracking progression rates observed with the application of seal coats.

The study of the consequences of inverted moduli profiles from high pavement temperatures at the pavement surface should be continued and validated with field experiments, including the performance of tack coats under these conditions.

In uniaxial fatigue cracking studies with the AMPT, other test configurations to overcome end breaks should be studied to reduce the problems with load eccentricity, to reduce specimen preparation times, and to be able test field specimens. Some advances have already been made in this area, but they still need improvement.

1 INTRODUCTION

1.1 INTRODUCTION

As indicated in the Transportation System Preservation (TSP) Research, Development, and Implementation Roadmap (2008) (*1*), one of the primary obstacles to the acceptance of pavement preservation (PP) by departments of transportation (DOT) is the general lack of knowledge as to its quantifiable benefits. This was indeed a relevant issue for the City & County of Honolulu (C&CH), whose pavement preservation program and pavement management system (PMS) were in their infancy at the start of this project and are still evolving. One of the challenges for PP acceptance is the quantification of the benefits in terms of life cycle costs, which requires proper consideration of PP performance and costs (including potential rehabilitation costs after several PP cycles), and rehabilitation or reconstruction costs for non-PP control sections and the shorter performance periods between them. Another concern is that condition surveys are often performed every 2, 3, or more years (or equivalently 1/2, 1/3, or less of the network is surveyed every year) due their high cost. This coarseness in the data makes it difficult to observe in detail the performance of some preservation treatments which may be limited to a relatively small number of years and the additional deterioration that would occur on sections without PP.

Although preservation treatments are intended to address non-load associated distresses, they may still be affected by debonding and cracking under some conditions. For high temperature environments, high temperature gradients near the surface of the pavement may induce high tensile and shear strains that may affect bonding and cracking of some treatments such as thin lift overlays (TLO).

Most agency guidelines provide estimates of the life of a given treatment and specify threshold traffic levels appropriate for their use, but it appears that the life estimates are based mostly on anecdotal evidence.

This project monitored the performance of control sections and sections with different PP treatments subjected to similar traffic levels and environmental conditions for a period of about three years (though visual observations were extended to more than four years). In addition, an experimental set up was developed to measure temperature with depth in Hot Mix Asphalt (HMA) exposed to normal environmental conditions in the state to study in the future the effect of high temperature gradients on asphalt concrete pavements and their potential effects on preservation treatments' performance. Finally, in pursuing testing for a Thin Lift Overlay (TLO) mix design with local aggregates and polymer modified binder available in Hawaii, issues were encountered when trying to evaluate its fatigue cracking performance using uniaxial fatigue testing. As a result, a new test was developed to overcome end failures in uniaxial fatigue testing at high temperatures relevant to Hawaii.

1.2 BACKGROUND

1.2.1 Pavement Preservation in Hawaii

Pavement preservation in Hawaii is in its infancy. Only some preservation treatments were being used at the start of this study and there was little information about their performance and quantification of its benefits. For this study, the University of Hawaii (UH) partnered with the City and County of Honolulu (C&CH) in the Island of Oahu, Hawaii, which has a road network with more than 3,500 lane-miles, and with the Hawaii Asphalt Pavement Industry (HAPI) and its members to apply preservation treatments on a sample of sections to monitor their performance in Honolulu.

HAPI facilitated the communication between contractors that participated in the study and the C&CH. Test and control sections were selected in collaboration with the C&CH and with HAPI. The application of PP treatments was also coordinated between UH, C&CH, and HAPI. The treatments included crack seal, fog seal, other seal coating systems offered locally, and slurry seals. Although there was a desired by the research team to monitor also the performance of thin lift overlay (TLO) mixes, several considerations precluded their consideration in this study, including their higher construction costs (the materials and labor for all the treatments were donated by the contractors that participated in the study and traffic control was provided by the C&CH), lack of an adequately researched TLO mix with local mix components, and their applicability to the relatively thin sections targeted by the C&CH.

Based on the discussions with C&CH and HAPI, the project scope included two sets of sections: a set of cul-de-sac sections and a set of sections on continuous stretches of road. For each set, sections with similar thickness (approximately 3 inches) of Hot Mix Asphalt (HMA), including control sections, were selected such that they were subjected to similar environmental conditions and traffic loading. The sections in cul-de-sacs were selected with the purpose of observing the performance of PP treatments under the high shear stresses caused by turning movements (mostly of refuse trucks.)

The pavement sections selected for this study were visually inspected (walking surveys) at short intervals during the study period to determine the treatment performance and the additional progression of deterioration on the control sections.

1.2.2 High Pavement Temperature Gradients

In general, pavement performance is significantly affected by local environmental conditions. Although for tropical climates (wet non-freeze) the temperature changes are substantially more moderate than for other climates, the environmental effects can still be substantial.

Consequently, an experimental set up was developed to measure temperature with depth in Hot Mix Asphalt (HMA) exposed to normal environmental conditions in the state with the purpose to help in the future study of the effect of high pavement temperature gradients on asphalt concrete pavements and their potential effects on preservation treatments' performance.

1.2.3 Thin Lift Overlay Mixes

As indicated above, it was not possible to include sections treated with TLO mixes in the field study. Nonetheless, it was desirable to study their applicability to Hawaii using local aggregates and polymer modified binder. Thus, an initial part of the effort of the study were directed towards designing a TLO mix and testing it for performance, with attention to high temperature conditions.

However, complications with uniaxial fatigue testing of the TLO mix with the Asphalt Mixture Performance Tester turned what was supposed to be routine performance testing into a full study of how to avoid end breaks on cylindrical specimens. This report documents the fabrication of dog-bone shape specimens that avoid end breaks even with expected variations of air voids (typically higher near the ends) and performed at higher than usual temperatures (40°C). The higher testing temperature tends to exacerbate the strain concentration problem that causes the end breaks.

2 LITERATURE REVIEW

2.1 INTRODUCTION

Today's economic environment requires that pavement networks be managed as opposed to be simply patched or reconstructed. As pointed out by Shahin (*2*), in the past, "the pavement's engineer experience tended to dictate the selection of Maintenance and Repair (M&R) techniques with little regard to life cycle costing nor to priority as compared to other pavement requirements in the network." It is important to consider the situation of every pavement section and allocate resources so that the whole network is maintained at the best possible condition level with a given level of funding or conversely, that a given average condition level is maintained with the lowest possible budget. These types of decisions are better made with the use of Pavement Management System (PMS) Software that can help identify appropriate courses of action. A Pavement Management System (PMS) consists of a set of procedures that assist in optimizing strategies for providing and maintaining pavements in a serviceable condition over a given period of time. It helps decision-makers to make efficient allocation of resources. At one level, it can be used for requesting/justifying an appropriate level of funding to maintain a pavement network. But it can also help identify the efficient allocation of resources to different M&R strategies. For example, there is ample evidence that the "worst first strategy", which has been commonly applied, is not the best one to follow.

Both, the City and County of Honolulu (C&CH) and the Hawaii Department of Transportation (HDOT) are currently undertaking efforts to enhance their pavement management practices to manage their respective networks: about 3,600 lane-miles of highways and streets for the C&CH and more than 2500 lane-miles for HDOT. In general, the implementation of a PMS requires several efforts including population of databases/GIS to manage the information (inventory, pavement condition, costs, guidelines, etc.), selection of cost-effective maintenance and rehabilitation (M&R) strategies and determination of associated costs, development of pavement deterioration models, development of M&R guidelines, establishment of communication protocols between those involved in PMS activities, etc.

As in many other agencies, traditionally, the major share of the pavement related expenditures has been focused on new construction and reconstruction and major M&R. However, there was a need to change the focus towards increasing the share of the budget allocated to *pavement preservation* to make a more efficient use of the available funding. Pavement preservation is a program of activities aimed at preserving the significant investment on the highway system. It requires that additional emphasis be placed on preventive maintenance to preserve and prolong the life of the system that has evolved over decades.

This chapter describes M&R practices on flexible pavements with a major emphasis on preventive/preservation maintenance activities, which as indicated before are a key component of cost-effective M&R strategies.

2.2 MAINTENANCE AND REHABILITATION CATEGORIES

There is an abundance of terms used in the pavement literature referring to pavement maintenance and rehabilitation (M&R). The following are relatively common terms used in the pavement management literature. The terms are not always mutually exclusive. Thus, some treatments may fall under more than one of the categories described below.

The following paragraphs discuss the terms pavement preservation, pavement rehabilitation and pavement reconstruction typically used for pavement management.

2.2.1 Pavement Preservation

As defined by the Federal Highway Administration's (FHWA) Pavement Preservation Expert Task Group (https://www.fhwa.dot.gov/preservation/memos/160225.cfm, last accessed May 2019): "Preservation consists of work that is planned and performed to improve or sustain the condition of the transportation facility in a state of good repair. Preservation activities generally do not add capacity or structural value but do restore the overall condition of the transportation facility." Since the above definition is not very specific about what it involves, pavement preservation can also be thought of as the sum of all activities undertaken to provide and maintain serviceable roadways, including *preventive maintenance (defined below) together with some corrective maintenance as well as minor rehabilitation projects*. According to this second description, pavement preservation is a more general term than preventive maintenance and can include limited corrective maintenance. This is convenient since it is often the case that some localized distress needs to be corrected before application of what is typically understood as a preservation treatment, which are preventive maintenance treatments intended to maintain roads in good condition but that do not add any structural capacity to the existing pavement.

2.2.2 Pavement Maintenance

In terms of maintenance, the FHWA Pavement Preservation Expert Task Group provides the following definition: "Maintenance describes work that is performed to maintain the condition of the transportation system or to respond to specific conditions or events that restore the highway system to a functional state of operation." Maintenance is a critical component of an agency asset management plan that is comprised of both routine and preventive maintenance. Pavement maintenance activities are key to pavement preservation. As indicated before, an effective pavement preservation program integrates many maintenance strategies and treatments. Pavement maintenance is described by others as doing inexpensive repairs on good roads to keep them good (*3*). According to the Asphalt Handbook (*4*), there are three categories of pavement maintenance, namely, preventive maintenance, corrective maintenance, and emergency maintenance. These are defined as:

Preventive maintenance activities are those performed with the primary objective of preserving the existing pavement and extending the life of the pavement by slowing its rate of deterioration and maintain or improve the functional condition. It is a strategy of surface treatments and operations intended to retard progressive failures. It is important to note that preventive maintenance activities are not intended to increase structural capacity. Preventive maintenance includes crack sealing, surface treatments, thin overlays, drainage maintenance, etc. Surface treatments that are less than two inches in thickness (typically 1.5 inches or less), which are not considered as adding structural capacity, fall under this category.

Corrective maintenance is performed after a deficiency occurs in the pavement, such as loss of friction, moderate to severe rutting, or extensive cracking. This may also be referred to as "reactive" maintenance. An example is a chip seal used to repair a low friction condition or the filling of ruts with slurry seal mix.

Emergency or safety maintenance is a stop-gap measure (also known locally as first-aid) performed shortly after an emergency situation, such as a severe pothole on a high-volume roadway that needs to be repaired immediately mostly for safety reasons and to maintain a road operational. This could also include temporary treatments that hold the surface together until a more permanent treatment can be performed.

2.2.3 Pavement Rehabilitation

Pavement rehabilitation is work undertaken to extend the service life of an existing pavement by enhancing its structural capacity to carry loads. This includes the restoration of the structural capacity, placing of a structural overlay to accommodate projected traffic loading, and/or other work required to return an existing roadway to a condition of structural and functional adequacy.

Note that it is not universally agreed that a rehabilitation treatment must enhance the pavement's structural capacity. For example, the Asphalt Institute (*4*) indicates that rehabilitation can be subdivided into minor and major, where minor rehabilitation treatments include non-structural enhancements such as thin functional overlays. Notice that a thin, non-structural overlay is also considered a preventive maintenance treatment, which explains why this type of overlay can often be regarded as part of either category of treatments. The difference is mostly related to the intent since it is accepted that a thin overlay does not add structural capacity. However, when applied to a pavement in good condition, the purpose is to extend the pavement life whereas when applied to a pavement in less than good condition its purpose is usually to restore the function of the pavement even if that happens for a relatively short time. Herein, thin overlays (with a thickness $\leq$ 1.5 in), will be regarded as preventive maintenance only.

The Asphalt Institute (*4*) indicates that major pavement rehabilitation, such as a thick overlay, adds structural enhancements to a pavement section. According to Galehouse (*5*), most rehabilitation projects are designed to last 10 to 20 years and although less costly than reconstruction, rehabilitation to improve the overall network condition still requires a prohibitive level of investment.

2.2.4 Pavement Reconstruction

Pavement reconstruction consists of construction of the equivalent of a new pavement structure which usually involves complete removal and replacement of the existing structure including new and/or recycled materials. It is typically a long-term action that is designed to last at least 20 years.

2.2.5 Maintenance Boundaries

Today's fiscal concerns are increasingly putting pressure to allocate infrastructure budgets more efficiently. Thus, the historical emphasis of local highway agencies on building new roads has shifted to maintaining and preserving existing pavement surfaces. Consequently, although all types of maintenance are needed in a comprehensive pavement maintenance program, nowadays more emphasis is being put on preventive maintenance activities to minimize the typically costlier corrective maintenance activities (costlier over the life cycle of the pavement). The goal of preventive maintenance is *completing the right repair on the right road at the right time.* Some manuals (*6*) indicate that preventive maintenance is six to ten times more cost-effective than a "do-nothing" maintenance strategy.

A major determinant of the most appropriate maintenance treatment is the current condition of the pavement. As illustrated in Figure 2-1, preventive maintenance is most appropriate for pavements in good condition, corrective maintenance is appropriate for pavements in fair condition, whereas emergency maintenance and rehabilitation are appropriate for pavements in poor condition. As discussed earlier, there are not always clear boundaries between when a treatment is preventive versus corrective, or corrective versus emergency.

The often-cited benefits of pavement preservation include improved customer service, substantial life cycle cost savings, and more stable budgets from year to year (*6*).

Preventive maintenance activities for flexible pavements can include conventional treatments such as crack sealing, chip sealing, fog sealing, rut filling, and thin overlays. They can also include newer technologies such as ultra-thin wearing courses, very thin overlays, and microsurfacing applications. Aside from crack treatments, all these treatments leave the pavement with a new wearing surface. A fog seal provides a new wearing surface, although it will generally provide lower friction than the original surface.

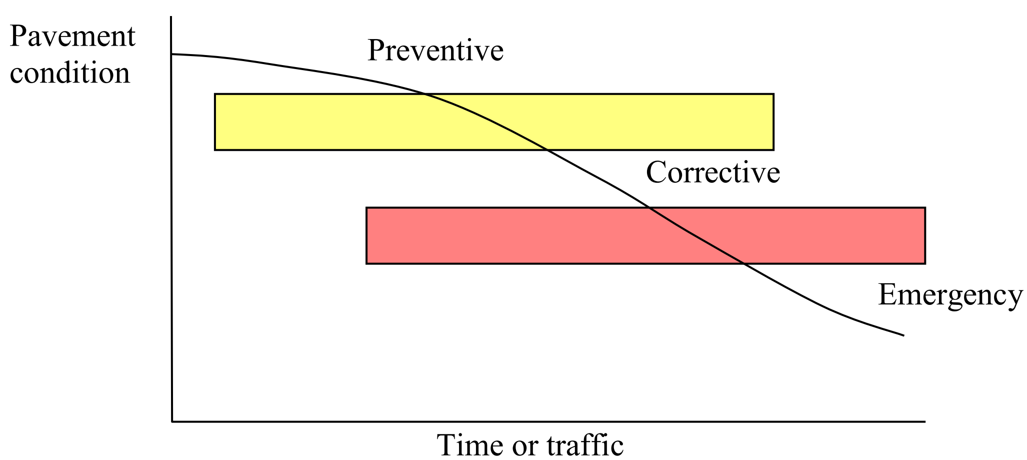


Figure 2-1 Maintenance Categories (source: Johnson 2000, (*6*))

2.3 WAITING UNTIL AFTER A FAILURE OCCURS IS NOT COST-EFFECTIVE

The condition of the pavement is directly related to the effectiveness of a preventive maintenance treatment. A preventive maintenance activity is cost effective for pavements in good condition since a relatively small investment is required to prolong the life of the pavement, although these must be applied at relatively short time intervals. Therefore, preventive maintenance is generally planned and cyclical in nature (*5*). On the other hand, for a pavement in bad condition, application of a preventive maintenance activity results in a waste of resources since it provides a very short-lived benefit relative to the costs. The interesting trade-off to analyze is between a strategy with recurrent preventive maintenance activities and one with longer spaced rehabilitations. As indicated before, it has been widely acknowledged that the former is more cost effective than the latter. This is like changing the oil in a car. One can do it every 3,000 miles (or whatever is appropriate for the car and type of oil) or wait much longer to make them. Although by waiting longer one spends less on oil changes, the car engine will most likely require costly repairs much earlier, resulting in overall higher life-cycle costs.

Figure 2-2 shows the relationship between pavement condition and time (or traffic). Often, preventive maintenance methods are designed to repair damage caused by the environment. Periodic renewal of the pavement surface prevents water from penetrating into the pavement structure by sealing the surface and controls the effects of oxidation, raveling, and surface cracking. Since environmental conditions remain consistent over time, so should the maximum time between preventive maintenance treatments.

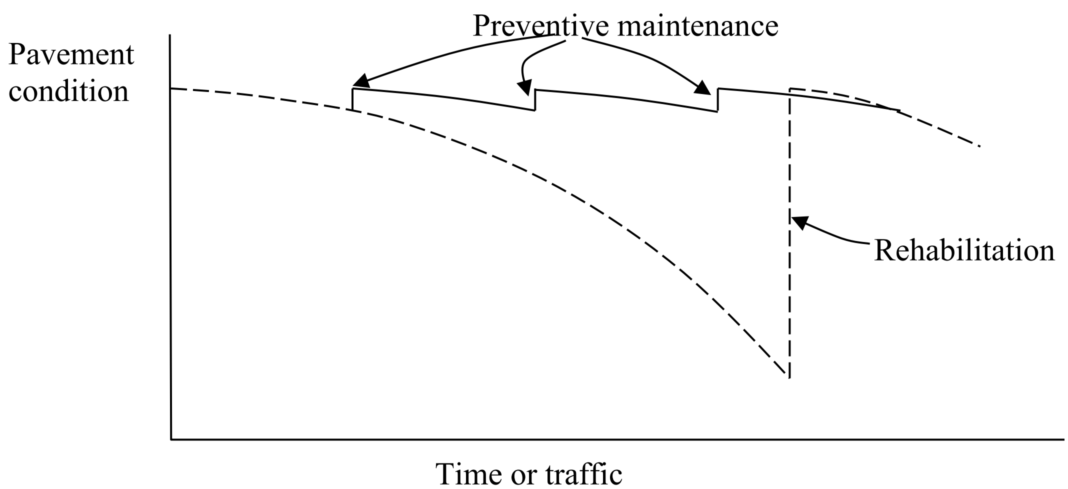


Figure 2-2 Performance of Preventive Maintenance Treatments

In the past, several factors precluded a more intensive use of preventive maintenance activities, including (*6*):

- “Many of the available preventive maintenance treatments were considered unsuitable for high-volume roadways.

- Lack of federal aid for maintenance encouraged agencies to allow pavements to deteriorate sufficiently to qualify for rehabilitation that was funded by federal aid.
- Information was lacking about the performance and cost-effectiveness of preventive maintenance practices.
- Highway agencies wished to minimize driver exposure to roadway operations and lane closures. This prevailing philosophy is reactive rather than proactive or preventive."

It is also more difficult to explain to the public the benefits of treating pavements in good condition when there is a large backlog of pavements in poor condition within the system. There is a tendency to concentrate on the urgent problems (e.g., pothole repair) at the expense of preventive maintenance. Although potholes must be repaired for safety reasons, that should not deter an agency from developing a cost-effective preventive maintenance program that gradually reduces the recurrent appearance of potholes by ensuring that pavements in good condition stay in good condition.

2.4 TYPES OF MAINTENANCE TREATMENTS

There are many different pavement maintenance techniques, including the do-nothing alternative. Since it is convenient to be familiar with the choices available, the list below introduces the different techniques. Most of the following descriptions are adopted with minor modifications from Minnesota (*6*) and Michigan (*7*) manuals.

2.4.1 Crack Sealing

A localized treatment method used to prevent water and debris from entering a crack, which might include routing to clean the entire crack and to create a reservoir to hold the sealant. It is only effective for a few years and must be repeated. However, this treatment is very effective at prolonging the pavement life. It includes the following two crack repair methods:

Clean and seal: Used on all types of cracks, it involves using a hot air lance or compressed air to blow out the debris in the crack, then filling with a sealant.

Rout and seal: Used on transverse and longitudinal cracks. It involves using a pavement saw or router to create a reservoir centered over existing cracks, and then filling with a sealant.

2.4.2 Crack Filling

Crack filling differs from crack sealing mainly in the preparation given to the crack prior to treatment and the type of sealant used. Crack filling is most often reserved for more worn pavements with wider, more random cracking.

2.4.3 Full-Depth Crack Repair

A *localized* treatment method to repair cracks that are too deteriorated to benefit from sealing or filling. Secondary cracking requires the reestablishment of the underlying base materials.

2.4.4 Fog Seal

An application of diluted emulsion (typically at a rate of 1:1) to enrich the pavement surface and delay raveling and oxidation. This is considered a temporary treatment.

2.4.5 Chip Seal/Seal Coat

Chip seals are used to waterproof the surface, seal small cracks, reduce oxidation of the pavement surface, and improve friction. They consist of one or more applications of emulsion and aggregate followed by rolling. The type of Chip Seal (single, double, or triple), and the size of the aggregate used in each pass will determine the overall depth of the seal. The term seal coat is often used as synonym of chip seals. However, in Hawaii, the term Seal Coat has typically been used to refer to a spray application of a mix of asphalt emulsion with 2 lb./gallon of fine sand.

2.4.6 Double Chip Seal

An application of two single chip seals. The second coat is placed immediately after the first. This treatment waterproofs the surface, seals small cracks, reduces oxidation of the pavement surface, and improves friction.

2.4.7 Slurry Seal

A mixture of fine aggregate, asphalt emulsion, water, and mineral filler, used when the primary problem is excessive oxidation and hardening of the existing surface. Slurry seals are used to retard surface raveling, seal minor cracks, and improve surface friction.

2.4.8 Microsurfacing

Microsurfacing is a mix of polymer-modified emulsion, well-graded crushed mineral aggregate, mineral filler (normally Portland cement), water, and chemical additives that control the break time. Microsurfacing differs from slurry seals in that it uses polymer modified asphalt and in that the curing process for microsurfacing is chemically controlled, versus the thermal process used by slurry seals and chip seals. Microsurfacing also may be used to fill ruts (*6*).

2.4.9 Thin Hot-Mix Asphalt (HMA) Overlays

These include dense, open, and gap graded HMA mixes that improve ride quality, reduce oxidation of the pavement surface, provide surface drainage and friction, and correct surface irregularities.

Table 2-1 lists the different maintenance techniques along with reasons for using each one of them. Average treatment life for some of the procedures are also summarized.

Table 2-1 Maintenance techniques for Asphalt Concrete Pavements (adapted from *6*)

Technique	Reasons for Use							Average Treatment Life (years)
					Cracking			
	Friction	Raveling	Rutting	Potholes	Low	Med	High	
Crack treatments								
Crack repair with sealing								
Clean and seal					X	X		3
Rout and seal					X	X		3
Crack filling						X	X	2-3
Full-depth crack repair							X	5
Surface treatments								
Fog seal		X						1-2
Seal coat (chip seal)	X	X						3-6
Double chip seal	X	X						7-10
Slurry seal	X	X						3-5
Microsurfacing	X	X	X					5-8
Thin hot-mix asphalt overlay		X	X					5-8
Pothole and Patching repair								
Cold-mix asphalt				X				1
Spay injection patching				X				1-3
Hot-mix asphalt concrete				X			X	3-6
Patching with slurry or microsurfacing material				X			X	1-3

3 FIELD STUDY: SECTIONS' SELECTION AND DESCRIPTION

3.1 INTRODUCTION

In the past, the application of pavement preservation (PP) treatments in Hawaii have been limited. The limited knowledge about their performance and benefits contributed to a certain reluctance to use PP treatments more often. Instead, most of the budget for pavements have been directed to either reconstruction or to pothole patching. This project was launched as a collaboration between the University of Hawaii at Manoa, a consortium member of the Center for Highway Pavement Preservation, with the City and County of Honolulu, which has a road network with more than 3,600 lane-miles, and the Hawaii Asphalt Pavement Industry (HAPI) with the objective of documenting PP treatments' performance in Honolulu.

Two sets of sections were selected for application of different treatments to quantify and demonstrate the benefits of PP. The sections for one of the sets were in cul-de-sacs whereas the sections for the other set were straight segments on low volume roads. For each set, control sections were also selected. The treatments applied were all used in Hawaii at the start of the study and included crack sealing, fog sealing, seal coating systems offered locally (mostly emulsions with sand), and slurry seal. These treatments were selected partly based on what was currently offered locally and partly on the preference of the C&CH for the selected type of roads. Other commonly used preservation treatments used in the continental US but not offered in Oahu at the start of the project, such as chip seal and microsurfacing, were not included in this study.

Since the selected sections were located in residential areas, several issues had to be addressed during the treatment application: advanced notification of limited or no access to certain roads to the neighbors, refuse truck coordination, re-routing of a bus route, and traffic control.

3.2 SELECTION AND LOCATIONS OF THE STUDY SECTIONS

3.2.1 General Location of the Sections in Oahu

Given the relatively short planned duration of the study to monitor PP treatments in Oahu, it was imperative to start the application of the treatments as soon as possible after the project start date in September 2014 so that the monitoring period was as large as possible (the original project duration was two years, including the time for planning and application of the treatments).

The initial effort of selecting the locations for the treatments and planning their application demanded coordination between personnel from the Department of Facilities Maintenance (DFM) of the City and County of Honolulu (C&CH), the Hawaii Asphalt Paving Industry (HAPI), and the University of Hawaii (UH). Consequently, after a first presentation at the HAPI office to C&CH personnel and contractors by the Principal Investigator (PI), a group composed of C&CH personnel, the director of HAPI, and the PI coordinated a first visit during the first week of September 2014 to candidate sections approximately 4 years old in 2014 in the Manoa area of Honolulu. Figure 3-1 shows an example of one of the sections considered in Manoa.

Figure 3-1 Example of a candidate section in Manoa, Honolulu.

Locations in the Manoa valley would have been convenient because of its proximity to the UH Manoa campus. Unfortunately, after the visit, it was agreed to look at other locations for the following reasons:

1. None of the sections presented any environmental cracking; however, it was desired to have sections with some environmental cracking to be able to evaluate crack sealing/filling by itself and in combination with seal coats and slurry seals.
2. The pavement surfaces themselves were still in relatively good condition. As shown in the close-up of Figure 3-1, in some situations some water damage (binder stripping) and loss of aggregate appeared to be in an initial stage, but this was not entirely obvious without a basis for comparison with the pavement surfaces when constructed.
3. In addition to the fact that Manoa is an area of Honolulu with large precipitations (Figure 3-2), the initially targeted months of application, November/December 2014, are typically among the wettest months of the year in the State (Figure 3-3). Therefore, there was a concern on the part of the contractors about potential cancellations that could have created conflicts with their routine work and thus, perhaps delay the application of these treatments for months.

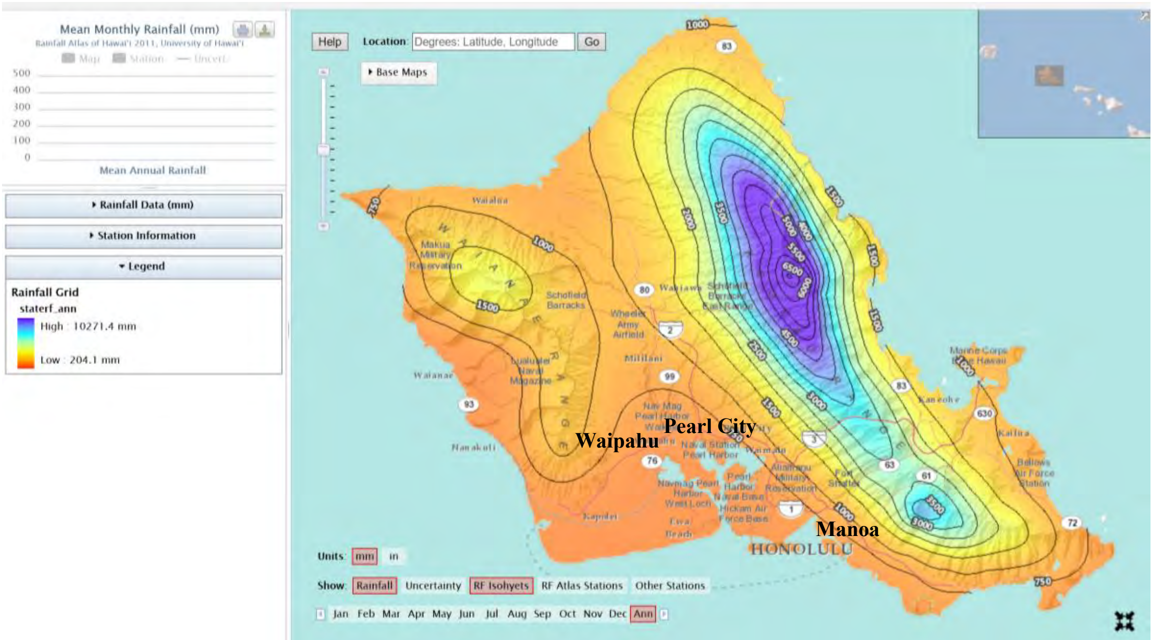


Figure 3-2 Map of annual precipitation in Oahu.

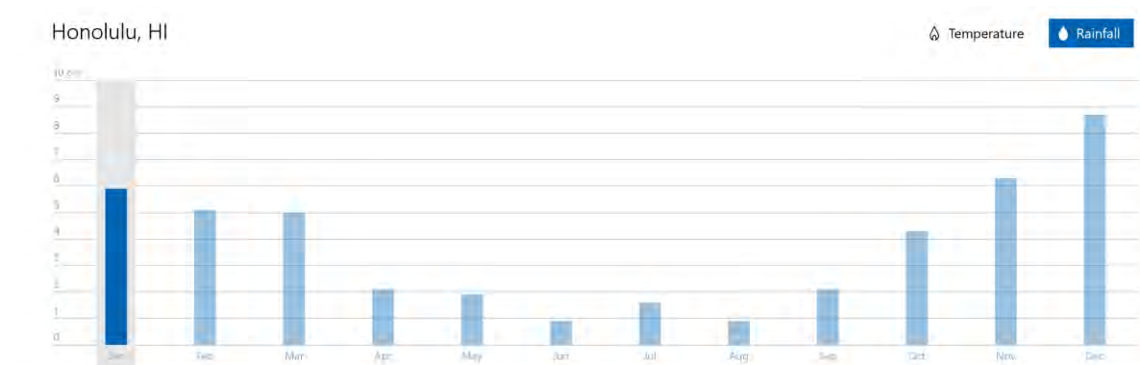


Figure 3-3 Monthly precipitation pattern in Honolulu.

Consequently, pavement sections were then considered in the Pearl City area of Honolulu, Oahu, with the three R's of pavement preservation treatments in mind: Right Road, Right Treatment and Right Time. A visit by all parties involved was coordinated for the third week of September 2014. Again, C&CH personnel (4 people), the director of HAPI, and the PI participated of this visit after which the sections were finally selected. In addition to the Pearl City locations, sections were selected in the nearby location of Waipahu to take advantage of slurry seal work already scheduled in that area. Figure 3-4 shows the general area of the locations finally selected for the study. The top-left photo in Figure 3-4 identifies the location of Oahu within the Hawaiian Islands and the top-right photo identifies the general study location within Oahu. The bottom photo identifies in more detail the zones containing the study sections in the Pearl City and Waipahu areas. In the bottom photo, cul-de-sacs approximately 100-ft long are shown in red and straight segments approximately 320-ft long are shown in orange.

Figure 3-4. General location of the study sections.

Because of the scale, the segments in Figure 3-4 are difficult to visualize. Thus, Figure 3-5 shows a close-up of some of the (a) straight segments and (b) cul-de-sacs selected, together with the delineation of the sections and the type of information collected about their locations in terms of latitude and longitude of both ends of the straight segments or of the end of the treatment for cul-de-sacs.

The last resurfacing of the roads in these areas were believed to have occurred between six to seven years from the targeted treatment application (right time) and were still in relatively good condition, with mostly environmentally induced cracking and/or weathering (right road).

(a) Straight segments.

(b) Cul-de-sacs.

Figure 3-5 General location of the study sections.

3.2.2 Existing Conditions

Figure 3-6 shows examples of two sections in which block cracking and some raveling (see the loose aggregate in the right picture) can be observed.

Figure 3-6. Typical conditions of sections in Pearl City.

Figure 3-7 shows additional examples of typical conditions on either the control sections or before treatment of the treated sections. As can be observed, most sections exhibited some cracking and, in some cases, an apparent aggregate loss (raveling).

Figure 3-7 Additional examples of existing conditions.

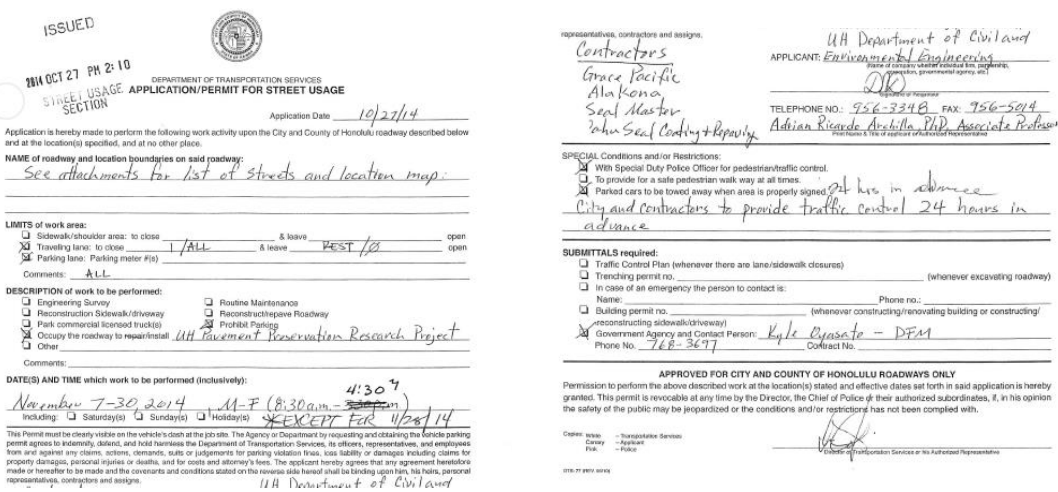
The details of the locations for all the sections and the type of treatment or control assigned to them can be found in Appendix A for straight segments and Appendix B for Cul-de-Sacs.

3.3 PRELIMINARY TASKS AND SELECTED PRESERVATION TREATMENTS

3.3.1 Preliminary Tasks

As mentioned before, this study is the result of a collaborative effort with contributions of the C&CH, HAPI and UH. All the contributions were needed to move the project forward.

Before any treatments could be applied on sections not involving slurry seals, the principal investigator had to obtain the street usage permit for the period scheduled for the treatments. Figure 3-8 shows the permit for the Pearl City locations and Figure 3-9 the necessary attachments with the list of streets and a map with the locations. Because of the time needed to obtain this permit, most work had to be schedule for November and December of 2014. No permits were needed for the Waipahu locations since these had already been scheduled by the C&CH.



ISSUED

2014 OCT 27 PM 2:10

STREET USAGE SECTION

DEPARTMENT OF TRANSPORTATION SERVICES

APPLICATION/PERMIT FOR STREET USAGE

Application Date 10/27/14

Application is hereby made to perform the following work activity upon the City and County of Honolulu roadway described below and at the location(s) specified, and at no other place.

NAME of roadway and location boundaries on said roadway: See attachments for list of streets and location map:

LIMITS of work area:
- ☐ Sidewalk/shoulder area: to close ______ & leave ______ open
- ☒ Traveling lane: to close 1 /ALL & leave REST /Ø open
- ☒ Parking lane: Parking meter #(s) ______

Comments: ALL

DESCRIPTION of work to be performed:
- ☐ Engineering Survey
- ☐ Reconstruction Sidewalk/driveway
- ☐ Park commercial licensed truck(s)
- ☒ Occupy the roadway to ~~repair~~/install UH Pavement Preservation Research Project
- ☐ Other
- ☐ Routine Maintenance
- ☐ Reconstruct/repave Roadway
- ☒ Prohibit Parking

Comments:

DATE(S) AND TIME which work to be performed (inclusively):

November 7-30, 2014, M-F (8:30 a.m.-4:30 ~~3:30~~ p.m.)

Including: ☐ Saturday(s) ☐ Sunday(s) ☐ Holiday(s) *EXCEPT FOR 11/28/14

This Permit must be clearly visible on the vehicle's dash at the job site. The Agency or Department by requesting and obtaining the vehicle parking permit agrees to indemnify, defend, and hold harmless the Department of Transportation Services, its officers, representatives, and employees from and against any claims, actions, demands, suits or judgements for parking violation fines, loss liability or damages including claims for property damages, personal injuries or deaths, and for costs and attorney's fees. The applicant hereby agrees that any agreement heretofore made or hereafter to be made and the covenants and conditions stated on the reverse side hereof shall be binding upon him, his heirs, personal representatives, contractors and assigns.

Contractors
Grace Pacific
Alakona
Seal Master
Oahu Seal Coating + Repaving

APPLICANT: UH Department of Civil and Environmental Engineering
(Name of company whether individual firm, partnership, corporation, governmental agency, etc.)

Signature of Applicant

TELEPHONE NO.: 956-3348 FAX: 956-5014

Adrian Ricardo Archilla, PhD, Associate Professor
Print Name & Title of applicant or Authorized Representative

SPECIAL Conditions and/or Restrictions:
- ☒ With Special Duty Police Officer for pedestrian/traffic control.
- ☐ To provide for a safe pedestrian walk way at all times.
- ☒ Parked cars to be towed away when area is properly signed. 24 hrs in advance

City and contractors to provide traffic control 24 hours in advance

SUBMITTALS required:
- ☐ Traffic Control Plan (whenever there are lane/sidewalk closures)
- ☐ Trenching permit no. ______ (whenever excavating roadway)
- ☐ In case of an emergency the person to contact is: Name: ______ Phone no.: ______
- ☐ Building permit no. ______ (whenever constructing/renovating building or constructing/reconstructing sidewalk/driveway)
- ☒ Government Agency and Contact Person: Kyle Oyasato - DFM
  Phone No. 768-3697 Contract No. ______

APPROVED FOR CITY AND COUNTY OF HONOLULU ROADWAYS ONLY

Permission to perform the above described work at the location(s) stated and effective dates set forth in said application is hereby granted. This permit is revocable at any time by the Director, the Chief of Police or their authorized subordinates, if, in his opinion the safety of the public may be jeopardized or the conditions and/or restrictions has not been complied with.

Copies: White - Transportation Services
Canary - Applicant
Pink - Police

Director of Transportation Services or his Authorized Representative

Figure 3-8 Street usage permit needed before any work.

UH Pavement Preservation Research Project
(Pearl City Area)

Street Name	From	To
Hookano St	Hookala St	Nanakai St
Hoolauna St	Hookala St	Wahinani St
Hoowali St	Hoomalu St	Wahinani St
Kaweloka St	Panee St	Kuahaka St
Hoolawa Pl	Hoolaulea St	End
Hooheno Pl	Hooheno St	End
Hooheno St	Hoolana St	Mauka End
Hoolana Pl	Hoolana St	End
Kalauipo Place	Kalauipo St	End
Kanihi Street	Kaweloka St	End
Kaumoli Place	Kaumoli St	End
Kaweloka Pl	Kaweloka St	End
Noelani Pl	Noelani Pl	End
Paaaina Pl	Paaaina St	End
Palamoi St	Paaaina St	End

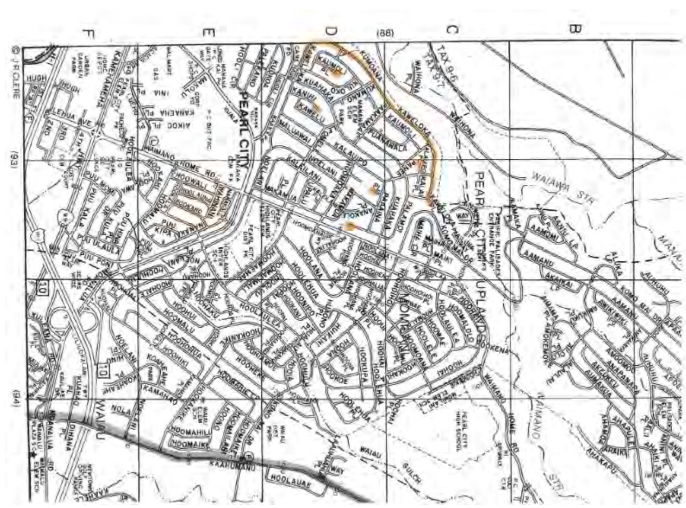
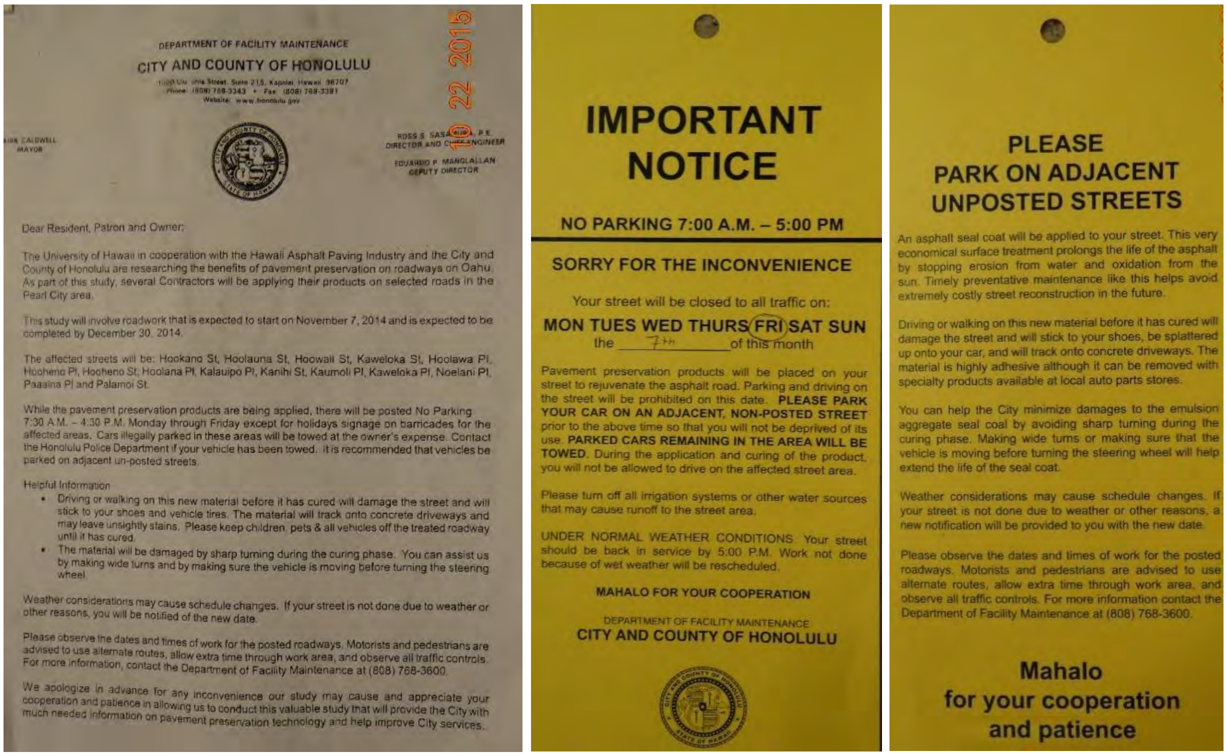


Figure 3-9 Attachments to street usage permit.

UH also delivered notices at least one week before the treatment and again two days before the treatment. Figure 3-10 shows the first iteration of notices that were hand delivered wherever possible or that were left on the door handles (some improvements in wording and times were made by the C&CH to these notices based on feedback received after the notices for this study were delivered).



10 22 2015

DEPARTMENT OF FACILITY MAINTENANCE

CITY AND COUNTY OF HONOLULU

1000 Uluohia Street, Suite 215, Kapolei, Hawaii 96707
Phone: (808) 768-3343 • Fax: (808) 768-3381
Website: www.honolulu.gov

KIRK CALDWELL
MAYOR

ROSS S. SASAMURA, P.E.
DIRECTOR AND CHIEF ENGINEER

EDUARDO P. MANGLALLAN
DEPUTY DIRECTOR

Dear Resident, Patron and Owner:

The University of Hawaii in cooperation with the Hawaii Asphalt Paving Industry and the City and County of Honolulu are researching the benefits of pavement preservation on roadways on Oahu. As part of this study, several Contractors will be applying their products on selected roads in the Pearl City area.

This study will involve roadwork that is expected to start on November 7, 2014 and is expected to be completed by December 30, 2014.

The affected streets will be: Hookano St, Hoolauna St, Hoowali St, Kaweloka St, Hoolawa Pl, Hooheno Pl, Hooheno St, Hoolana Pl, Kalauipo Pl, Kanihi St, Kaumoli Pl, Kaweloka Pl, Noelani Pl, Paaaina Pl and Palamoi St.

While the pavement preservation products are being applied, there will be posted No Parking 7:30 A.M. – 4:30 P.M. Monday through Friday except for holidays signage on barricades for the affected areas. Cars illegally parked in these areas will be towed at the owner's expense. Contact the Honolulu Police Department if your vehicle has been towed. It is recommended that vehicles be parked on adjacent un-posted streets.

Helpful Information

- Driving or walking on this new material before it has cured will damage the street and will stick to your shoes and vehicle tires. The material will track onto concrete driveways and may leave unsightly stains. Please keep children, pets & all vehicles off the treated roadway until it has cured.
- The material will be damaged by sharp turning during the curing phase. You can assist us by making wide turns and by making sure the vehicle is moving before turning the steering wheel.

Weather considerations may cause schedule changes. If your street is not done due to weather or other reasons, you will be notified of the new date.

Please observe the dates and times of work for the posted roadways. Motorists and pedestrians are advised to use alternate routes, allow extra time through work area, and observe all traffic controls. For more information, contact the Department of Facility Maintenance at (808) 768-3600.

We apologize in advance for any inconvenience our study may cause and appreciate your cooperation and patience in allowing us to conduct this valuable study that will provide the City with much needed information on pavement preservation technology and help improve City services.

IMPORTANT NOTICE

NO PARKING 7:00 A.M. – 5:00 PM

SORRY FOR THE INCONVENIENCE

Your street will be closed to all traffic on:

MON TUES WED THURS FRI SAT SUN

the 7th of this month

Pavement preservation products will be placed on your street to rejuvenate the asphalt road. Parking and driving on the street will be prohibited on this date. **PLEASE PARK YOUR CAR ON AN ADJACENT, NON-POSTED STREET** prior to the above time so that you will not be deprived of its use. **PARKED CARS REMAINING IN THE AREA WILL BE TOWED.** During the application and curing of the product, you will not be allowed to drive on the affected street area.

Please turn off all irrigation systems or other water sources that may cause runoff to the street area.

UNDER NORMAL WEATHER CONDITIONS. Your street should be back in service by 5:00 P.M. Work not done because of wet weather will be rescheduled.

MAHALO FOR YOUR COOPERATION

DEPARTMENT OF FACILITY MAINTENANCE
CITY AND COUNTY OF HONOLULU

PLEASE PARK ON ADJACENT UNPOSTED STREETS

An asphalt seal coat will be applied to your street. This very economical surface treatment prolongs the life of the asphalt by stopping erosion from water and oxidation from the sun. Timely preventative maintenance like this helps avoid extremely costly street reconstruction in the future.

Driving or walking on this new material before it has cured will damage the street and will stick to your shoes, be splattered up onto your car, and will track onto concrete driveways. The material is highly adhesive although it can be removed with specialty products available at local auto parts stores.

You can help the City minimize damages to the emulsion aggregate seal coal by avoiding sharp turning during the curing phase. Making wide turns or making sure that the vehicle is moving before turning the steering wheel will help extend the life of the seal coat.

Weather considerations may cause schedule changes. If your street is not done due to weather or other reasons, a new notification will be provided to you with the new date.

Please observe the dates and times of work for the posted roadways. Motorists and pedestrians are advised to use alternate routes, allow extra time through work area, and observe all traffic controls. For more information contact the Department of Facility Maintenance at (808) 768-3600.

Mahalo for your cooperation and patience

Figure 3-10 Notices delivered to residents.

3.3.2 Selected Preservation Treatments

The treatments selected for this project were all available in Hawaii. These included:

- Crack seal
- Fog Seal
- Seal Coat (asphalt emulsion with a certain proportion of sand, typically 2 lb. per gallon but for one treatment it was applied with 4 lb. per gallon)
- Slurry Seal

HAPI members Alakona Corp., Crafco, Inc., GP Roadway Solutions (in collaboration with Goldwings Supply Service, Inc.), Oahu Sealcoating and Paving LLC, and SealMaster Hawaii contributed to the project by donating the materials and labor required to apply the various treatments. HAPI involvement was crucial for coordinating with the contractors and for securing their participation.

In addition to allowing the use of the selected streets for the study and actively helping in selecting the study sections, as illustrated in Figure 3-11, the C&CH paid for traffic control (including barricades with notices two days before the scheduled treatment) and police presence during the treatments application and curing (Figure 3-12). At the beginning of the process, a “Local Traffic Only” sign was used instead of a “Road Closed” sign, an error that was corrected later to avoid people attempting to drive on the freshly applied treatments.

The C&CH also helped in the coordination with the re-routing of the bus (for one street that was part of a bus route) and coordinating with refuse collection.

Figure 3-11 Traffic control paid by the C&CH.

Figure 3-12 Police presence paid by the C&CH.

Other treatments such as chip seals and microsurfacing were not available in Oahu at the start of the study and therefore were not available for this study.

It was also desired to include in the field study thin lift overlays (TLO). However, there were several reasons why this was not possible in the short time frame available to plan the study. First, unlike for the other type of seals, TLO mixes were more generic in the sense that any contractor with Hot Mix Asphalt (HMA) expertise could produce the mixes. In addition, they would have required a larger scale of work to make the equipment mobilization worthwhile. Consequently, it was more difficult to find a single contractor willing to donate the materials, labor, and equipment costs for this work or to coordinate between several contractors. Furthermore, TLO mixes that could be produced with local aggregates and binder had not been previously researched. Therefore, the study of TLO mixes in this research was limited to laboratory testing and as indicated before, this effort morphed into the development of a test configuration for uniaxial testing that avoided end failures.

Although all the selected treatments were available in the Oahu, except for slurry seals (and crack filling prior to slurry seal application), they had not been used routinely in C&CH roads.

The following is the list of products provided by each contractor or group of suppliers and contractors. The specification sheets and product descriptions can be found on the suppliers' websites:

- SealMaster®/Hawaii
    - Plasti-Pave™ (Pavement Rejuvenator)
    - MasterSeal™ Ready to Use" (Asphalt Based Pavement Sealer Fortified with Gilsonite)
    - OptiPave Plus™ Ready to Use" (Asphalt Based Pavement Sealer Fortified with Gilsonite)
    - Liquid Road™ (Bituminous Surface Treatment)
    - CrackMaster™ PL-HT (Hot Pour Crack Sealant)

- Grace Pacific Roadway Solutions (GPRS) in association with Crafco, Inc. and Goldwings Supply Service, Inc.
    - Roadsaver 211 by Crafco
    - CarbonSeal-HF Seal Coat (Cabonyte Systems Inc.)

- Alakona Corporation
    - Slurry seal

- Oahu Seal Coating and Paving
    - Brewer Cote (Brewer Cote® is a high in solids, concentrated refined tar emulsion pavement sealer)
    - Hot Applied Rubberized Sealant (ROAD WORKS Materials, LLC)

With the exception of Oahu Seal Coating and Paving, that treated a single cul-de-sac, the products listed above were applied in both a cul-de-sac and a straight segment. The treatments applied by SealMaster®/Hawaii were completed in early November 2014. The treatments applied by Grace Pacific Roadway Solutions were completed in mid-November 2014 whereas the treatment of Oahu Seal Coating a Paving was completed in late January 2015. The slurry seal by

Alakona Corp. followed their own schedule to fulfill their contract with the C&CH but the treatments selected for this study were performed in December 2014. Crack sealing was performed in all seal coated sections prior to the seal coat application using the using the crack sealer listed under each company above.

3.4 TREATMENTS' APPLICATION

In this project, observing the application of the treatments was useful to document practices followed by different contractors in terms of, among other things, different sealing practices of cracks, sealing of pavement/gutter joint, prevention of sealers going into the gutter, and cleaning cracks and pavement surface. For example, in terms of sealing cracks, one contractor elected to do mostly clean and seal with only a few feet of the cracks being routed for demonstration only whereas the other contractor elected to do significantly more rout and seal.

3.4.1 Crack Sealing, Gutter/Pavement Joint Sealing, and Gutter Protection

In the long term, one would expect that properly routing and sealing of cracks would tend to prevent the ingress of moisture into the pavement for a longer period than simply cleaning and sealing the cracks. Given the short duration of this project, however, it was considered very likely that no clear durability advantage of routing and sealing over cleaning and sealing could be observed during the study period. To date, both types of treatments are still holding relatively well when comparing clean and seal cracks greater that about 10 mm (3/8 inch) to the routed and sealed cracks. Figure 3-13 shows examples of each type of treatment. Further discussion of the performance of these treatments is provided in the next chapter.

Figure 3-13 Examples of routing and sealing (left) and cleaning and sealing (right).

The contractors performing mostly clean and seal generally elected to use pour-pots as shown in Figure 3-14. Sealing of cracks with these devices is quite efficient in terms of the speed of application. In addition, immediately after sealing, the cracks were treated with products such as Glenzoil 20 Plus, a biodegradable, non-toxic liquid that prevents tracking and picking of freshly applied hot-melt sealants.

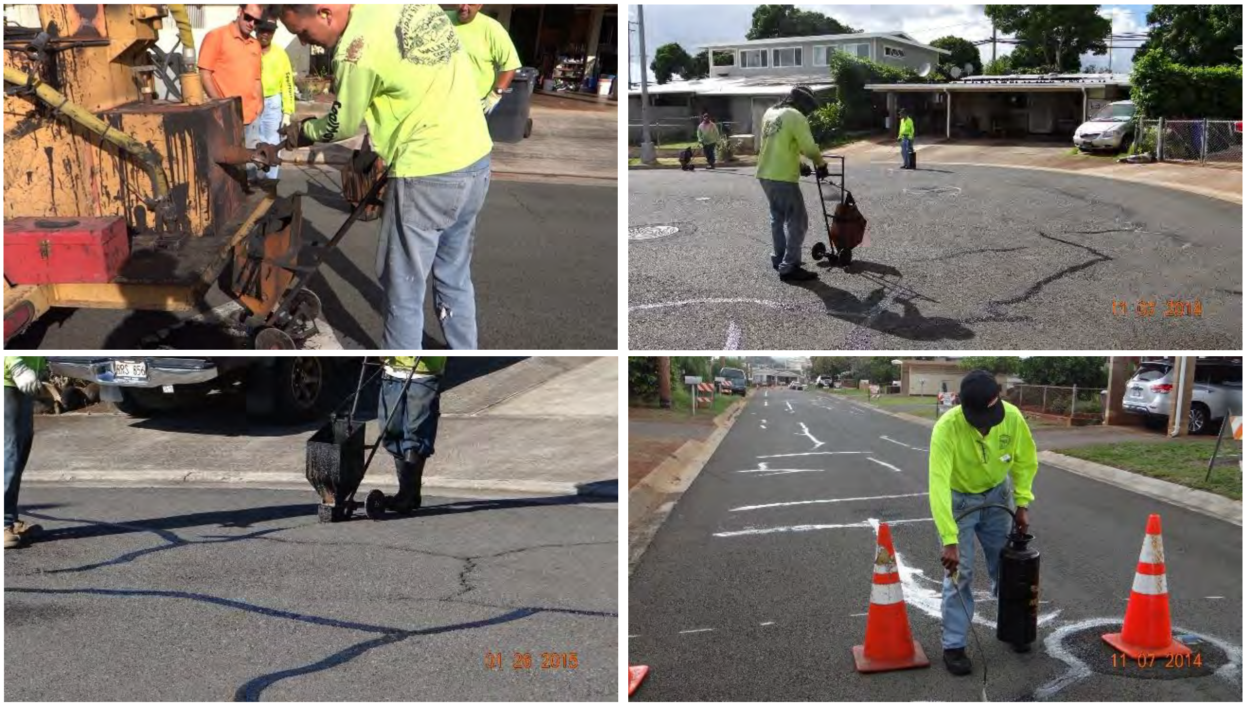


Figure 3-14 Use of pour-pots for crack sealing and treatment of the sealer to avoid tracking of the crack sealer.

The contractor that chose to rout a larger proportion of cracks used the process illustrated in Figure 3-15 from left to right and top to bottom. First, a router was used to create a properly sized reservoir and then the cracks were clean of debris. The sealer material, previously heated in a melter at the appropriate temperature, was applied with a wand and then squeegeed. In general, although an overband was created with the squeegee, the sealer in the crack was left slightly recessed (Figure 3-16).

The same contractor chose to seal the pavement/gutter joint. This is considered good practice as a substantial quantity of water can infiltrate into the pavement structure through these joints. It is recommended that sealing of the joint be required in the specifications to decrease the possibility of water ingress through the joint. Figure 3-17 illustrates this practice for a cul-de-sac section before it was sealed. Note also the loose aggregate accumulated in the gutter after cleaning the pavement surface, a clear indication that the pavement surface was raveling before it was sealed.

Whether the application of seal coats is performed by a spreader or by spraying the sealer, the gutters need to be protected. Again, different contractors used different practices. In one case, as illustrated in Figure 3-18, the contractor used tape edging the pavement/gutter joint. Then after sealing the joint, the sealer was carefully poured from a low height with the spreader and then spread out with a brush. Instead, the other contractors used a board while spreading the sealer as shown in Figure 3-19. Both procedures appear to produce similar results, though the latter appears to be more efficient in terms of productivity.

Figure 3-15 Sequence of photos illustrating the crack sealing process used in two sections.

Figure 3-16 Sealed cracks were left slightly recessed.

Figure 3-17 Filling of the joint between the pavement and the gutter.

Figure 3-18 Use of tape to avoid spreading of the emulsion into the gutter.

Figure 3-19 Use of a board to avoid spreading of the emulsion into the gutter.

3.4.2 Seal Coats

As mentioned before, the term “sealcoat” in Hawaii is used to denote a mix of emulsion with different sand size particles in different proportions (2 to 4 lb. per gallon depending on the product specification). Figure 3-20 shows the sand used in one of the products and its addition to the emulsion.

Figure 3-20 Sand used in seal coat and mixing of sand and emulsion.

Before their application, the pavement surfaces were cleaned either with blowers or in one case by power washing. As shown in Figure 3-21, as the pavement ages, the pavement surface may have a substantial amount of loose aggregate, thus making this operation extremely important. It is important to note that often, the amount of loose aggregate was not as obvious to the naked eye until the cleaning operation started.

Figure 3-21 Use of blowers to clean the surface of loose aggregate and dust.

Power washing appears to take out an important additional amount of dust that would otherwise stay in the pavement surface (Figure 3-22). In addition, its use may also be advantageous in surfaces with large oil spots. As explained later, based on the limited observed performance in this study, there is no evidence that this translates in better performance. Note that in addition to the power washing, this operation requires drying of the cracks prior to their filling. In the pavement section shown in Figure 3-22, a heat lance was used for this purpose. As shown in Figure 3-23, this method results in very clean cracks, but it also requires taking proper environmental precautions to catch the contaminated water, which adds to its cost. Figure 3-24 shows the contractor set-up for this purpose.

Figure 3-22 Use of power washing to clean the pavement surface.

Figure 3-23 Very clean crack obtained by power washing.

Figure 3-24 Environmental precautions for power washing.

Two coats were applied for all the sealcoat products. Either a manual sprayer or a spreader was used. For some products, the spreader was used in the first coat and the sprayer in the second. Figure 3-25 shows sealcoat applications with both types of equipment.

Figure 3-25 Application of seal coats: Manual spraying (left) and Spreader (right).

As illustrated in Figure 3-26, the same manual spraying procedure was used to apply the pavement rejuvenator (fog seal).

Figure 3-26 Pavement rejuvenator application.

3.4.3 Slurry Seal

Similarly to other treatments, slurry seals require prior preparation work such as crack sealing, surface cleaning, and manhole protection. Figure 3-27 shows the sweeper truck used for cleaning of the surface before the slurry application and after, to remove aggregates dislodged from the slurry during the first few days. The figure also shows the protection used in manhole covers. The slurry seal application was performed with a typical truck used for this purpose.

Figure 3-27 Aggregate sweeping (left) and manhole cover (right).

Figure 3-28 Slurry seal application.

4 PRESERVATION TREATMENTS' PERFORMANCE OVER THE STUDY PERIOD

4.1 INTRODUCTION

This chapter describes the performance of the preservation treatments over the study period together with the performance of some control sections. Originally, the research plan included the creation of video-logs over time for each section. However, immediately after starting the project, walking surveys were found to be more practical since it was realized that during the study period most issues would be related to either appearance of new cracks or propagation of existing cracks, fading of surface seals, and presence or lack of raveling.

With respect to cracks, unless a sophisticated automated technology with downward pictures or lidar (Light Detection and Ranging) technology is used, it is much easier to observe and measure cracking on a walking survey than with a video log with a camera facing forward. As an alternative, an attempt was initially made to quantify cracking with a walking survey using a handheld GPS (Figure 4-1). This had the advantage that a permanent record of the locations of the cracks could be created. However, that was found to be too time consuming, particularly for highly meandering cracks. Thus, its use was not considered sustainable for the whole study period. Furthermore, even though the sections were in urban areas with low traffic, the data collection still had to be interrupted frequently because of traffic. In addition, it was not possible to collect information from videos or with a GPS below parked vehicles. However, this could be accomplished with relatively minor errors with a measuring wheel.

Consequently, except for the first survey on which some measurements were performed with a GPS, the cracking lengths on each section were obtained with a simple measuring wheel. Most the cracking observed in the treated segments were low to medium severity. Since the severity level changes frequently, the total length of cracking was obtained irrespective of severity.

In term of fading of fog seals and seal coats and raveling of untreated sections, visual observations were used. Measuring surface texture with a sand patch test was not in the work plan since there was little time between the selection of sections and start of treatments to collect this information. Furthermore, although its use would have been useful for comparing treated and untreated sections or the texture of different treated sections, this would have been limited anyway because of number of measurements that would have been needed for repeatability on every study section and on every survey. Given the section sizes, several tests would have been required per section on each survey to quantify reliably any change in texture over time.

Despite these limitations, several interesting observations were obtained throughout the study.

Figure 4-1 Examples of initial efforts to quantify distresses with a handheld GPS.

4.2 CRACKING TRENDS

This section discusses the observed performance of the control and treated sections in terms of cracking. Other issues observed during the study are discussed in detail for each section Appendix C and the main observations are discussed in section 4.3. The discussion about cracking progression is divided first into the types of treatments, namely, crack sealing, seal coats (including fog seal), and slurry seals and within a type of treatment into the type of segments (straight and cul-de-sac). Within each treatment category, the performance of the control section is discussed first followed by the performance of the corresponding treated segments.

The following discussion about cracking concentrates on “total” cracking length regardless of type, severity and whether a crack is sealed or not. Most of the cracking observed is environmentally induced block cracking. However, measuring areas with block cracking would have produced less information about the cracking progression since some sections already had a substantial portion of their areas with block cracking. Also, as discussed later, some sections with bus loading also showed signs of fatigue cracking. But the identification of fatigue cracking is not easy in earlier stages since traffic on residential city streets is less channelized than on typical rural highways. Thus, separating cracks into different types would have likely resulted in some cracks being miss-classified over time, with even more noise because of inconsistences over time or even double counting within a single survey.

Separating cracking into severity levels with a visual inspection was also found to be impractical since at times, because of traffic interruptions, it was hard enough to keep track of what cracks had already been surveyed. Also, as depicted in several photos later in the report, as the crack sealing deteriorates, it is difficult to identify in many situations whether a crack is still properly sealed or not. Because of these uncertainties, it was found that it would be difficult to maintain a consistent record of the length of sealed cracks with good performance, the length of sealed cracks with some type of problem, and the length of new cracks. This was desirable for assessing the performance of the crack sealer itself, but initial attempts resulted in some inconsistent results and thus the idea was abandoned. Note that distress identification protocols such as the Federal Highway Administration’s (FHWA) Long Term Pavement Performance (LTPP) Distress Identification Manual (*8*), consider sealed cracks as contributors to distress types such as block and longitudinal cracking. Thus, at least in this regard, including sealed cracks in the measurement of total cracking is consistent with LTPP. The only exception was made for measuring cracking on slurry seals since it is often difficult to identify the sealed crack locations immediately after the treatment application.

Table 4-1 summarizes the cracking length data collected over the study period. The blank cells represent data points that were considered be erroneous or missing. Sections in cul-de-sacs are identified as such below the section name. The following sections provide the interpretation of these data.

Table 4-1 Cracking lengths measured over time and section areas.

Section	Treatment Type	Area (ft^2)	Cracking Length (ft)						
			Dec-14	Mar-15	Aug-15	Mar-16	Jun-16	Dec-16	Jan-18
Hoolauna St.	Control	6443	1178	1151	1230	1279	1341	1225	1472
Hoowali St.	Crack Sealing	6555	850	739	782	967	810	934	1014
Hookano St.	Crack Sealing	6675	1199	1137	1306	1199	1225	1266	1411
Palamoi St. Cul-de-sac	Control	3951		594	661	670	670		
Kaweloka Pl. Cul-de-sac	Crack Sealing	4168		870		859	885	865	996
Paaaina Pl. Cul-de-sac	Crack Sealing	4343	390	475	530	498	515	571	621
Kaweloka St. Section 1	Fog Seal	7680		303	323	370	405	610	661
Kaweloka St. Section 2	Seal Coat	7680		171	303	291	636		968
Kaweloka St. Section 3	Seal Coat	7680		484	663	778	789	1004	1287
Kaweloka St. Section 4	Seal Coat	7680	383		426	583	673	1025	1479
Kaweloka St. Section 5	Seal Coat	7680	282		567	704	697	750	726
Kaweloka St. Section 6	Control	7840	606	666	690	786	774	830	
Kaweloka St. Section 7	Control	7840	494	644	626	743	715	768	
Kaweloka St. Section 8	Control	7744		820	787	922	881	921	
Kaweloka St. Section 3	Control	7744		452	505	682	742	801	
Hulahe St.	Slurry Seal	33857	692		100	395	628	1366	1231
Kaumoli Pl. Cul-de-sac	Control	3887		330	401	395	388	520	
Hoolawa Pl. Cul-de-sac	Fog Seal	3561	54	96		101	106		97
Kanihi St. Cul-de-sac	Seal Coat	4298	177	150	239	329	335	398	457
Kalauipo Pl. Cul-de-sac	Seal Coat	3871	268	445	418	493	500	591	650
Hoolana Pl. Cul-de-sac	Seal Coat	3530		367	383	457	499	537	583
Hooheno St. Cul-de-sac	Seal Coat	3563	282	321	345	428	456	485	561
Hooheno Pl. Cul-de-sac	Seal Coat	3886	133	146	188	201	258	305	321
Hiana Pl. Cul-de-sac	Slurry Seal	7958	599		57	168	186	240	289
Hapapa Pl. Cul-de-sac	Slurry Seal	4669	364		174	344	292	424	478

4.2.1 Crack Sealing Sections

Crack Sealing in Straight Sections

Figure 4-2 shows the three 320-ft long sections selected for monitoring the crack sealing performance over the study period. The section on Hoowali St. (the left most section in the figure) was treated by SealMaster Hawaii using SealMaster's CrackMaster PL-HT®, whereas the section on Hookano St. (the right most section in the figure) was sealed by Grace Pacific Roadway Solutions with Roadsaver 211 by Crafco. The section on Hoolauna St. (the section in the middle) was selected as a control section. At the time treatments were assigned, these three sections were considered suitable for comparing crack sealing treatments because they showed a significant level of non-load related cracking (environmental cracking such as transverse and block cracking and longitudinal joint cracking). However, in retrospect, given the large level of raveling observed in subsequent surveys, these sections would have been good candidates for some surface sealing treatments together with crack sealing.

Figure 4-2 Locations of the three straight sections selected to observe crack sealing performance.

The straight sections exhibited initial levels of cracking ranging from 800 to 1200 linear feet. After about three years, those had increased by about 200 to 275 ft. Figure 4-3 to Figure 4-5 show the cracking measurements with time for the three sections. Since the measured areas of the sections were slightly different from each other because of slightly different road widths, the labels in the figures show the cracking length per unit area in ft/ft^2. This also facilitates the comparison with the performance of sections in cul-de-sacs and of sections with other treatments, which in some cases had larger differences in areas.

These figures illustrate the measurement errors from survey to survey. In addition to issues mentioned above, such as the use of different technologies (the first measurement was performed with a GPS and the rest with a measuring wheel) and the presence of parked vehicles on the streets, other issues contributing to the error terms are the different crack openings at different times of the year or time of day (which may make visibility of some thin cracks difficult) and either double counting or missing some cracks when the cracking pattern gets complex (this is believed to have occurred mostly when the measurements had to be temporarily paused because of local traffic).

For comparison, it is important to note that the cracking length at the beginning of the study in the Hoowali Street section was about 50% lower than those in the other two sections. Although inference with a single comparison like this is inherently limited, the trends are consistent with the expectation that sealing cracks will have some retardation effect on the appearance of new cracks as less water infiltrates through the pavement surface. Most of the cracking is environmentally induced (as indicated by the block patterns observed), yet some of it can still be accelerated by traffic loads. This is seen by the slope of the trend of cracking length per unit area with time, which indicates that cracking increased at a rate of about 0.355 ft/day/10^4ft^2 in the control section (Figure 4-3) whereas it increased at a rate of about 0.264 ft/day/10^4ft^2 on the section on Hookano Street (Figure 4-4), with about the same initial cracking.

Without detailed information about the asphalt concrete thickness on each section, the characteristics of the mixes used, and the dates on which the sections were built; it is not possible to know the reasons for the substantially lower initial cracking on Hoowali Street. On the one hand, this may be because of better performance of the section (better asphalt mix, thicker asphalt mix, etc.) and on the other hand, it may simply be a question of the timing of paving. Nevertheless, despite the lower level of cracking (that would typically allow new cracking to appear at a higher rate with all else equal), the cracking rate of about 0.305 ft/day/10^4ft^2 (Figure 4-5) is still lower than the 0.355 ft/day/10^4ft^2 for the control section.

In summary, these trends show that crack sealing appears to have a beneficial effect reducing the rate of cracking increase by reducing the infiltration of water into the pavement though it will not stop the progression of cracking due solely to environmental effects. Thus, in order to maintain the benefits obtained by crack sealing of pavements, it is desirable to have a program that regularly seals new cracks, particularly on sections with higher traffic loadings.

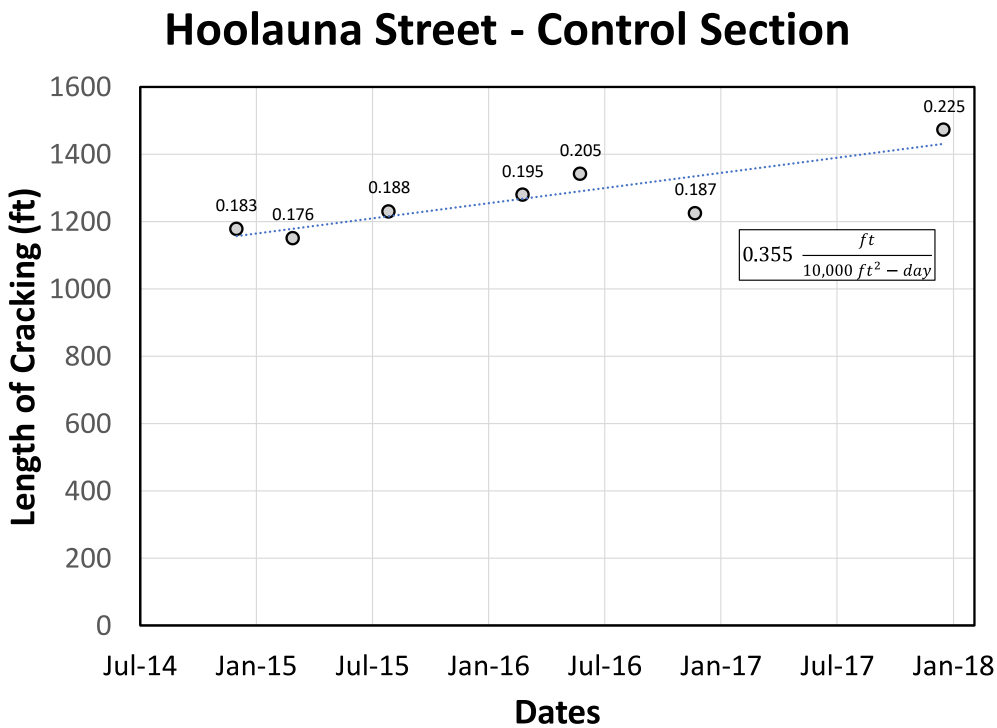


Figure 4-3 Cracking length progression over time in the control section in Hoolauna Street.

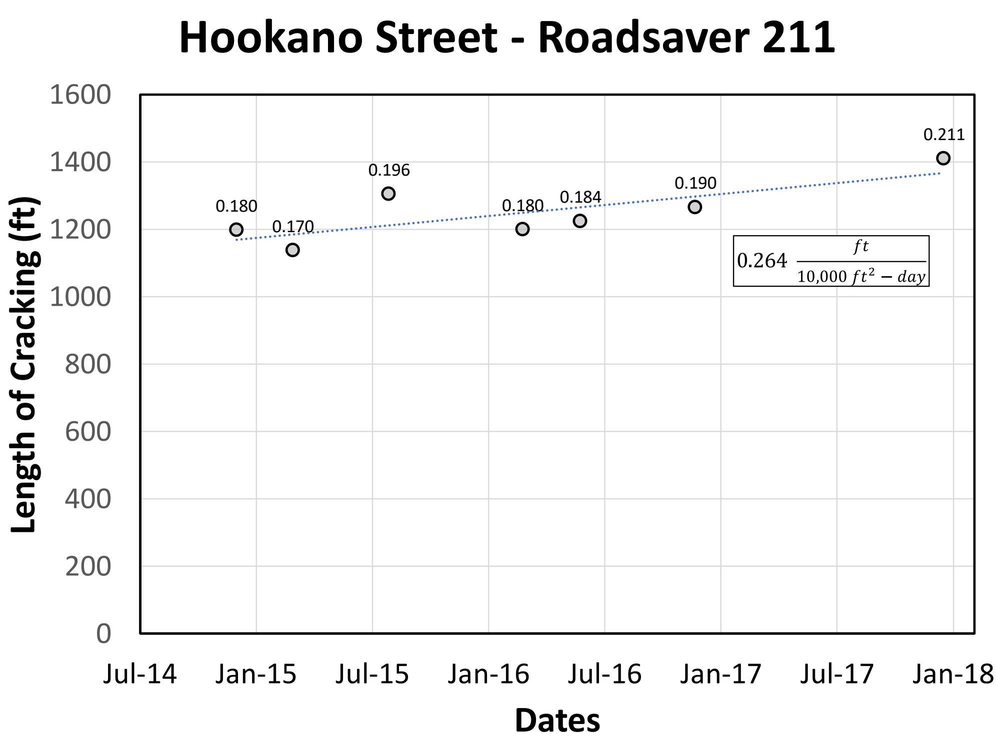


Figure 4-4 Cracking length progression over time in Hookano Street, crack sealed section.

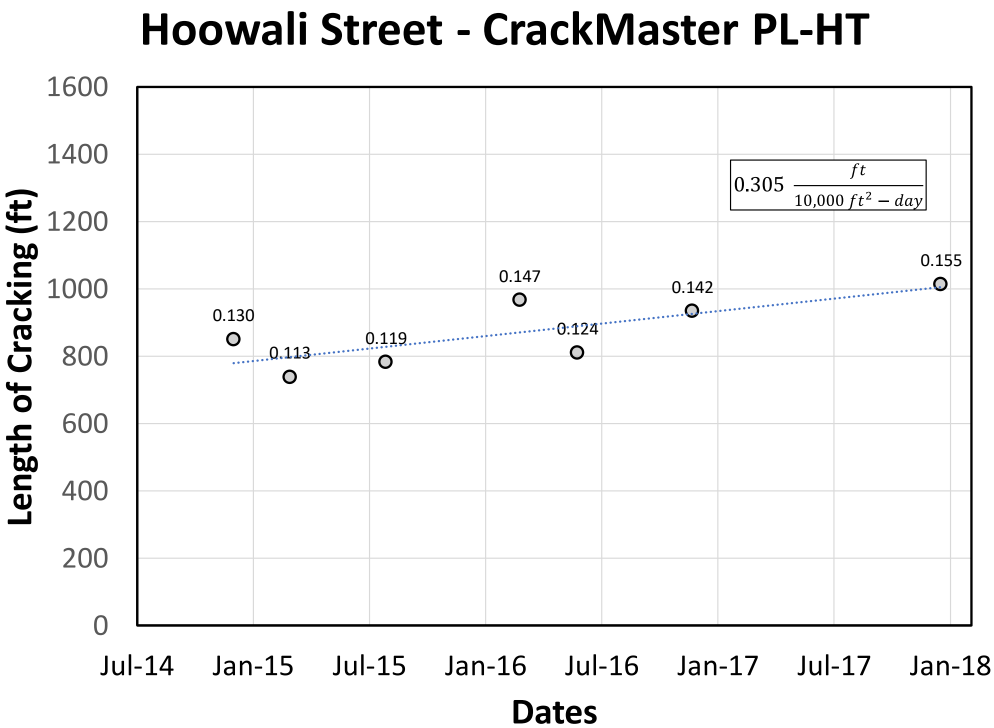


Figure 4-5 Cracking length progression over time in Hoowali Street, crack sealed section.

Crack Sealing in Cul-de-sacs Sections

Figure 4-6 shows the sections selected for observing the crack sealing performance on cul-de-sacs. The section on Palamoi Street was used as a control section. As for the straight sections, one section, the one on Kaweloka Place, was crack sealed by SealMaster Hawaii using SealMaster's CrackMaster PL-HT, whereas another section in Paaaina Place was crack sealed by Grace Pacific Roadway Solutions together with Goldwings Supply Service, Inc. using Roadsaver 211 by Crafco.

Unfortunately, the control section on Palamoi Street was crack sealed and then sealed before the end of the study period. Consequently, the last observation for this section was performed on June 2016. Also, because of the rush with the initial treatment of the sections, measurements of the length of cracking was not performed on the first survey in this section. The trend is shown in Figure 4-7. As before, the labels above the points show the cracking per unit length (ft/ft^2). The first recorded cracking per unit area, 0.150 ft/ft^2, is of the same order as that observed in the straight control section, albeit smaller. The rate of increase of 0.363 $ft/day/10^4 ft^2$ is slightly larger (compared with the value of 0.355 $ft/day/10^4 ft^2$ in the straight control section), but also more uncertain as it was observed for only about half of the time.

As shown in Figure 4-8, the Kaweloka Place section exhibited a much higher initial cracking per unit area, 0.209 ft/ft^2. Thus, it is not surprising to see that between the higher initial cracking and the application of the crack sealing, the rate of cracking progression in this section was lower, 0.281 $ft/day/10^4 ft^2$.

It is important to stress that, a priori, the crack sealing was expected to reduce the rate of cracking progression but in this case, this seems to have been further helped by the high initial amount of cracking (thus leaving a smaller potential for cracking development).

In contrast, as shown in Figure 4-9, the initial cracking in the Paaaina Place section was only 0.090 ft/ft^2 which is about 40% percent less than the first observation in the control section and less than half the initial cracking in the Kaweloka Place crack sealed section. Therefore, the potential for the development of new cracking in this section is higher than those in the other two. Consequently, it is not surprising to see that the rate of increase of linear cracking with time is the highest for this section, 0.385 $ft/day/10^4 ft^2$, though slightly higher than the value for the control section.

Figure 4-6 Locations of the three cul-de-sac sections selected to observe crack sealing performance.

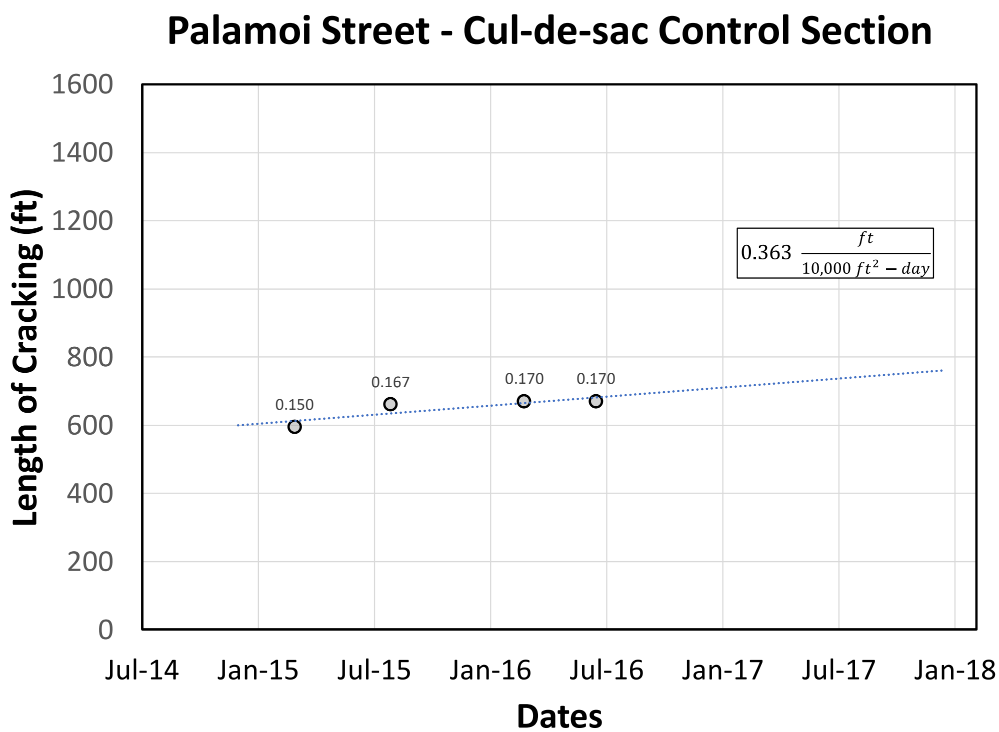


Figure 4-7 Cracking length progression over time in the cul-de-sac control section in Palamoi Street.

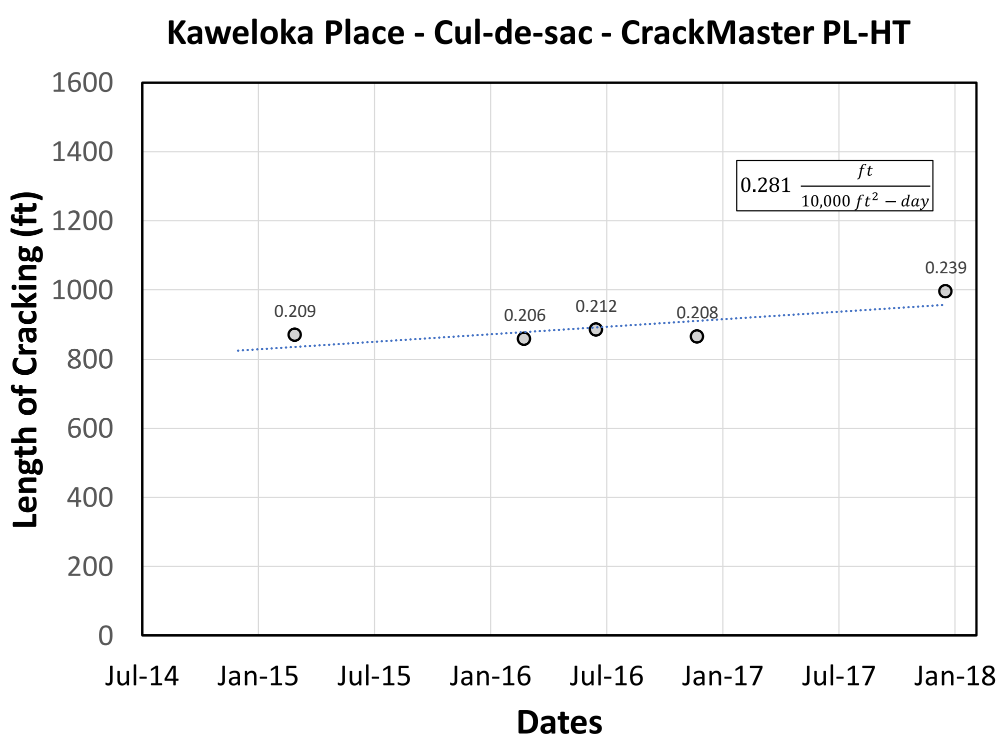


Figure 4-8 Cracking length progression over time in Kaweloka Place, cul-de-sac crack sealed section.

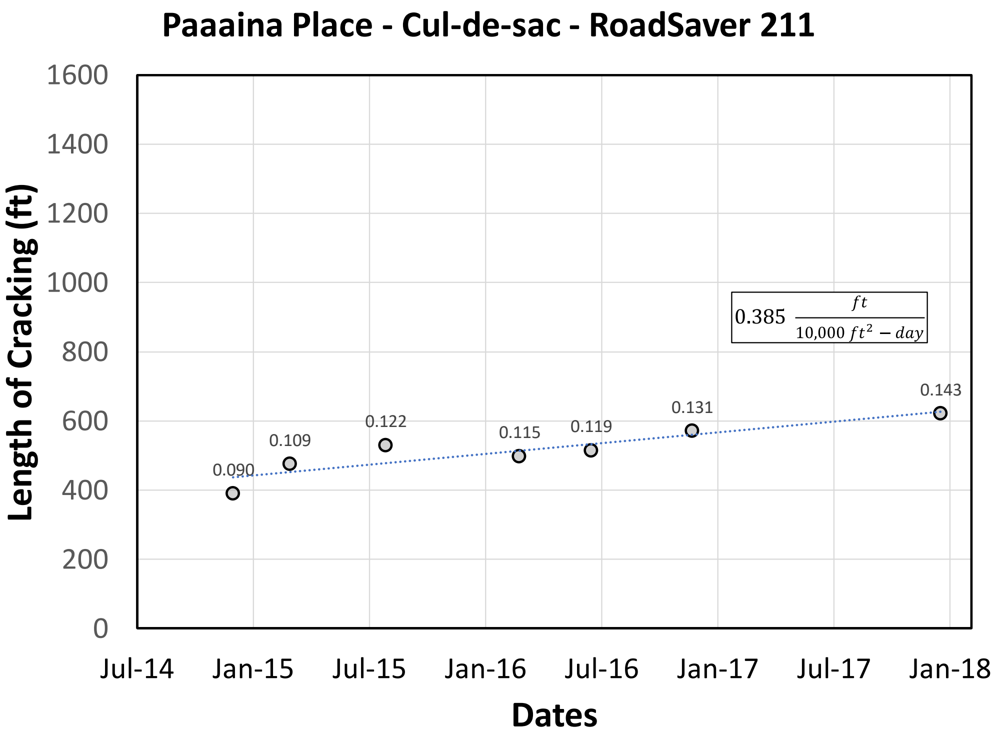


Figure 4-9 Cracking length progression over time in Paaaina Place, cul-de-sac crack sealed section.

As for the straight sections, it is not possible to know the reasons for the substantially different initial cracking on each section without detailed information about their asphalt concrete thicknesses, the characteristics of the mixes used, and the exact dates on which the sections were built.

Although the comparisons in the cul-de-sac sections are less revealing than those in the straight sections, the trends still indicate that crack sealing provides a beneficial effect by reducing the rate of cracking increase.

B.1.1 Seal Coat Sections

As discussed previously, in Hawaii, the term seal coat has traditionally been used for applications of an emulsion with a certain amount of sand (typically with about 2 lb. to 4 lb. of sand per gallon). This section discusses the performance of the treatments falling into this category. The performance of the two sections treated with a fog seal is also examined.

On each treated section, crack sealing was first applied followed shortly by two coats of the product assigned to the section. At the start of the study, there was some uncertainty as to the type of deterioration that would develop on these treatments. Nevertheless, early on, it was clear that given the existing thin hot mix asphalt thicknesses, cracking would continue progressing over time. Hence, cracking was one of the distresses monitored. As for the sections that were crack sealed only, the total length of cracking was monitored regardless of severity and whether they were sealed or unsealed. This was possible because the sealed cracks were still visible on these relatively thin coats. Note that in general the length of sealed cracks (as seen by the overband on the pavement surface) slightly overestimates the actual length of cracking. This is because crack sealing is commonly extended a little beyond the end of the cracks when using the squeegee to level the material poured into the crack or to clean the excess material on the pour-pot left after releasing its handle.

An advantage of measuring the total amount of cracking (sealed, unsealed, and partially sealed cracks) is that it was not necessary to identify the source of the crack. This would have been challenging because the seal coats on top of sealed cracks often cracked relatively soon because of high strains caused by large opening and closing movements due to large temperature differentials. Note that as shown later in Chapter 5, daily temperature fluctuations of the order of 35ºC (63ºF) are common. Although in general the crack sealer may have been performing adequately, this was not always entirely obvious. Thus, it would have been quite difficult to classify these as sealed, partially sealed, or unsealed cracks (although it was suspected that the crack sealer was performing adequately, this could not be stated with certainty). Thin cracks on the seal coats were also often observed in areas without sealed cracks. Again, it was not always obvious whether these were caused by new cracks in the existing pavement that were reflecting on the seal coat or whether the new cracks were confined to the seal coat only. Thus, the measurements described later include all the sealed cracks and any cracking noted on the surfaces of the seal coats.

For other issues such as wearing off or fading of fog seals and seal coats and raveling of untreated sections, visual observations were used. Since these are subjective evaluations, they are discussed in the chronological observations for the respective treatments. The general discussion of seal coats below for straight sections and cul-de-sacs concentrates on the rates of cracking progression after treatment and the comparison with the control sections.

Seal Coats in Straight Sections

Figure 4-10 shows that all the treated and control straight sections for seal coats were selected along Kaweloka Street in Pearl City. Consistent with the crack sealing study sections, all the sections were originally 320 ft long (with widths of about 24 ft). Originally, 8 sections were selected: sections 1 through 5 to be treated with different preservation treatments and sections 6 through 8 as controls. However, since sections 1 through 4 were located on a bus route but section 5 was not, it was decided to add an additional section, identified as section 3’ between sections 3 and 4 as a control for the sections on the bus route.

Section 1 through 4 were treated with proprietary products by SealMaster®/Hawaii after the cracks were sealed with SealMaster’s CrackMaster^{TM} PL-HT. Section 1 was treated with Plasti-Pave^{TM} (https://www.sealmasterhawaii.com/wp-content/uploads/sites/2/2013/10/Plasti-Pave-Spec.pdf last accessed 05/08/2019), an acrylic reinforced asphalt emulsion pavement sealer and rejuvenator used in this study as a fog seal application.

Section 2 was treated with Liquid Road^{TM}, which is described as a polymer-modified, fiber reinforced asphalt emulsion coating that is job-mixed with specially graded aggregate. This is a seal coat containing an amount of sand (about 4 lb. of sand per gallon) that is larger than what typically used in other seal coat applications in the state (about 2 lb. of sand per gallon). SealMaster®/Hawaii webpage (https://sealmaster.net/pdf/specification/Sealmaster%20spec%20sheets/LiquidRoad-Roads.pdf - last accessed 05/08/2019) provides details of the gradation but it is basically material smaller 2 mm. Because of the larger amount of aggregate, this sealer provides a treatment that is thicker than other seal coats and provides more micro-texture.

Figure 4-10 Locations of the straight seal coat sections on Kaweloka Street in Pearl City.

Section 3 was treated with "MasterSeal™ Ready to Use" (http://www.sealmasterhawaii.com/wp-content/uploads/sites/2/2014/12/MasterSeal-RTU-Hawaii-updated-December-2014.pdf - last accessed 05/08/2019 - last accessed 05/08/2019), which is described as a ready to use clay-stabilized asphalt emulsion pavement sealer fortified with Gilsonite (a naturally occurring bitumen with a relatively high melting temperature) and sand for slip resistance and added durability.

Finally, section 4 was treated with "OptiPave Plus™ Ready to Use" (http://www.sealmasterhawaii.com/wp-content/uploads/sites/2/2017/06/062017-OptiPave-Plus-RTU-Hawaii.pdf - last accessed 05/08/2019), which is described as a ready to use clay stabilized asphalt emulsion pavement sealer fortified with Gilsonite and fortified with TopTuff (a polymer additive) and sand.

Section 5 was treated by Grace Pacific Roadway Solutions with CarbonSeal-HF after crack sealing the cracks with RoadSaver 211 by Crafco, which is a proprietary product of Carbonyte Systems Inc. CarbonSeal-HF. (http://www.carbonyte.com/ Road_Grade_Sealers.html - last accessed 05/08/2019).

Figure 4-11 shows the cracking measurements with time for section 3', the control section with bus traffic. Bus route 54 is scheduled on this section with 17 trips per day on weekdays and 14 on weekends. Thus, the weighted average number of bus passes per day is 16.1, which is equivalent to about 5900 buses/year. Note that the average truck factor derived in a previous study for buses in the state is 1.62 (*9*). Although it is likely that in this area the truck factor is lower because of the fewer passenger carried at the end of the route, the value is unlikely to be lower than 1.0 since the bus configuration on this route include articulated buses. Another source of heavy loading in this section are refuse trucks, but this loading is common to all section in the study.

Based on their visual appearance, the condition of all the straight sections on Kaweloka Street were better than those of the straight sections selected for the monitoring of crack sealing. This is illustrated in terms of cracking in control section 3'. As of March 15, 2015, the length of cracking on the section was 452 ft, or about $0.058\ ft/ft^2$. The value of $0.058\ ft/ft^2$ is about two to three times smaller than those shown in Figure 4-3 to Figure 4-5 for the straight sections in the cracking study. Thus, because of the combination of a smaller length of existing cracking and the additional bus loading, the potential for a higher rate of cracking progression was higher. Indeed, the slope of the trend with time of the cracking length per unit area was 0.756 $ft/day/10^4ft^2$, which is more than double the value of 0.355 $ft/day/10^4ft^2$ observed for the control section in Hoolauna Street used for monitoring crack sealing (Figure 4-3).

Figure 4-12 to Figure 4-15 show the cracking measurements with time for Sections 1 through 4, treated respectively with Plasti-Pave^{TM}, Liquid Road^{TM}, MasterSeal^{TM} RTU, and Opti-Pave Plus^{TM} RTU. As for control section 3', the initial cracking lengths and cracking lengths per unit area were smaller than those of the sections used in the crack sealing study, thus leading to a higher potential for developing additional cracking with all else equal (note that the first survey was performed with GPS and some of the information was lost, which explain why the measurement before treatment application is missing in some of these figures).

One surprising observation that immediately stands out from these results is that except for the section treated with the fog seal (Plasti-Pave^{TM}), which had a cracking progression rate of 0.505 $ft/day/10^4ft^2$, the cracking rates in the other treated sections were higher than the 0.756 $ft/day/10^4ft^2$ of the control section. Specifically, the values were 1.021, 1.256, and 1.338 $ft/day/10^4ft^2$ for the sections treated with Liquid Road, MasterSeal^{TM} RTU, and Opti-Pave Plus^{TM} RTU, respectively. No clear explanation can be found for these results, but the following provides some speculative arguments about potential causes. A major difference between the sections with seal coats and the control section is that the later had an aged grey color while the treated sections were black. Therefore, it is reasonable to expect that the sealed sections are absorbing more solar radiation during the day and that this, in turn, is leading to a higher daily pavement temperature range, translating into a higher rate of progression of environmental cracking. However, it seems implausible that additional environmental cracking is the sole reason for the large increases in the rate of cracking growth. Since the higher cracking progression rates of these sections, relative to those in the crack sealing study, can be attributed in part to the heavier bus loading, it is likely that there is a synergy between the additional environmental cracking (which would not be sealed) and loading, particularly in the presence of water in the base. Note that in this regard, one issue common to some areas of Honolulu with large slopes and drainage problems is that of substantial water flows under pressure running underneath the pavement. This is illustrated in Figure 4-16 taken during the demonstration of a product for pothole patching. Note that this photo was taken after the water had been sucked with a pump and after futile attempts to dry the pothole with a heat lance since the water kept rising slowly in a clear, sunny day. The situation on Kaweloka Street does not appear to be as critical, but still, the average grade (including ups and downs) over more than a mile is about 3% (the average grade on the downgrade portions is about 4.7%). Although this analysis is speculative, there were some indications of pumping on some of the cracks.

It should be noted that the results for section 3, treated with MasterSeal™ RTU, were also affected by a water main break soon after the start of the study (this was noted on the survey of 8/27/2015). Cracking on the portion affected was not collected from that day onward (initially, a provisional patch was performed and then two large patches repairing the affected areas were done). The length of the area affected by those patches was 54 ft or about a sixth of the section's length. However, for public relations reasons related to a request from neighbors when the City and County of Honolulu major visited the site, the application of the first coat on this section was extended 48 ft, which almost compensate the length lost in the patch (albeit with only one coat). Consequently, cracking was not collected on the 54 ft affected by the patches, but it was on the additional 48 ft treated with only one coat. Thus, although additional cracking related to the water main break may have affected the results, it is believed that this was not the main cause for the cracking to be higher than on the control section.

Note that the above speculations about the higher environmental cracking because of higher surface temperatures and the synergy between this additional environmental cracking and loading do not explain why the cracking progression rate in section 1, treated with PlastiPave™, was lower. The color of its surface immediately after treatment application had the same black appearance as the surfaces of the other three sections, so it should also lead to higher maximum pavement temperatures during the day. Yet, it cracked less than the control section. The difference is that, in this case, the treatment consists solely of a thin film of binder intended to rejuvenate the surface and make it more elastic whereas the other treatments contain different amounts of sand to provide a wearing surface. Thus, for a given amount of stretching, the binder between sand particles in the seal coats would be subjected to much higher strains. Apparently, the lower binder strains in the fog seal and its rejuvenation capabilities may help to counteract the effects of higher temperatures and lead to lower cracking than that observed on the control section.

Figure 4-17 to Figure 4-19 show the cracking measurements with time for control sections 6 to 8. The initial cracking on these sections ranges from about 500 ft to 800 ft, or in terms of cracking per unit area from 0.063 to 0.103 ft/ft^2 (note that for section 8, the first measurement is not available). As for control section 3', the initial cracking lengths were smaller than those of the sections used in the crack sealing study, thus leading to a higher potential for developing additional cracking with all else equal. However, unlike for section 3', the rates of cracking were of the same order of those for the straight sections in the crack sealing study, even though the later had much higher initial cracking lengths. In this case, the cracking grew at 0.379, 0.402, and 0.240 ft/day/10^{4}ft^2 for control sections 6, 7, and 8 respectively, which is about half the value for control section 3’ (0.756 ft/day/10^4ft^2). This appears to indicate that the bus loading was indeed an important contributing factor in the cracking progression of sections 3’ and 1 through 4. One potential factor driving the lower cracking rate in section 8 may be its higher initial cracking length, which is about 25% higher than those in sections 6 and 7. This may have reduced the potential for further environmental cracking. It is also interesting to note that section 7 had the largest grade with an average of about 2.8%, section 6 had an average slope of about 1%, and section 8 had the lowest with an average of about 0.6%. In addition to having the lowest average grade, section 8 contains a crest, so it is expected that any water infiltration would tend to run downstream. On the other hand, the average grade of section 6 was not much higher than that of section 8, but it is downstream of a portion of road with a larger average grade (of about 4% for a quarter of a mile). Therefore, there is a higher potential for underground water flows running with some pressure underneath it. Although the traffic loading on these sections is lighter, there may still be some synergy with environmental cracking. Again, all these are speculative arguments, but they are consistent with the order of the observed cracking rates.

Figure 4-20 shows the cracking trend for section 5, treated with CarbonSeal-HF. Consistent with the control sections 6, 7, and 8, that have no bus traffic, the rate of increase of cracking of 0.467 ft/day/10^4ft^2 was significantly smaller than those observed in the treated sections with bus traffic (0.756 ft/day/10^4ft^2). Nevertheless, similarly to what was observed for the sections with bus traffic, this rate was higher than any of the values for the control sections in the previous paragraph. However, in this case, the difference was smaller. A few factors are worth mentioning here. On the one hand, the finished color of CarbonSeal-HF is not black but a dark gray. In addition, the treatment started to fade much earlier than other treatments. Thus, the maximum pavement temperature increase should be lower than the corresponding values for the other treatments. This would tend to result in fewer additional environmental cracks. On the other hand, only about half of the section was crack sealed, which would tend to result in additional cracking caused by traffic loading. However, since there was no bus traffic, this is not believed to have been a significant factor.

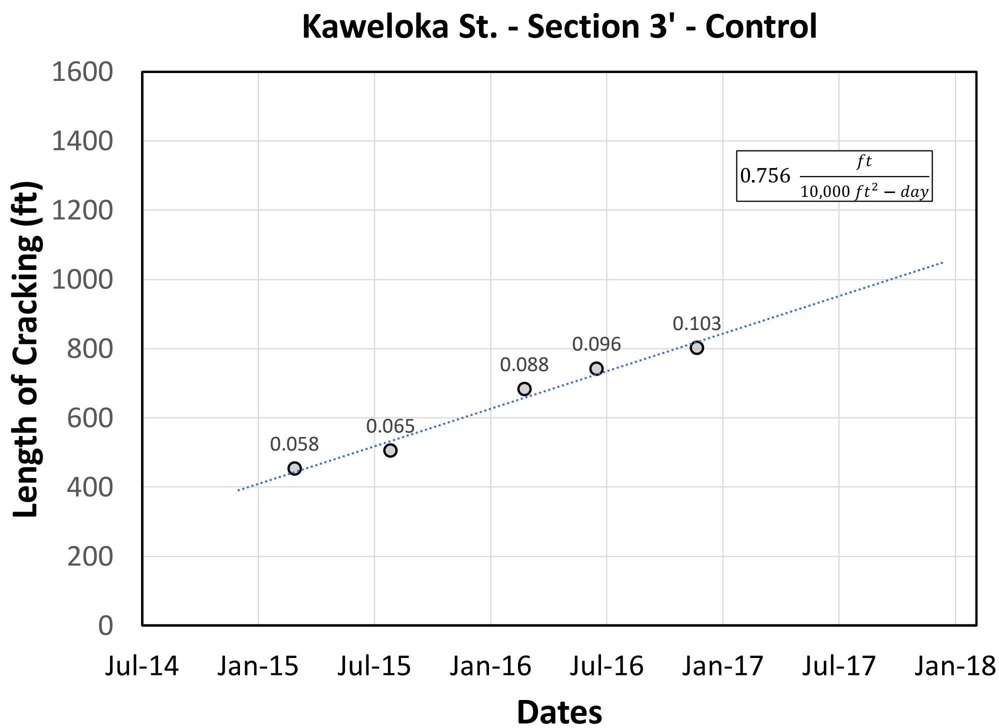


Figure 4-11 Cracking length progression over time in Kaweloka Street - Section 3’, control section.

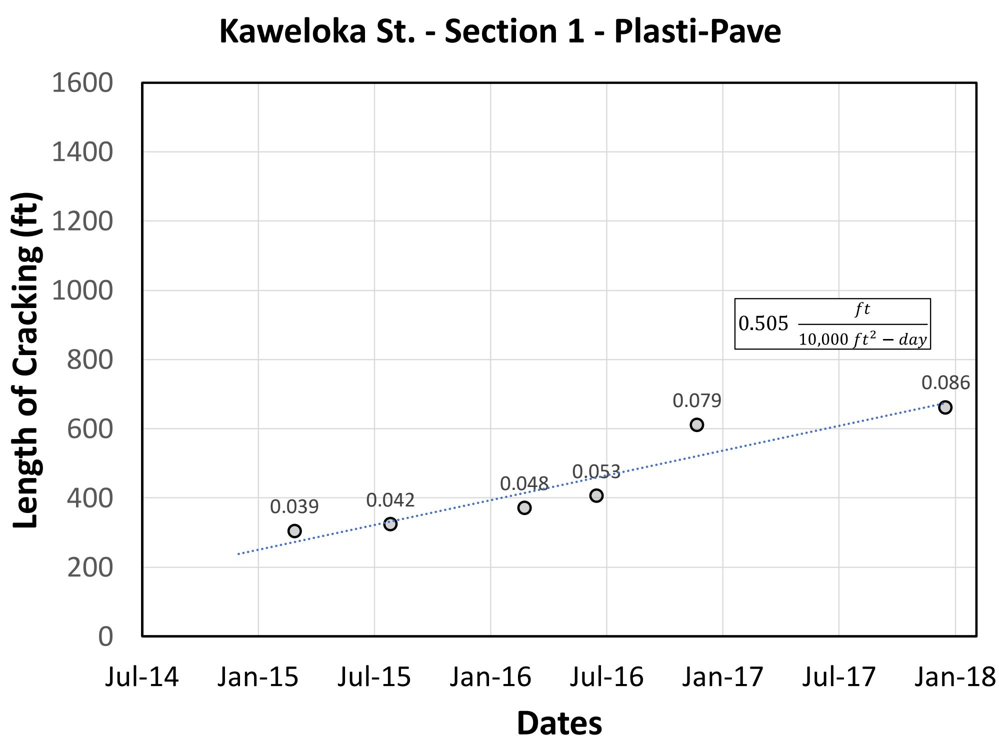


Figure 4-12 Cracking length progression over time in Kaweloka Street - Section 1, treated with SealMasters®/Hawaii Plasti-Pave.

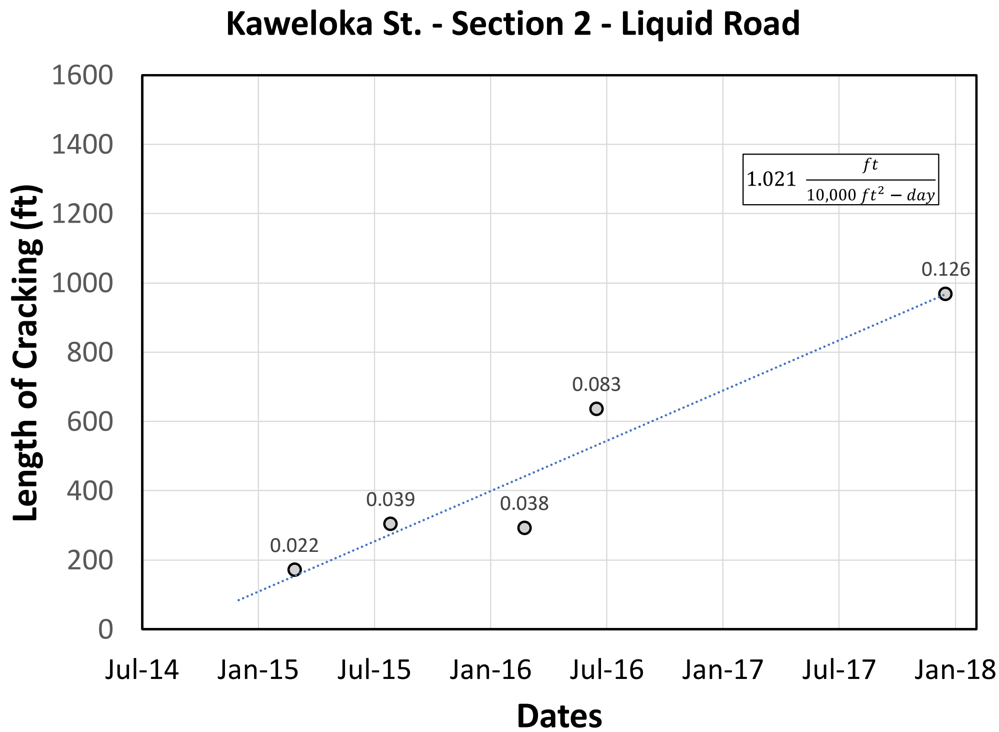


Figure 4-13 Cracking length progression over time in Kaweloka Street - Section 2, treated with SealMasters®/Hawaii Liquid Road.

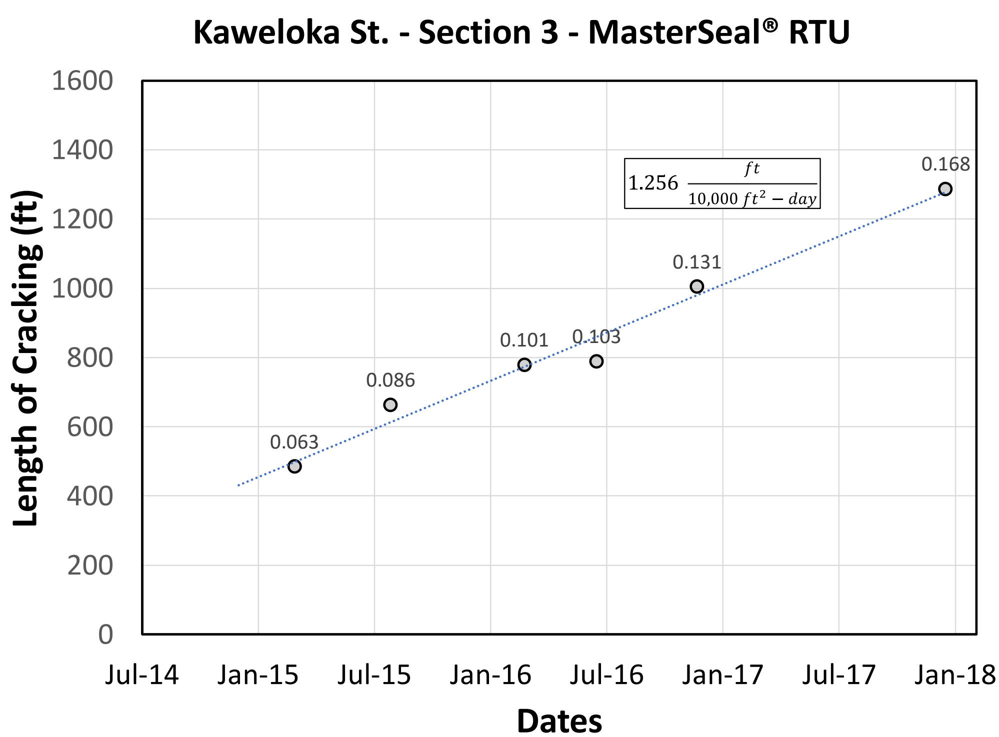


Figure 4-14 Cracking length progression over time in Kaweloka Street - Section 3, treated with SealMasters®/Hawaii MasterSeal Ready to Use.

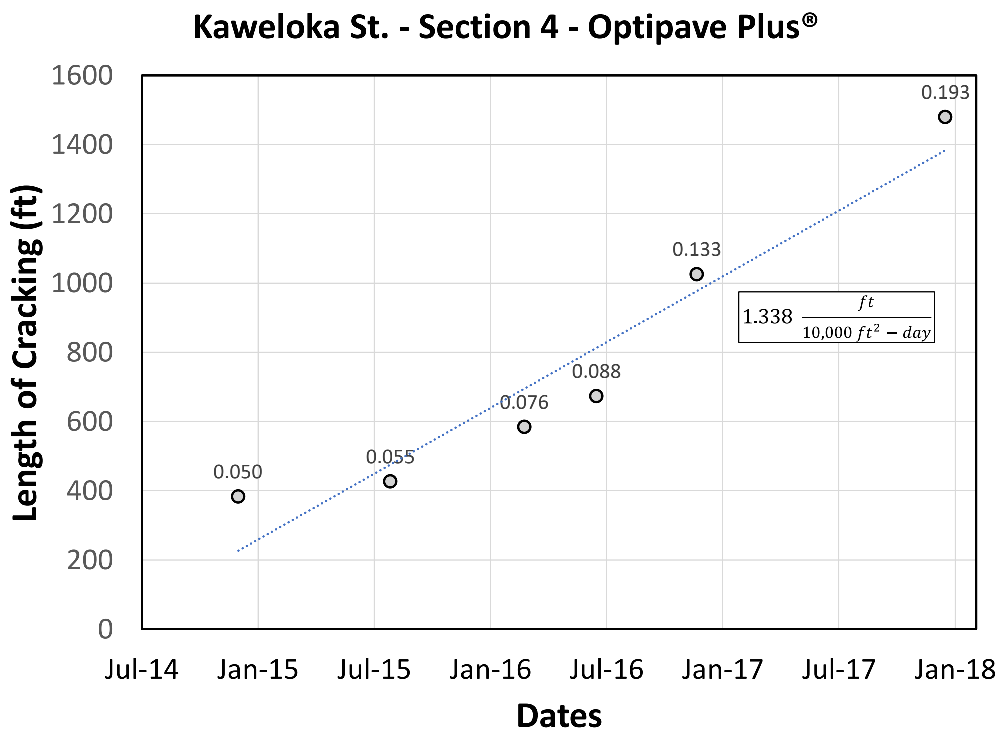


Figure 4-15 Cracking length progression over time in Kaweloka Street - Section 4, treated with SealMasters®/Hawaii OptiPave Plus Ready to Use.

Figure 4-16 Example of water raising from underlying layers through a pothole in a road with high longitudinal slow.

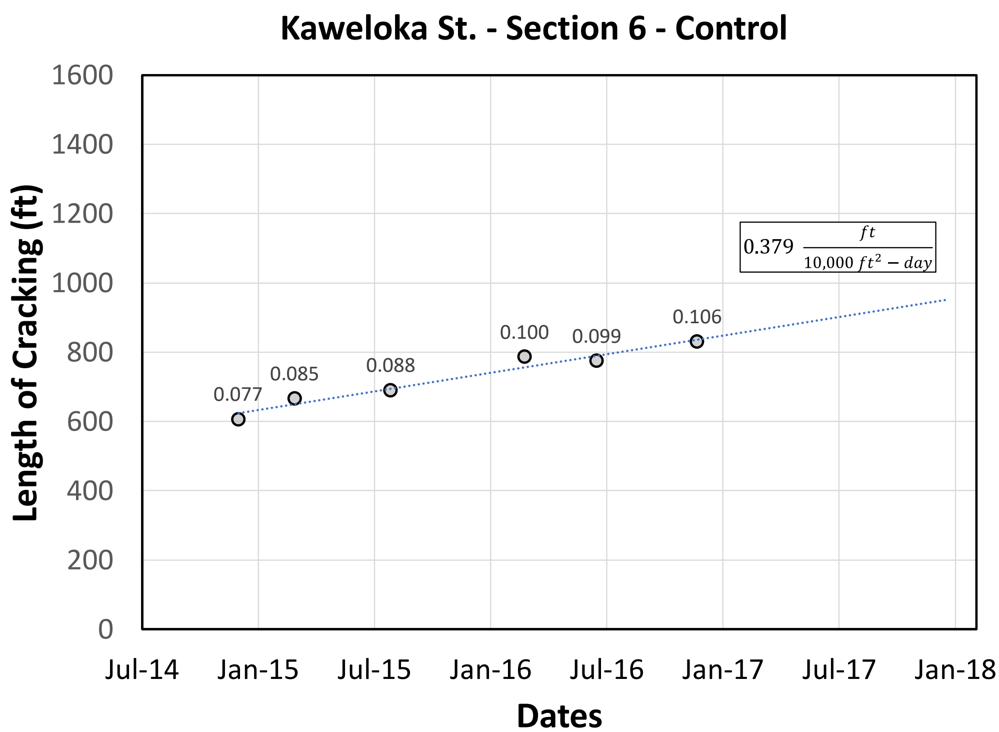


Figure 4-17 Cracking length progression over time in Kaweloka Street - Section 6, control section.

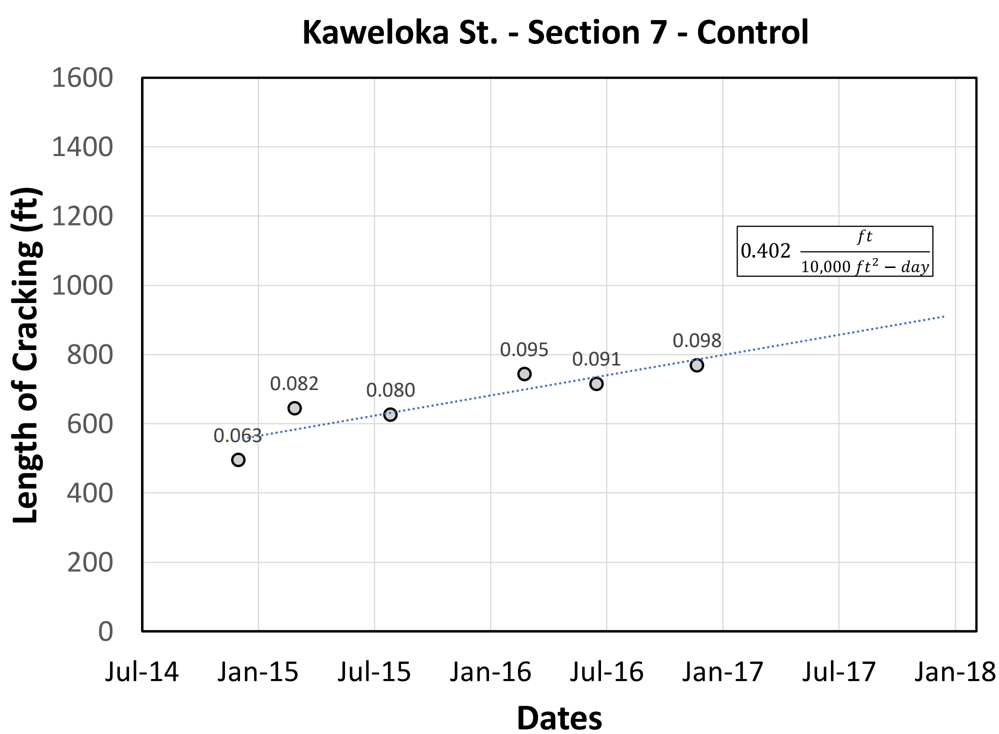


Figure 4-18 Cracking length progression over time in Kaweloka Street - Section 7, control section.

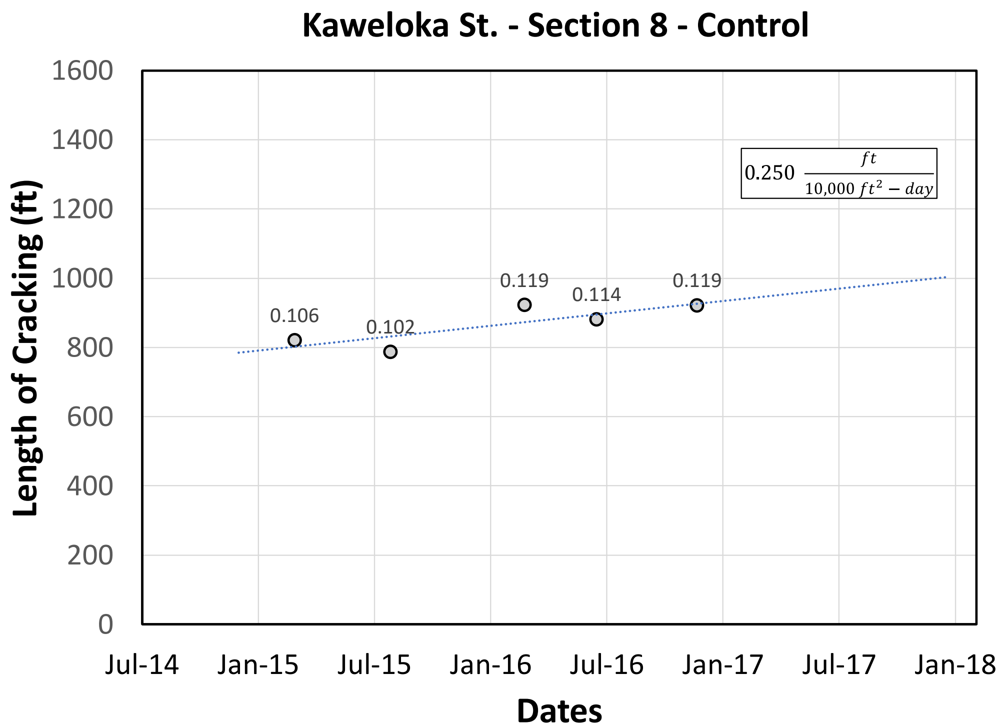


Figure 4-19 Cracking length progression over time in Kaweloka Street - Section 8, control section.

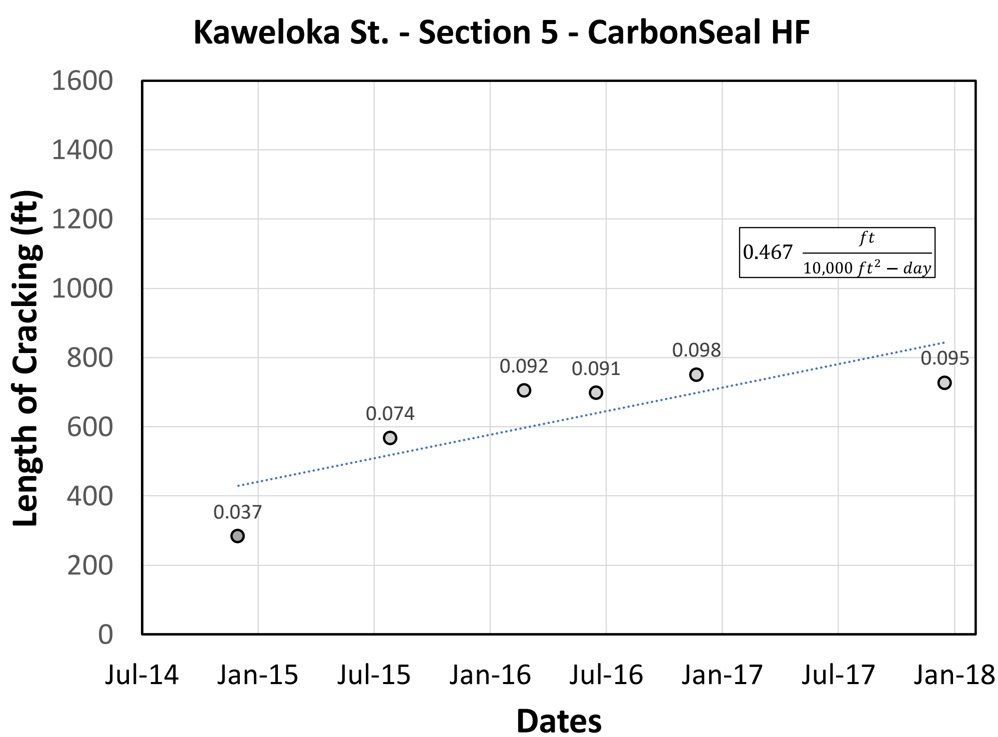


Figure 4-20 Cracking length progression over time in Kaweloka Street - Section 5, treated with CarbonSeal-HF.

Seal Coats in Cul-de-sac Sections

The locations of the sections for monitoring the performance of seal coats in cul-de-sacs were dispersed over larger area in Pearl City. The specific locations are shown in Appendix B. In addition to the products used in the straight sections (Plasti-Pave^{TM}, Liquid Road^{TM}, MasterSeal^{TM} RTU, and OptiPave Plus^{TM} RTU by SealMaster/Hawaii® and CarbonSeal-HF by Carbonyte Systems Inc.), one section was selected for treatment with Resurfacer by Brewer Cote. The work on that section was performed by Oahu Sealcoating & Paving LLC.

In the following discussion, the first observation was not included in the trend calculations since the section had not yet been treated and because of the different technology was used to collect the data. When available, the corresponding point is marked differently with a square symbol.

Figure 4-21 shows the cracking measurements with time for the control section on Kaumoli Place. This section was seal coated before the end of the study. Therefore, unlike for other sections, there is no observation for January 2018. The cracking progression growth was 0.576 ft/day/10^4ft^2, which represent a 62% increase with respect to the average rate (0.349 ft/day/10^4ft^2) of the three sections without bus traffic that were used as control for straight sections. Nevertheless, it is believed that this rate overestimates the actual rate because the last observation in December 2016 was obtained when the cracks in the section already had been sealed. Note that the section on Palamoi Street, which was selected as control for the crack sealing sections, can also be used as a reference here (there is nothing particularly different about this section and it is closer to most of the cul-de-sacs treated with seal coats). Recall that the rate for the Palamoi Street section was estimated as 0.363 ft/day/10^4ft^2 but that this value was also estimated with fewer observations. Thus, the rates from the two sections that can be used as reference have more uncertainty associated with them. In summary, based on the information of the two control sections on Kaumoli Place and Palamoi Street, the best estimate of the rate of cracking progression is between 0.363 and 0.576 ft/day/10^4ft^2. However, based on the values observed for the other sections in the crack sealing study, values closer to the lower end of the range seem more plausible.

The results for the other cul-de-sac sections discussed next appear to confirm that the cracking in the treated cul-de-sacs tend to be higher than for straight sections.

As in the case of the straight sections, the cracking trend on the section with PlastiPave^{TM} was an exception. In this case, the cracking rate shown in Figure 4-22 came out to be 0.190 ft/day/10^4ft^2, which is much lower than that of the control section (about one third lower). The reasons are believed to be the same as discussed for this treatment in straight sections. Another factor in this particular case may have been that the surface was usually dirty with clay material. Although this was thought to be a problem, it may also have altered the amount of solar radiation absorbed. Note that a final measurement on this section on 5/24/2019 resulted in a measurement of 175 ft. When this value was included in the rate calculation, the resulting rate was slightly smaller (0.178 ft/day/10^4ft^2). This measurement was considered important as it verified that rate was not artificially low but a real representation of the cracking rate on the section.

Figure 4-23, Figure 4-24, and Figure 4-25 show the cracking trends for the cul-de-sac sections treated Liquid Road, MasterSeal^{TM} RTU, and Opti-Pave Plus^{TM} RTU, respectively. The respective values were 0.669, 0.646, and 0.638 ft/day/10^4ft^2. They are moderately higher than the higher estimate for the control sections of 0.576 ft/day/10^4ft^2 but substantially higher than the lower estimate of 0.396 ft/day/10^4ft^2. Note that this observation is consistent with the thesis that the higher temperatures in the pavements due to absorption of solar radiation lead to additional cracking.

Figure 4-26 shows the cracking trend for the section on Hooheno Street, treated by Oahu Seal Coating and Paving with Resurfacer by Brewer Cote. In this case, a slight increase in the cracking rate to 0.672 ft/day/10^4ft^2 is noted in the trend. This observation does not provide evidence that a benefit is obtained by performing power washing of the cracks and the pavement surface as was done on this pavement section.

Finally, Figure 4-27 shows that the rate of cracking increase for the section treated with CarbonSeal-HT was 0.460 ft/day/10^4ft^2. Since this value is within the range for the control sections discussed above, nothing can be said conclusively about whether the rate of cracking progression is higher or lower than for the control sections. As speculated before, if the values closer to the lower limit were indeed more plausible, this would still indicate a slight increase in the rate with the application of the seal coat. Regardless of how this treatment compares with the control sections, its cracking progression rate is lower than any of the values for the other seal coated sections in cul-de-sacs (except for the value for the section treated with PlastiPave™). As discussed before, this may be related to the fact that CarbonSeal-HT has a dark gray color instead of the black color of the other treatments, and that started fading much earlier, which may lead to slightly lower maximum pavement temperatures.

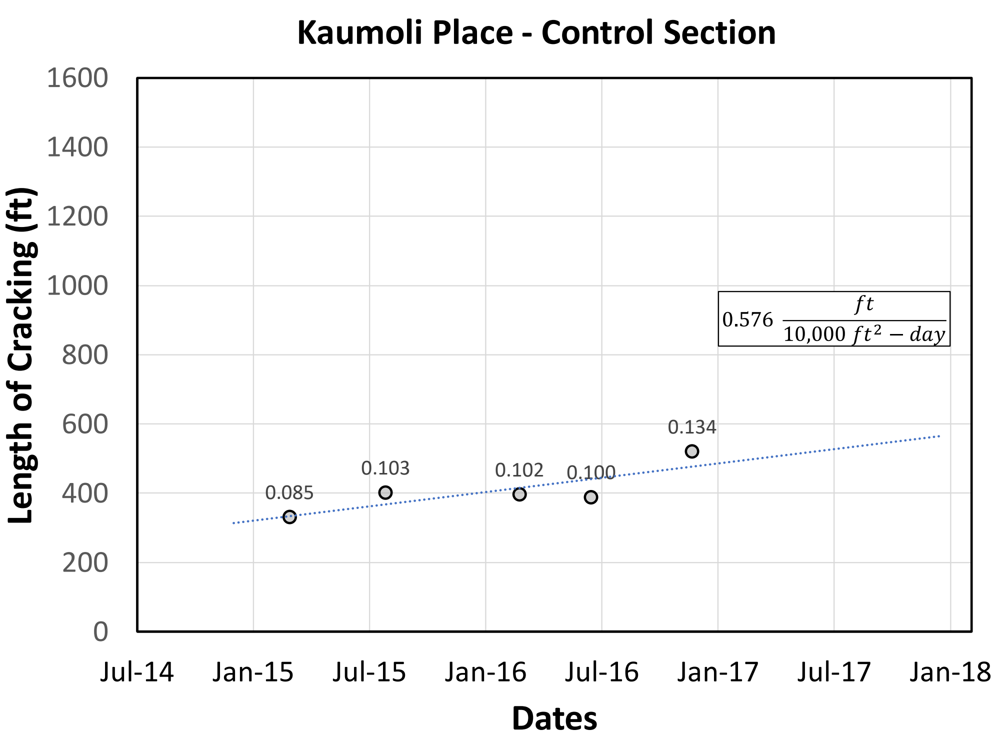


Figure 4-21 Cracking length progression over time in the cul-de-sac control section on Kaumoli Place, Pearl City.

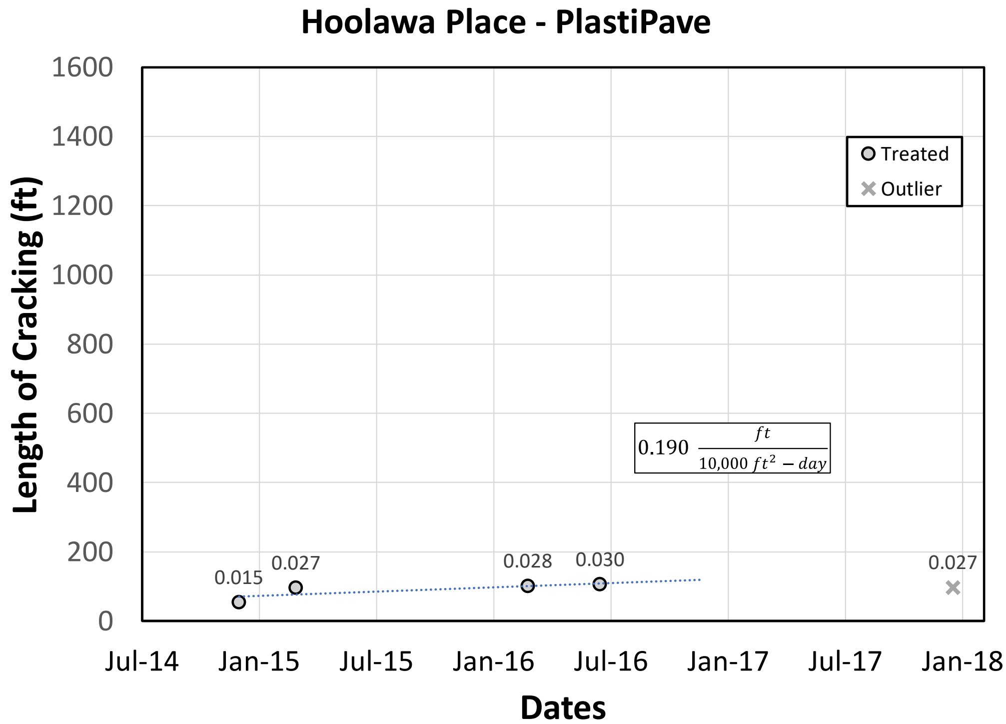


Figure 4-22 Cracking length progression over time in Hoolawa Place, treated with SealMasters®/Hawaii Plasti-Pave.

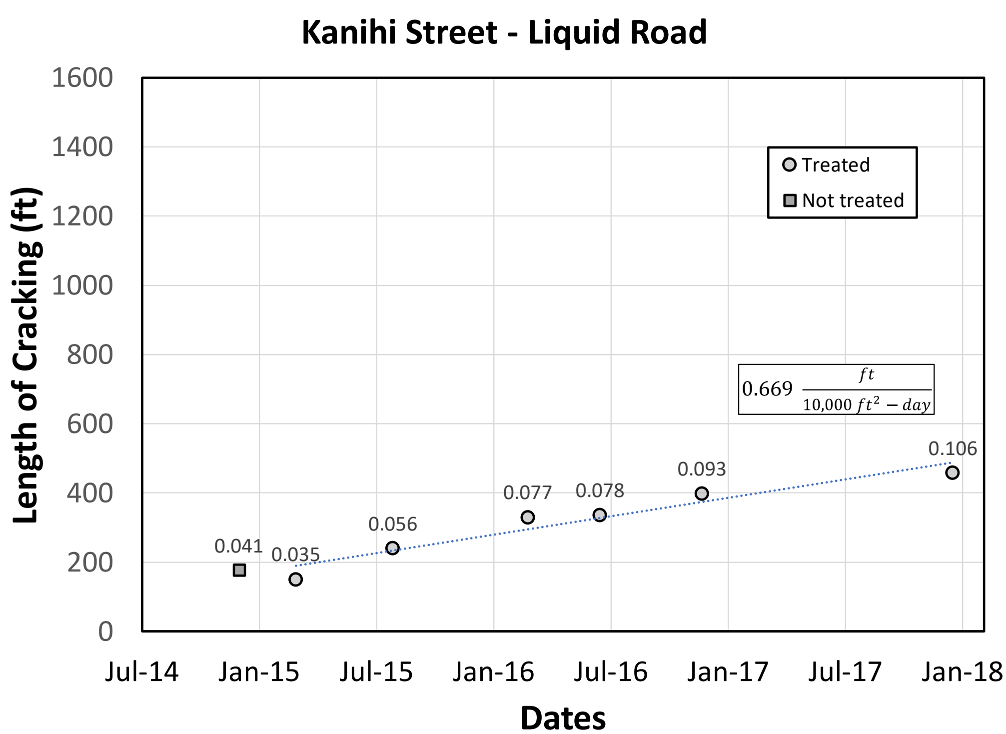


Figure 4-23 Cracking length progression over time in Kanihi Street, treated with SealMasters®/Hawaii Liquid Road.

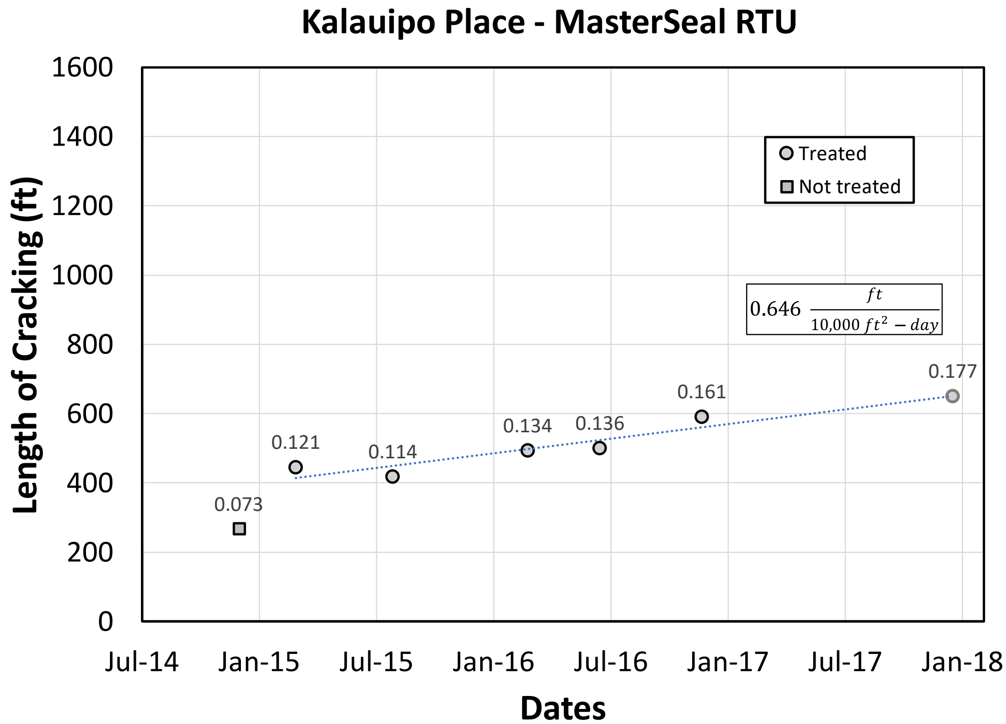


Figure 4-24 Cracking length progression over time in Kalauipo Place, treated with SealMasters®/Hawaii MasterSeal™ Ready to Use.

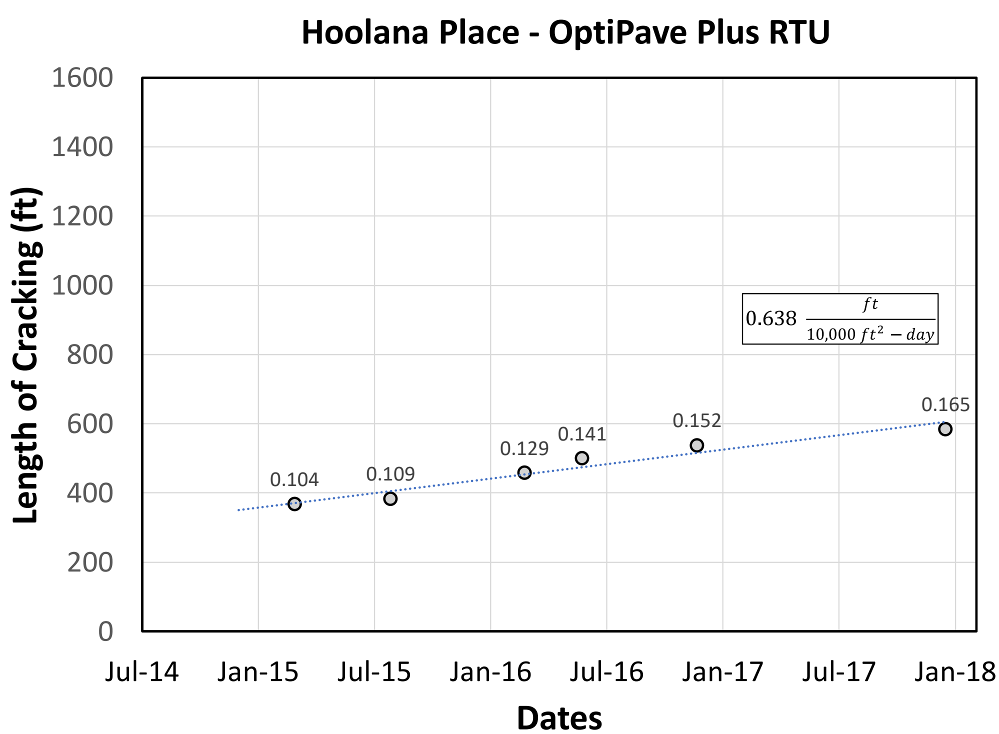


Figure 4-25 Cracking length progression over time in Hoolana Place, treated with SealMasters®/Hawaii OptiPave Plus™ Ready to Use.

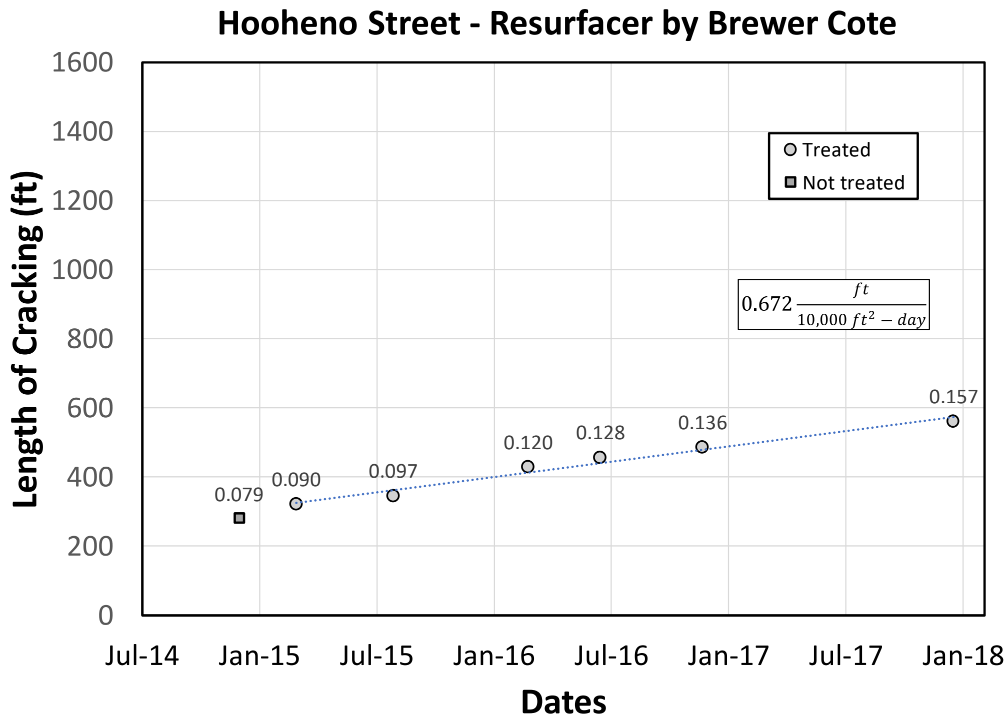


Figure 4-26 Cracking length progression over time in Hooheno Street, treated with Resurfacer by Brewer Cote (work performed by Oahu Seal Coating and Paving).

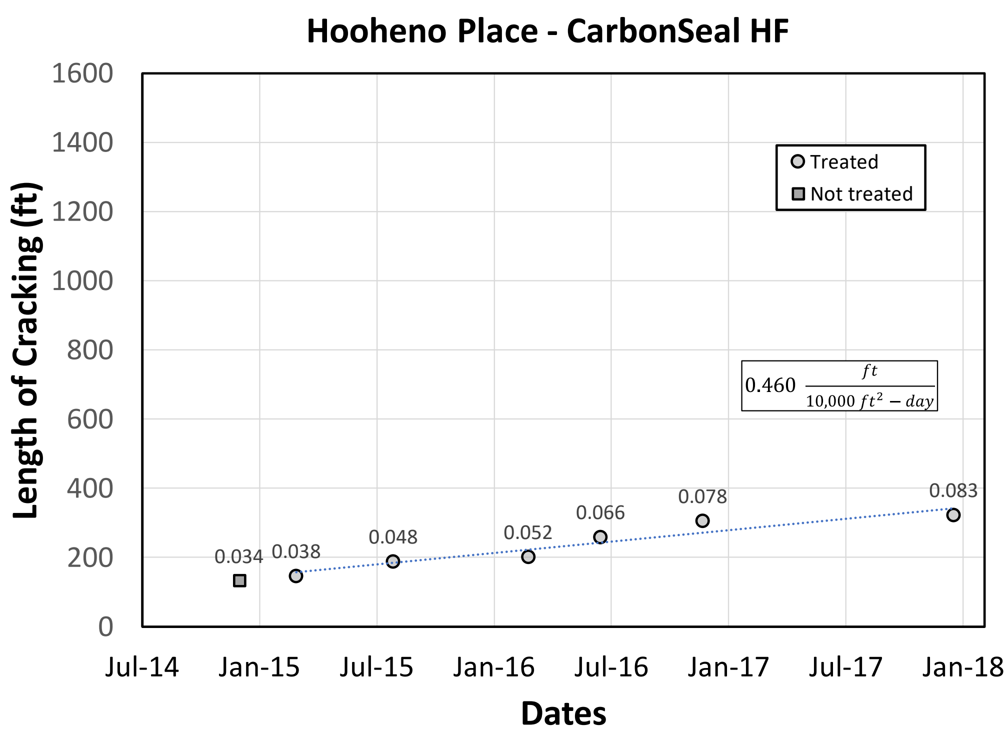


Figure 4-27 Cracking length progression over time in Hooheno Place, treated with CarbonSeal-HF by Carbonyte Systems Inc.

4.2.2 Slurry Seal Sections

This section discusses the performance of the treatments falling into the slurry seal category. Unlike all the other treatments, these pavement sections were not treated specifically for this study but instead they were selected from work already programmed by the City and County of Honolulu (C&CH) in area of Waipahu. The slurry seal treatments were applied by Alakona Corporation under contract with C&CH. One long straight away section and two cul-de-sacs sections were selected for monitoring. Their locations within Waipahu are shown in Figure Figure 4-28. These sections were selected in big part because their programmed application matched the beginning of this study.

Since eventually all the Waipahu area would be treated, it was not possible to select nearby control sections. Consequently, the same straight and cul-de-sac sections selected in the study of seal coats are used as a baseline reference.

In all slurry sealing jobs monitored, crack sealing was first applied followed by a single application of slurry. One advantage of selecting this pre-programmed work was that there was in general additional time between the crack sealing operation and the application of the slurry seal.

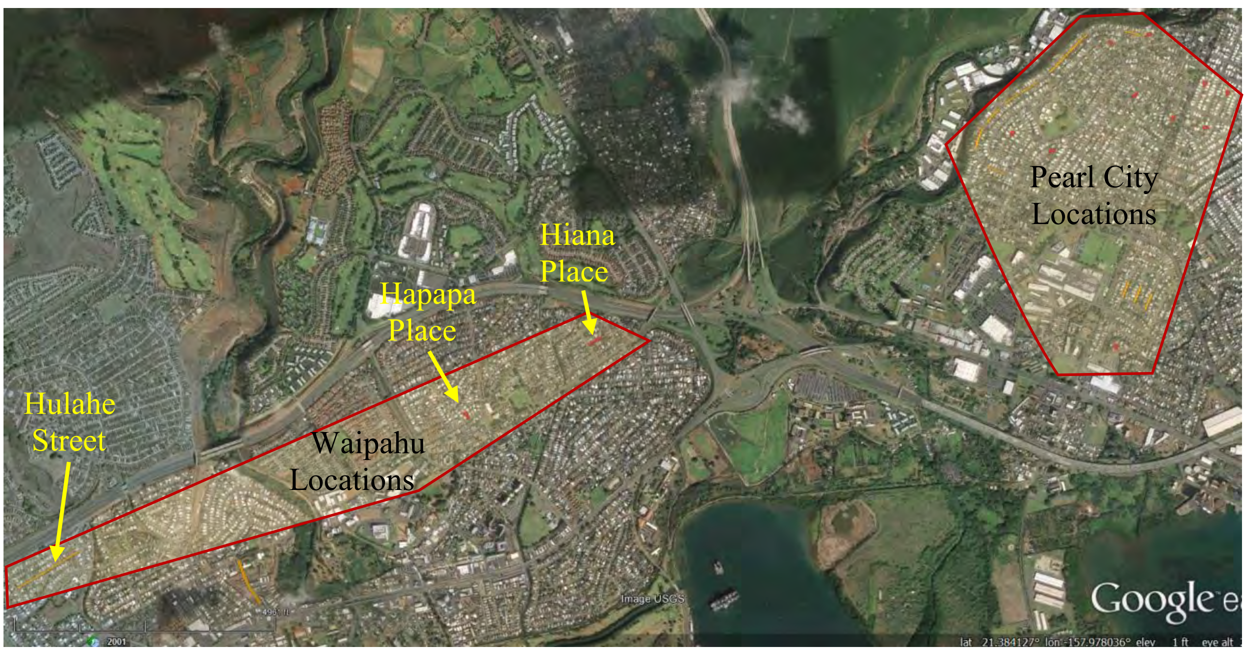


Figure 4-28 Locations of the slurry seal section in Waipahu.

Since slurry seals are thicker than the other seal coats considered in this study, identification of previously sealed cracks underneath slurry seals is more difficult than for seal coats, or sometimes simply not possible, particularly shortly after the treatment application (over time, sealed cracks underneath the slurry seal tend to become more visible). Thus, trying to monitor the total length of cracking, regardless of whether a crack was sealed or not, would have resulted in more uncertain measurements since it would have been difficult to discriminate whether a new crack on the surface of the slurry seal corresponded to an entirely new crack or to an existing sealed crack. Therefore, the total length of cracking, as seen on the surface of the slurry seal, was monitored regardless of severity. Note that this is different from what was measured in the seal coat study, where the sealed cracks were added to the length of new cracks. However, both types of measurements should result in similar information about the rate of increase of cracking on a section.

As in the study of seal coats, visual observations were used for other issues such as raveling of the slurry seal surface and other defects. These are discussed in the chronological observations for the respective sections in Appendix C.

Slurry Seal in a Straight Section

A single long section on Hulahe Street, treated on 12/17/2014, was selected to monitor the slurry seal performance on straight sections. This section has no bus traffic, so it was considered comparable to the sections without bus traffic on Kaweloka Street. The original plan was to subdivide this section into four different sections of about the same length (320 ft) used for other treatments; however, for practical reasons, this road was monitored as a single 1400 ft long section. Its average grade is about 0.5%, but because of ups and downs, 1.5% is more representative of the grade vehicles face on most of the road.

Figure 4-29 shows the cracking trend observed in this section. The big drop in cracking length from the measurement when the section had not yet been treated to the first observation after the slurry seal application is simply a reflection of the fact that, as explained earlier, existing sealed cracks were not recorded in the cracking length.

The cracking length per unit area before the treatment application was only 0.020 ft/ft^2, which is much lower than the values of 0.077 ft/ft^2 and 0.063 ft/ft^2 observed for control sections 6 and 7 without bus traffic on Kaweloka Street. The initial value for the other control section without bus traffic on Kaweloka Street, section 8, which has a more comparable grade, was estimated to be around 0.100 ft/ft^2. Thus, the lower initial level of cracking in Hulahe Street may result in a higher potential for additional new environmental cracking.

As shown in Figure 4-29, the observation obtained on 12/13/2016 was considered an outlier since the higher cracking length on that date was believed to be caused by cracking around another water main break. Excluding that observation, the estimate of the cracking progression rate on this section is 0.374 ft/day/10^{4}ft^2. This value is of the same order of those estimated for control sections 6 and 7, respectively 0.379 ft/day/10^{4}ft^2 and 0.402 ft/day/10^{4}ft^2, but higher than the value of 0.250 ft/day/10^{4}ft^2 estimated for section 8. These results complicate comparisons with the Kaweloka Street sections. On the one hand, if everything were equal, one could conclude that the slurry seal does not significantly alter the cracking progression rate; but on the other hand, given the initially much lower cracking length in the section, the potential for additional environmental cracking is higher. Of course, other factors could play a role in these comparisons as well. Nevertheless, similarly to what was observed for the other treatments, although the application of slurry seal may alter somewhat the rate at which the cracks appear, it does not seem to alter much the cracking pattern that would have eventually appeared had the treatment not been applied. In this pavement section, most of the cracking was longitudinal. In only a few places, a block cracking pattern was seen.

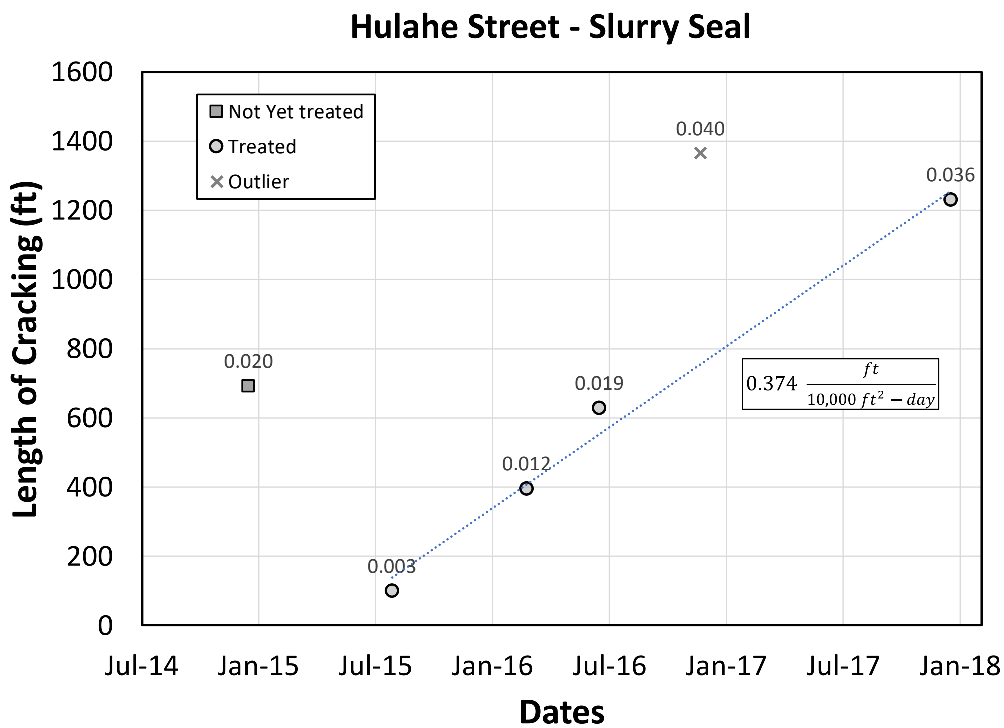


Figure 4-29 Cracking length progression over time in the Hulahe Street section, treated with Slurry Seal by Alakona Corporation.

Slurry Seals in Cul-de-sac Sections

Figure 4-30 shows the cracking trend in the Hiana Place section while Figure 4-31 shows the trend on the Hapapa Place section. The estimated rates for these sections are 0.312 ft/10^4ft^2/day and 0.698 ft/10^4ft^2/day, respectively. These values are quite different from each other, but this may be explained in part by the different section areas. Although the Hiana Place section does contain a cul-de-sac with a diameter of about 60 ft, its length is 268 ft. Consequently, the contribution to the cracking length within the 208 ft straight portion represents a much higher share of the cracking in the section than for the typical 100 ft-long sections of the other cul-de-sacs in this study (with just about a 40 ft straight portion contribution). The geometry of the Hapapa Place cul-de-sac is closer to the typical geometry in the other cul-de-sac sections. Specifically, this section has a length of 132 ft and a diameter of 63.7 ft. Because of this, the Hapapa Place measurements are expected to be more representative for comparison with the other cul-de-sacs.

The results are indeed consistent with these observations. For example, the 0.312 ft/10^4ft^2/day rate in the Hiana Place section is of the same order but smaller than the 0.374 ft/10^4ft^2/day estimated for the Hulahe Street also treated with slurry seal. It is interesting to note that the crack length in the Hiana Place section never got back to the level before the treatment application.

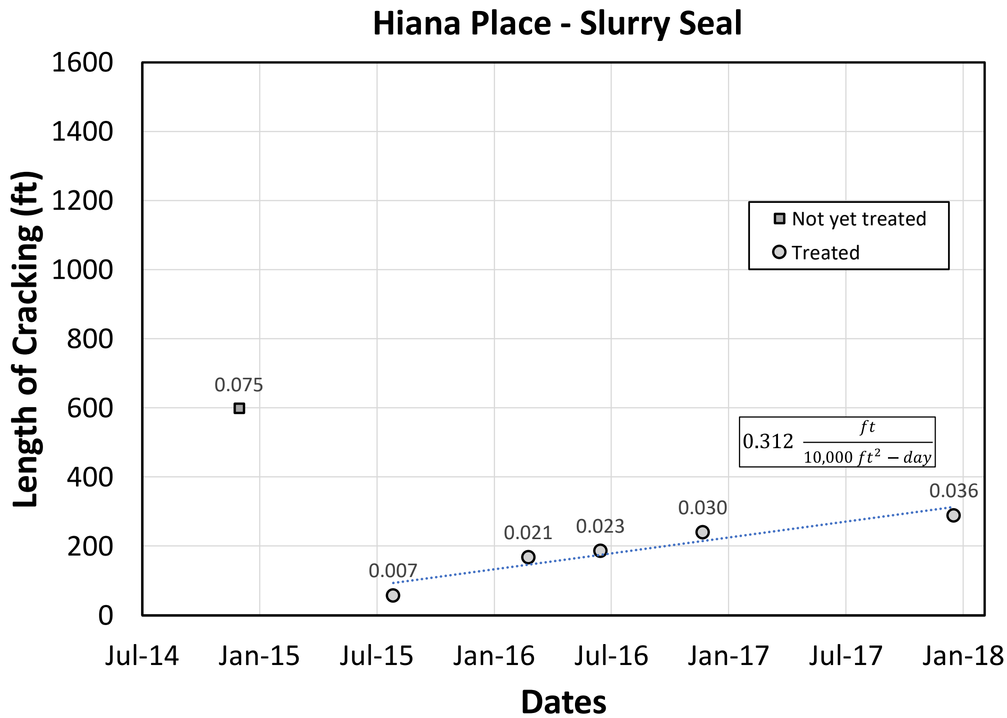


Figure 4-30 Cracking length progression over time in Hiana Place, treated with Slurry Seal by Alakona Corp.

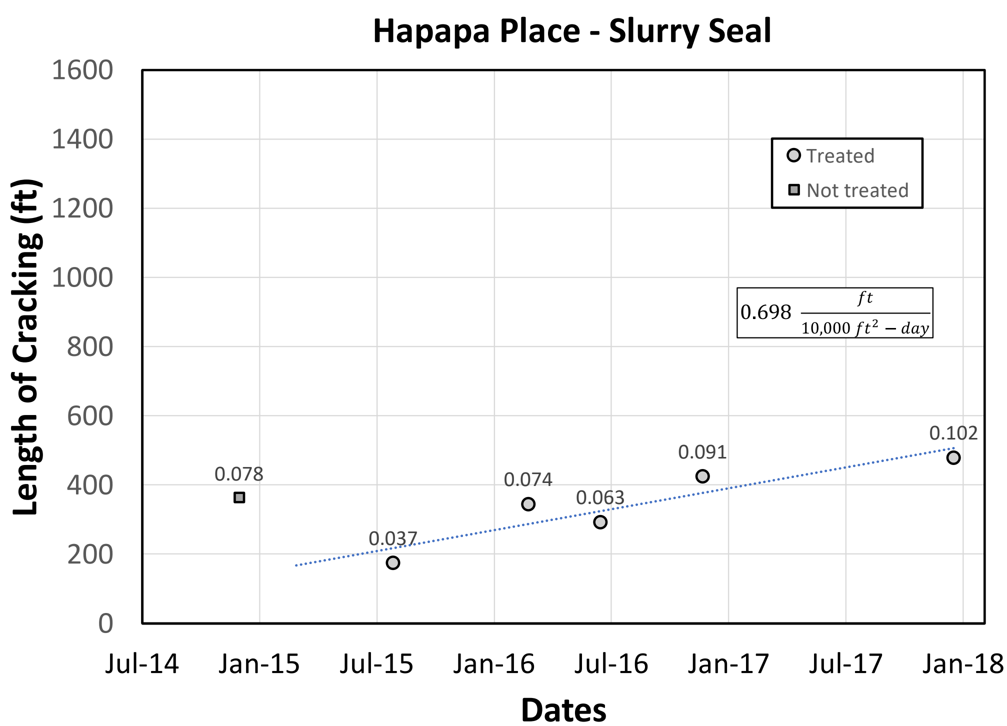


Figure 4-31 Cracking length progression over time in Hapapa Place, treated with Slurry Seal by Alakona Corp.

On the other hand, the value of 0.698 $ft/10^4ft^2/day$ in the Hapapa Place cul-de-sac is strikingly close to several of the values estimated for other cul-de-sac sections treated with seal coats. Specifically, recall that the values estimated for the sections treated with Liquid Road, MasterSeal^{TM} RTU, OptiPave Plus^{TM} RTU, and Resurfacer were 0.669, 0.646, 0.638, and 0.672 $ft/10^4ft^2/day$, respectively.

4.3 SUMMARY OF OBSERVATIONS FROM THE MONITORING STUDY AND RECOMMENDATIONS

A main goal of this study was to quantify the benefits of different pavement preservation treatments to facilitate their adoption and use in pavement preservation programs in a tropical environment such as Hawaii.

The previous section described in detail the cracking progression rates observed in the study. Except for the quantification of cracking rates with the different treatments (and without them), other observed performance issues are difficult to quantify. The other issues observed during the study period are discussed in chronological order for each pavement section in appendix C). The subjectivity in the evaluation of some of these issues makes the development of recommendations difficult. This is particularly true about the treatment lives, as the observation period was only slightly more than 3 years (but an additional visual observation was performed after 4.5 years). Nevertheless, the observations in the study are helpful to provide some guidance on their benefits and some minimum treatment lives. This section summarizes the findings from the combined observations about cracking rates in the previous section and any other issues observed during the study period discussed in chronological order for each section in the lengthy appendix C.

4.3.1 Seal Coats and Slurry Seal

A difficulty with the determination of a treatment's life is that there is no clear threshold for when a treatment stops being effective. Clearly, pavement preservation treatments are used to extend the pavement service life. But these treatments in general, and certainly those evaluated in this study, do not add any structural capacity. The life extensions are in the form of difficult to quantify benefits such as reductions in raveling or lower rates of water infiltration into the pavement structure, which help to preserve the integrity of the pavement surface and its structure. However, quantification of raveling is complicated. Most distress surveys either record its existence or not on a certain area without regard to its degree or severity level (*8*). Yet, development of raveling is usually very gradual as illustrated in many of the photographs presented in this study. Consequently, except for clearly severe cases, quantifying areas affected by raveling becomes quite challenging and subjective, leading to high uncertainties in reported values. For this reason, no attempts were made in this study to measure areas with this distress, as it was believed that such observations would have been inconsistent over time.

At first sight, the functional condition of treated and untreated sections may appear to be similar. However, as shown for several sections, there were clear indications of some raveling in the untreated sections (loose aggregates, missing coarse aggregates, and loss of fine aggregate/mastic), while no such indications were seen in the treated sections. But what are the benefits of the avoidance of some aggregate loss on the surface? Again, this is difficult to quantify. However, this is akin to quantifying the benefits of a single oil change in a car. One can usually get away with extending the time of a single oil change or even skipping it once, but if no oil change is ever performed or if they are performed on much longer cycles than recommended, the car engine life will be shortened significantly. In the context of pavements, this will be manifested in surfaces reaching states like those shown in Figure 4-32. At that stage, the functional problem requires an expensive solution, which could have been avoided with proper timing of maintenance or preservation activities. Even if the problems arise from mix design of the wearing course, a preservation treatment has the potential to lengthen the useful life of the original surface. These examples illustrate what would eventually happen on roads left untreated.

Figure 4-32. Illustrations of the disintegration of the pavement surface from severe raveling left untreated and the unsightly stop-gap repairs needed.

In this study, a clear benefit was observed on the sections treated with seal coat/slurry seal in terms of protection of the existing surface from developing further aggregate loss or raveling. In all cases, regardless of whether the treatment was applied on a straight segment or a cul-de-sac, any incipient raveling was completely arrested during the study period. Furthermore, the seal coats and slurry seals controlled the effects of oxidation on the existent pavement while providing a new thin sacrificial layer. For most sections, there was still a high color contrast between the treated and untreated pavement surfaces at the end of the study period. Thus, provided the pavement is kept in sound structural condition and water infiltration into the underlying layers is minimized, the life extension of this treatments can be regarded as the life of the treatment itself.

It is important to note that some treatments started to wear off or fade earlier than others. One particular seal coat product started to fade before two years; and after three years, it had faded substantially, showing an uneven appearance (see the discussion for section 5 on Kaweloka Street). But even in that case, no signs of raveling were noted on the treated section after three years while they were quite evident in the adjacent untreated pavement surfaces. After 4.5 years, the treatment on that section was no longer providing protection. Thus, based on that treatment performance, the minimum effective duration of seal coats is at least three years. Nevertheless, the "treatment surface" at the end of the period on most of the treated sections was still in relatively good condition after 4.5 years (note that "treatment surface condition" should not be confused with the "pavement condition"). Consequently, even though it is recognized that most of the treatments may last longer, conservatively, it is recommended to use 4 years as the life of seal coats for programming pavement preservation work on low volume city streets. Note that for the Liquid Road seal coat, which is a thicker application, the 4-year recommendation is considered too low, as after 4.5 years there is still a considerable wearing thickness. Thus, a 5-year life is recommended for Liquid Road.

Slurry seals are even thicker applications that provide substantial sacrificial material. Based on their appearance at the end of this study and other informal observations in the Waipahu area, which has been preserved with slurry seals for more than 5 years, the use of a 6-year life is recommended for programming purposes for the same type of road.

Although the lives of some treatments may be longer, those cannot be recommended based on the time-limited observations in this study. In addition, no recommendation can be given for higher volume roads since such roads were not observed. These are likely to suffer a faster wearing off rate. Until better local estimates are available, for higher volume roads such as arterials, local agencies would need to rely on estimates such as those in Table 2-1 or similar.

Note that the above recommendations are linked to the provisions that the pavement is structurally adequate and that water infiltration into the underlying layers is minimized. Regarding the pavement structure, it is important to stress that the selection of an adequate thickness of asphalt concrete at the pavement design stage is an integral part of pavement preservation. In this study, this issue came about by chance because of the different performance of the sections with and without bus traffic. Clearly, the much larger rate of cracking increase together with some signs of fatigue cracking in the sections with bus traffic indicated that their pavement thicknesses were inadequate for the existing traffic loading. Thus, the benefits of pavement preservation in this situation are very limited because the pavement structure is inadequate. This is evidenced by the photos in Figure 4-33, which shows fatigue cracking progressing in all the sections with bus traffic on 05/24/2019.

Regarding water in the pavement structure, pavement preservation can help by reducing the amount of water infiltration through cracks into the underlying layers. Crack sealing is the appropriate treatment for this purpose. All the sections that were seal coated or slurry sealed in this study were previously crack sealed. Thus, all the sections started with a completely sealed surface.

Figure 4-33 Fatigue cracking progression in the sections with bus traffic.

A very surprising result of this study was that the sections that were seal coated were observed to have higher rates of cracking length increase than the control sections. This was observed consistently in straight and cul-de-sac sections. Apparently, the black color of the treatments makes the pavement surfaces (and hence the asphalt concrete underneath) reach higher maximum temperatures, which in turn lead to faster environmental cracking. However, the increased on cracking rates were more dramatic in the bus loaded sections, indicating that there is an interaction between the additional environmental cracking caused by the higher temperatures and traffic loading. As seen in the top right photo in Figure 4-33, in some situations the fatigue cracking appears to be more developed in a treated section than on the adjacent untreated pavement.

The practical consideration of the above finding is that the frequency of crack sealing on sections with seal coat treatments (as discussed later) should not be reduced with respect to untreated sections. In fact, in this situation, it would be convenient to use the shortest practical cycle to preserve the investment in the seal coat.

4.3.2 Fog Seal

The fog seal applied to the straight section on Kaweloka Street started to fade significantly between two and three years in service, which is consistent with the upper limit of the typical recommendation of between 1 to 2 years for fog seals. However, the sealer left on the pavement surface at the end of the study period still occupied many of the valleys between aggregates and may have still been contributing to the reduction of raveling. Note that no notable raveling was noted in this section throughout the study. Consequently, a conservative estimate for the life of this treatment is 2 years for sections with low volume.

On the other hand, no fading was seen after three years for the section in cul-de-sac, which is reasonable since it was subjected to the much lower level of traffic imposed mostly by the vehicles accessing the houses in the cul-de-sac. On the other hand, after 4.5 years, the treatment is fading is areas exposed to water running on its surface. Thus, for cul-de-sacs, the above life estimate can be extended to 3-years.

What was surprising about this treatment is that in both cases, the straight section and the section in cul-de-sac, the rate of cracking increase in the treated sections were lower than those in the corresponding control sections, which in turn were lower than the rates in the sections treated with other seal coats and slurry seal. Apparently, the rejuvenator function of the fog seal overcomes any increased in temperature range caused by the darker color of the pavement surface with the fog seal.

4.3.3 Crack Sealing

Both the “clean and seal” and “rout and seal” procedures were used in this study to seal cracks in both straight away and cul-de-sac sections. In general, the sealant in cracks sealed with the “rout and seal” method was still performing adequately at the end of the study period, maintaining contact with the crack walls and effectively sealing the cracks. A similar finding was made for cracks sealed with the “clean and seal” method when their width was somewhere larger than about 10 mm (3/8 in). In general, the crack sealer often stopped performing well in thinner cracks sealed with the “clean and seal” method within 1.0 to 1.5 years. In very thin cracks, sometimes practically no sealer was seen inside the crack. In those cases, the sealer does not go deep enough within the crack. On wider cracks, but still smaller than about 10 mm (3/8 inch), the sealer is still subjected to strain levels that are too high for the sealant or the bond between the sealant and the crack face. Note that 10 mm (3/8 inch) is an approximate value.

The question of what method to use in a given situation depends on prevailing costs and agency policies and preferences, which is beyond of the scope of this study. Clearly, for thin cracks, the “rout and seal” method provides a longer and more effective sealing since it guarantees an adequate reservoir with vertical faces to which the sealer can bind and enough width that makes the strain in the binder and the bonding forces with the crack walls to reach adequate levels for good performance. On the other hand, because of its lower costs, the “clean and seal” method can be used more often to reseal previously sealed cracks. This may be preferable when revisiting sections in short cycles to seal new cracks and resealed exposed thin cracks. However, in situations where it is essential to avoid all water infiltration into the pavement structure, the “rout and seal” procedure may be preferable.

In the straight sections, crack sealing was found to have a beneficial effect by reducing the rate of cracking increase. Although the cracking was mostly environmental, the reduction of water infiltration appears to reduce any contribution to the crack growth by traffic loading. The results in the cul-de-sac sections were not as revealing, but still consistent with the reduction of the rate of cracking increase.

The findings in this study support the adoption of continuous crack-sealing programs where sections are revisited recurrently to seal new cracks and to reseal previously sealed cracks that have been exposed. A cycle of at most two to three years is recommended, since the cracking length increase in such a period is significant. In addition, the sealant in some of the sealed cracks will stop performing at a faster rate as the sealer ages.

5 MONITORING OF TEMPERATURE VARIATIONS OVER TIME WITH DEPTH

5.1 INTRODUCTION

Top-down fatigue cracking (TDFC) is a common type of distress observed in many parts of the US and other countries (*9*) on heavy duty Hot Mix Asphalt (HMA) pavements. It is also suspected to be common on thick HMA pavements in Hawaii (*10*). Figure 5-1 shows the cracking pattern observed on a portion of Highway 72, Kalanianaole Highway in Oahu, which is a typical well-developed cracking pattern observed on two-lane two-way (TLTW) state highways in Hawaii. The meandering longitudinal cracks on the wheel paths are quite evident but these are accompanied but other transverse cracks. To some, this pattern may look like that arising from block cracking enhanced by loading. However, as illustrated in Figure 5-2 for a newer pavement surface on another section of the same highway, it is typically the opposite, with the cracks starting mostly longitudinally in the wheel paths because of loading.

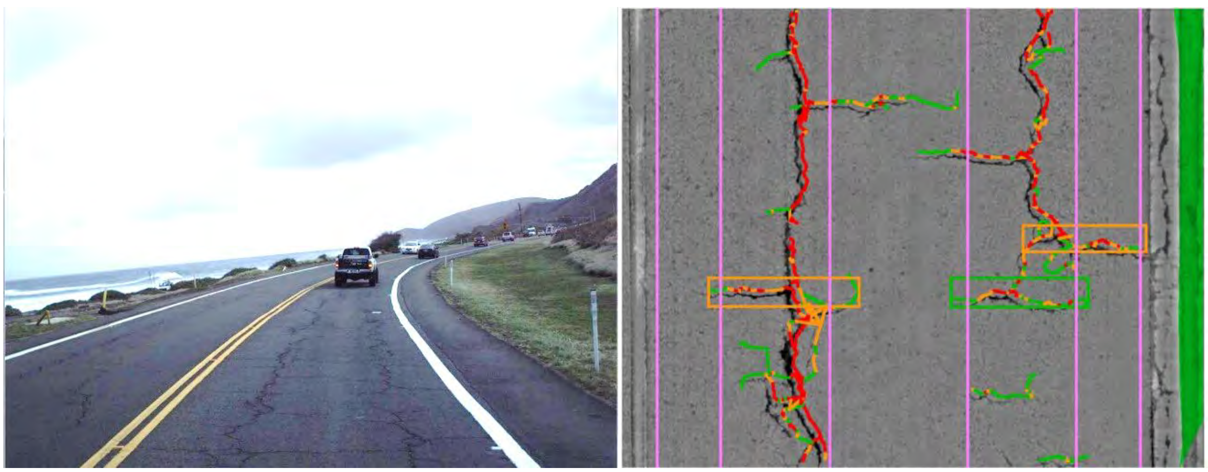


Figure 5-1. Cracking pattern commonly observed on TLTW state highways in Hawaii.

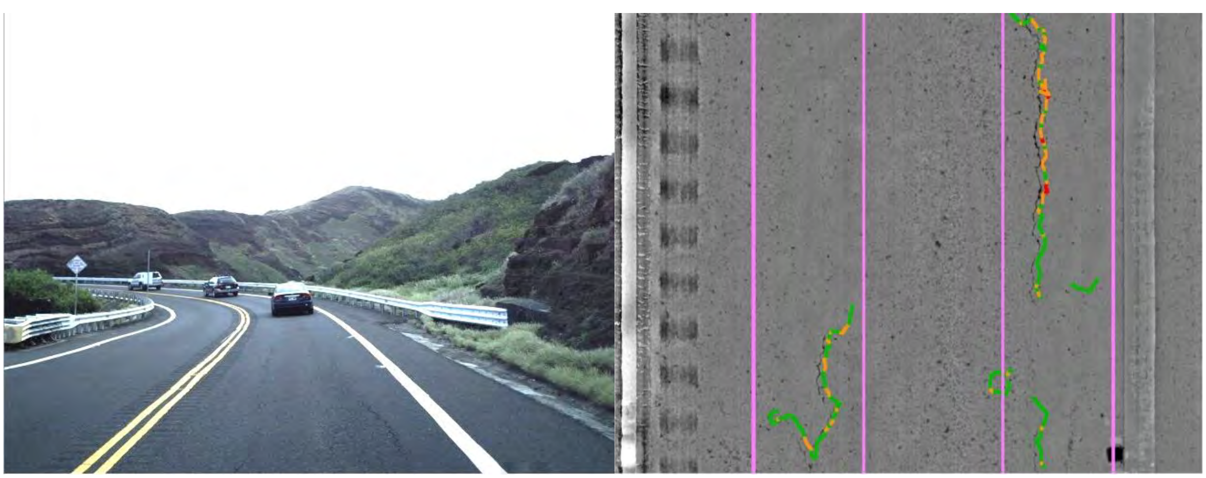


Figure 5-2. Typical early-stage cracking pattern observed on TLTW state highways in Hawaii.

To understand the potential effectiveness of different preservation countermeasures, it is important to have a better understanding of the factors that cause it. However, TDFC modeling is still limited in current state of the practice tools such as the Pavement ME design software (*11*) (the commercial version of the Mechanistic Empirical Pavement Design Guide or MEPDG (*12*)). New models based on fracture mechanics concepts have been proposed (*13*), but they are so recent that they have yet to be validated and adopted.

Several factors usually associated with intermediate pavement temperatures affecting TDFC have been studied in the literature. However, for tropical regions such as Hawaii, in which pavement surface temperatures are quite high for several hours of the day throughout the year, there are still potentially important factors that have not received enough consideration. These factors are: HMA moduli distribution with depth, variations in modulus with confinement level, and stress induced anisotropy arising from different moduli in tension and compression at high temperatures. These factors have the potential to significantly affect the distribution of stresses and strains in the pavement structure and thus the location where cracks originate when the pavement surface temperature is high.

An extreme high temperature profile with depth (high temperatures at the surface and high gradients with depth) can by itself significantly affect the distribution of stresses and strains in the pavement structure and thus the location where cracks originate. Previous research using pavement temperature profiles with depth, estimated from pavement surface temperatures throughout the day, showed that a scenario with lower HMA moduli at the top of the layer and higher at the bottom is quite plausible (*14*). Such an inverted moduli profile can lead to the highest tensile strain being located at the edge of the load near the surface instead of at the bottom of the HMA (*14*). At that location, high shear strains also occur.

In addition, the performance of thin lifts of HMA placed on top of existing pavements depend on the quality of the bond between new and existing surfaces. The shear strength developed by tack coated interfaces has been shown to be temperature dependent (*15*). The shear and tensile strength of the bond provided by tack coats is one of the factors potentially leading to debonding issues and associated cracking. As concluded in (*16*), "near-surface longitudinal cracking can likely develop in a pavement with a debonded strip along an interface below the wheel path." But that report also highlights the need to learn more about the debonding mechanism by stating: "Therefore, future efforts towards mitigating near-surface longitudinal cracking should focus on preventing debonding in the first place." The authors of that report also indicate that it remains to be seen whether strength is a meaningful property in terms of the resistance of a bonding agent to breakdown under repeated bending-induced shear stress.

Under conditions of high temperatures at the pavement surface and relatively high temperature gradient with depth, the maximum shear stresses may still occur near the bottom of the layer, however, the maximum vertical/horizontal shear stresses, which are more relevant for the shear performance of tack coats, also occur near the surface at the edge of the load.

Given the importance that temperatures may have on TDFC and debonding of thin lifts, this chapter concentrates on measurements over time of pavement temperatures with depth on a thick HMA sample on top of granular material simulating a pavement structure. It is expected that the information developed in this chapter can contribute to further analyses of these issues in Hawaii and other states with similar maximum pavement temperatures.

5.2 PAVEMENT TEMPERATURE MEASUREMENTS

5.2.1 Pavement Temperature Measurement Setup

The setup used to monitor pavement temperatures with depth shown in Figure 5-3 consisted of a Styrofoam box holding a datalogger together with a stack of two 6-inch diameter by 6-inch high Hot Mix Asphalt (HMA) specimens located on top of 6 inches of granular base material (also with 6-inch diameter to induce one-dimensional heat flow). The mix used was a standard HDOT mix type IV with 4% air voids (this mix also meets the Superpave 12.5 mm gradation requirements). A circular 6-inch hole was performed on the individual panels of Styrofoam cut to the desired dimensions from larger commercial panels sold at a home improvement store. These panels were then stacked and glued (with a non-toxic glue for Styrofoam) to form a paralepidid (a box). The HMA samples fitted the circular holes tightly. Nevertheless, to ensure that heat flow was unidirectional, an epoxy putty was used to fill any gaps (see top right photo in Figure 5-3).

Figure 5-3. Styrofoam box setup used to monitor pavement temperature with depth.

The individual panels were cut to a size that permitted the 6-inch circular hole to be on one side of the panel, thus leaving space on the other side to hold the data logger. In two of the individual panels, a rectangular cut was performed to hold the data logger. A lid of Styrofoam was also created to insulate the datalogger and minimize any heat exchange through small holes carved at an interface between two panels that were created for the thermocouples to reach the sample.

In order to add the granular material, the top of the HMA was placed flush with the top Styrofoam panel. Then, the box was turned around to add the granular base material and compact it (the compaction was limited to avoid damaging the Styrofoam). The bottom of the base was then covered with drywall tape to hold the aggregate in place, while minimizing the alteration of heat flow to any contacting surface below the box.

The data logger could read 8 thermocouples simultaneously. The thermocouples were inserted into small holes drilled horizontally on the HMA samples at approximate depths from the top of the box of 6, 19, 38, 64, 89, 152, 254, and 305 mm (0.25, 0.75, 1.5, 2.5, 3.5, 6, 10, and 12 inches). The first seven values correspond to the depths within the HMA that the MEPDG (*12*) would use to compute pavement temperatures for a pavement with 12 inches of HMA. The last thermocouple was placed at the interface between the bottom of the HMA and the granular base material.

The Styrofoam was finally covered with duct tape in part to protect it from the sun and water and in part to avoid separation of individual panels while being moved.

The box was placed for a couple of days at the Materials Research and Testing Lab of the Hawaii Department of Transportation, but because of shade hitting the setup too early, the box was then moved for a couple of weeks to the Black Plumeria HMA Plant located in San Island in Honolulu to test it. After confirming that it was working as desired, it was then moved one last time to the Asphalt Hawaii terminal located in the Campbell Industrial Park in Kapolei (west side of Oahu). Both locations have plenty of sun exposure, but the second location was preferred because of the larger space available, which provided more opportunities to avoid shades reaching the box before dusk. Figure 5-4 shows the box at the San Island location.

5.2.2 Temperature Measurements

Figure 5-5 shows an example of the data collected with the datalogger with temperatures collected at five-minute intervals. These data show some important variation of temperature with depth. It is important to note that at about 2:30PM, the shade from a trailer at the plant was reaching the measurement box, which explains the sudden drop in temperatures at that time. Nevertheless, in this example, the temperature appears to have already peaked. This was the main reason why the box was then moved to the Asphalt Hawaii terminal location in Kalaeloa where this situation could be avoided. However, it is interesting to note that Figure 5-5 corresponds to the date when the maximum pavement temperature was measured throughout this study, namely about 58ºC about 6 mm below the pavement surface.

Figure 5-6 shows similar results for three consecutive days at the Asphalt Hawaii terminal location. This figure includes the day when the maximum temperature at that location was recorded (56.2 ºC). Note that the patterns from day to day differ mostly in that there are certain sudden drops in temperature that are most notable on the thermocouples closer to the pavement surface.

Figure 5-4 Styrofoam box with HMA, granular base, and datalogger used to collect mix temperatures with depth.

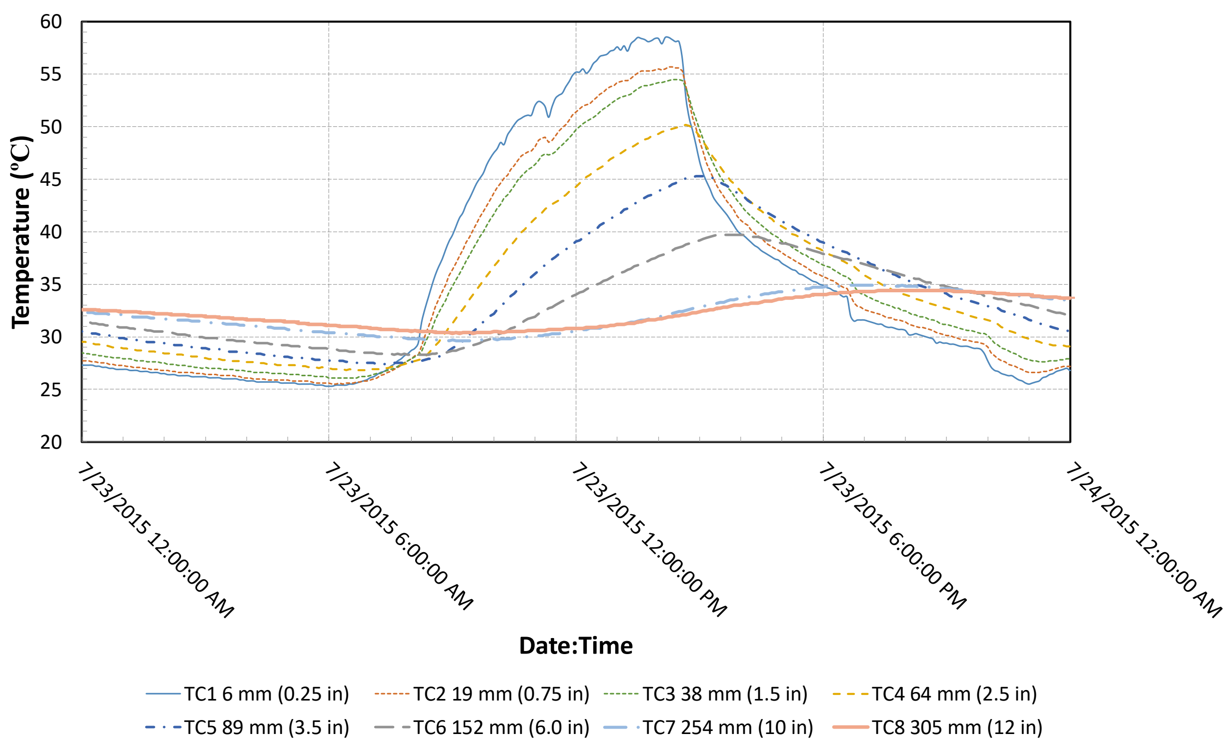


Figure 5-5 Temperature variations with depth throughout the day at the San Island location.

In some cases, the drops in temperature noted above can be quite significant. For example, the sudden drop for the thermocouple at the 6-mm (0.25-inch) depth on 8/25/2015 was about 15ºC in about 15 minutes, or equivalently about 1ºC per minute. Although of less magnitude, similar drops are seen for the thermocouples at depths of 19 mm (0.75 inches) and 38 mm (1.5 inches). These drops are likely the results of passing rains that cool down the surface very quickly, which is not uncommon in Hawaii. Such changes could clearly contribute to the environmental cracking noted in chapter 4.

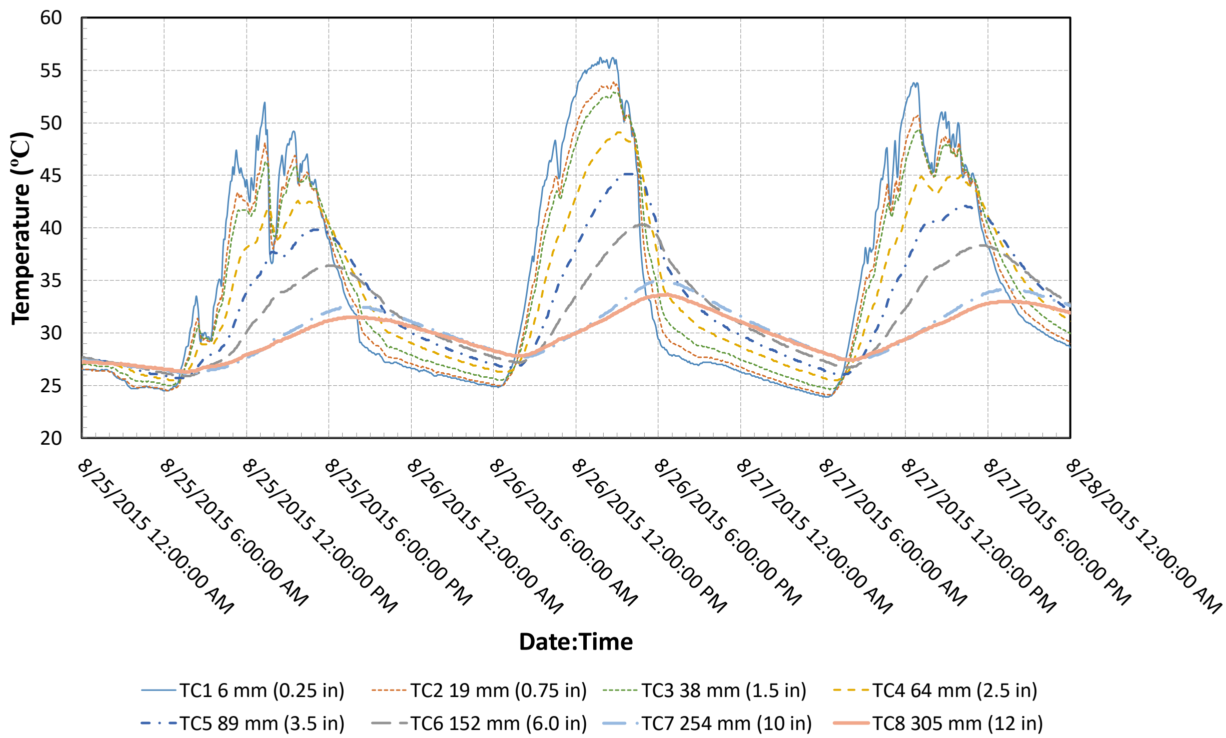


Figure 5-6 Temperature measurements obtained over a three-day period at the Asphalt Hawaii Terminal in Kalaeloa, Oahu.

Figure 5-7 shows the daily temperature fluctuations observed between 8/14/2015 and 8/8/2016. Since as shown in the previous figures the curves for the different thermocouples cross, for clarity, only the curve for the top thermocouple closest to the surface (0.6 mm) and the one deepest in the HMA (254 mm) are shown. This figure highlights that, at this location, the daily maximum temperatures at about 6 mm below the surface are consistently above 40ºC and quite often above 45ºC. These temperatures are important because depending on the speed and HMA aging, near these values is where the maximum strains flip from occurring at the bottom of the HMA layer to near the top at the edge of the load. This is discussed further later.

The figure also shows that while there are seasonal and daily variations, the pavement temperatures deep in the HMA layer fluctuate from an average of about 25ºC in the Winter to an average of about 30º in the summer. Note that these temperatures were about 3ºC higher at the beginning than at the end. It is suspected that this difference may a consequence of the changes in moisture that the 6 inches of base material experienced in the field.

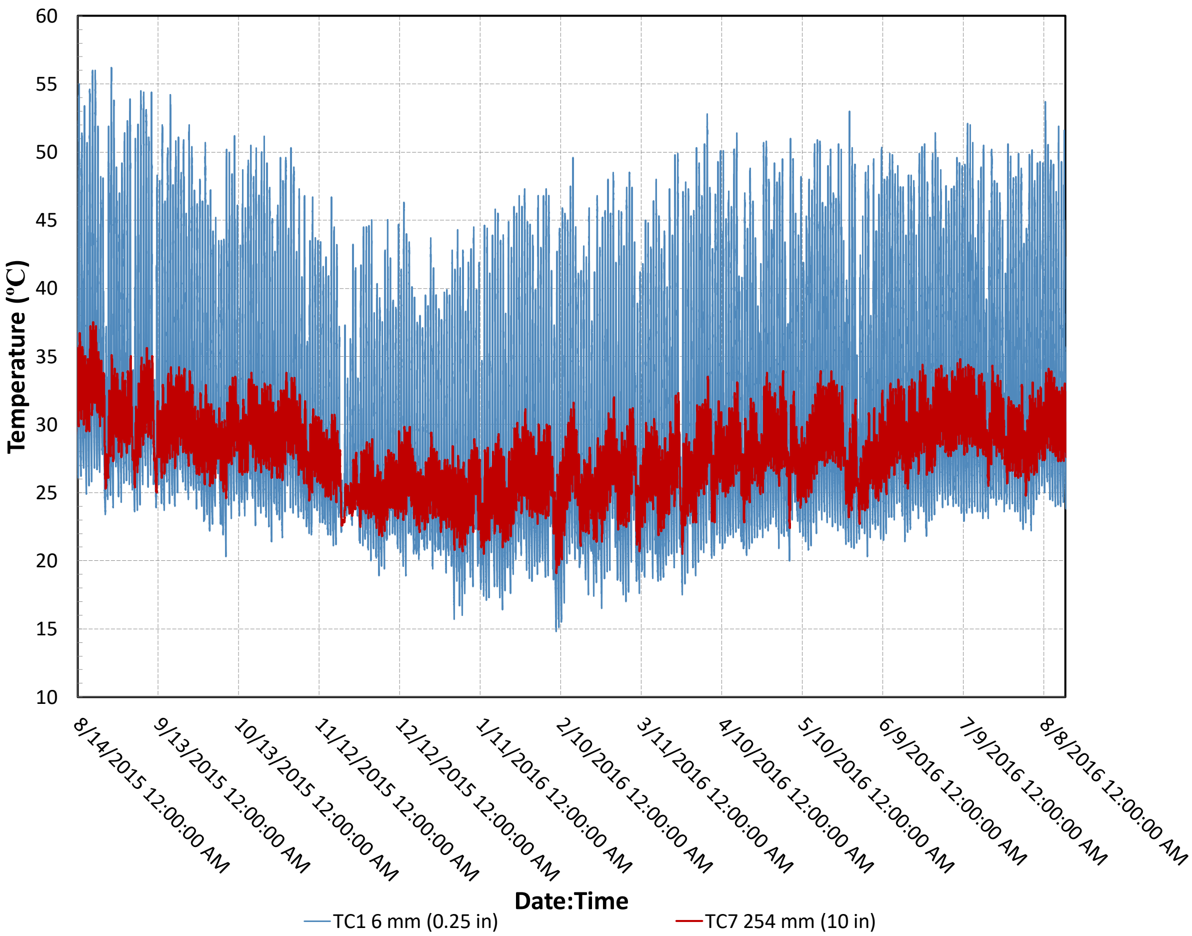


Figure 5-7 Temperature fluctuations with observed between August 2015 and August 2016.

Usually, fatigue cracking is deemed to occur at intermediate temperatures around 20 ºC, but Figure 5-7 clearly shows that conditions leading to such pavement temperatures at 6 mm below the surface (or at any larger depth) are practically non-existent at this location.

Figure 5-8 shows a comparison of the temperature profiles derived in (*14*) from surface temperatures measured from 6:00 AM until after 4:00 PM on July 27, 2014 with a few selected measured temperature profiles from this study (3 temperature profiles from a summer day and 1 from a winter day). It is seen that there are indeed temperature profiles that match quite closely the temperatures derived with finite differences in the top 102 mm to 127 mm (4 to 5 inches). The deviations between measured and theoretical values with larger depths are not surprising for several reasons. First, the finite difference analysis was based on assumed material properties such as its density, thermal conductivity, mass specific heat, and a limiting temperature with depth. For the latter, the value was assumed to be 24.6°C (76.3°F) in the finite difference analysis (note how the winter profile appears to approach a value close to this whereas the summer profiles appear to converge towards a higher value).

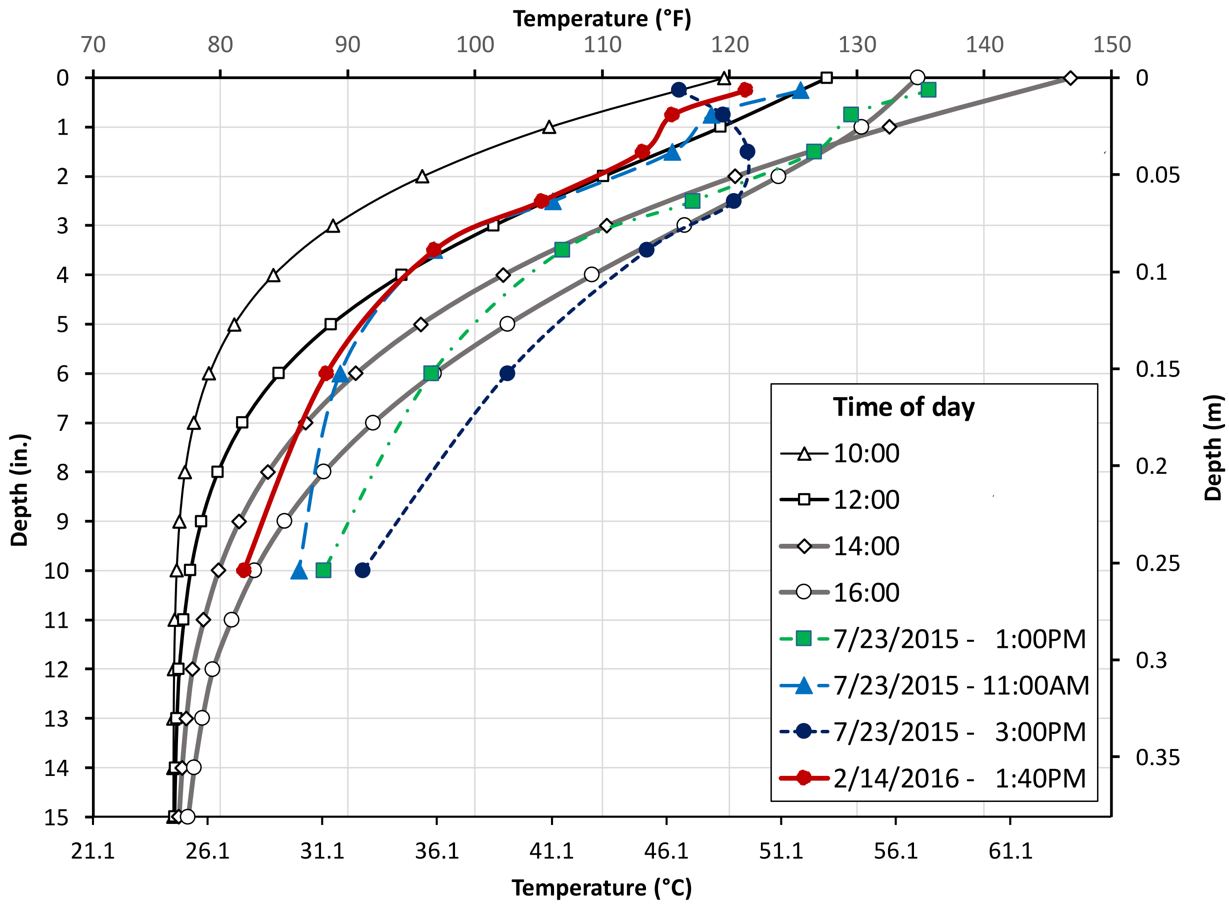


Figure 5-8 Estimated temperature profiles on a structure with 12 inches of HMA.

On the other hand, the border conditions at the bottom of the box may not exactly represent the heat flux in an actual pavement. Despite these differences, these measurements give some reassurance that predicted conditions in (*14*) can indeed happen often. This is shown later, after some examples of the consequences on the stress and strain distributions are presented.

The 5-min pavement temperatures at the different depths were used to create empirical cumulative probability distributions corresponding to the different depths as shown in Figure 5-9. Interestingly, the distributions corresponding to higher depths were nicely S-shaped, which correspond to symmetric density functions. In contrast, the density functions become quite asymmetric closer to the surface of the pavement. The figure also shows that nearly 82.5% of the time the temperatures at 6 mm from the surface are below 40ºC, which of course it means that about 17.5% of the time are above it. Again, the relevance of this is discussed later.

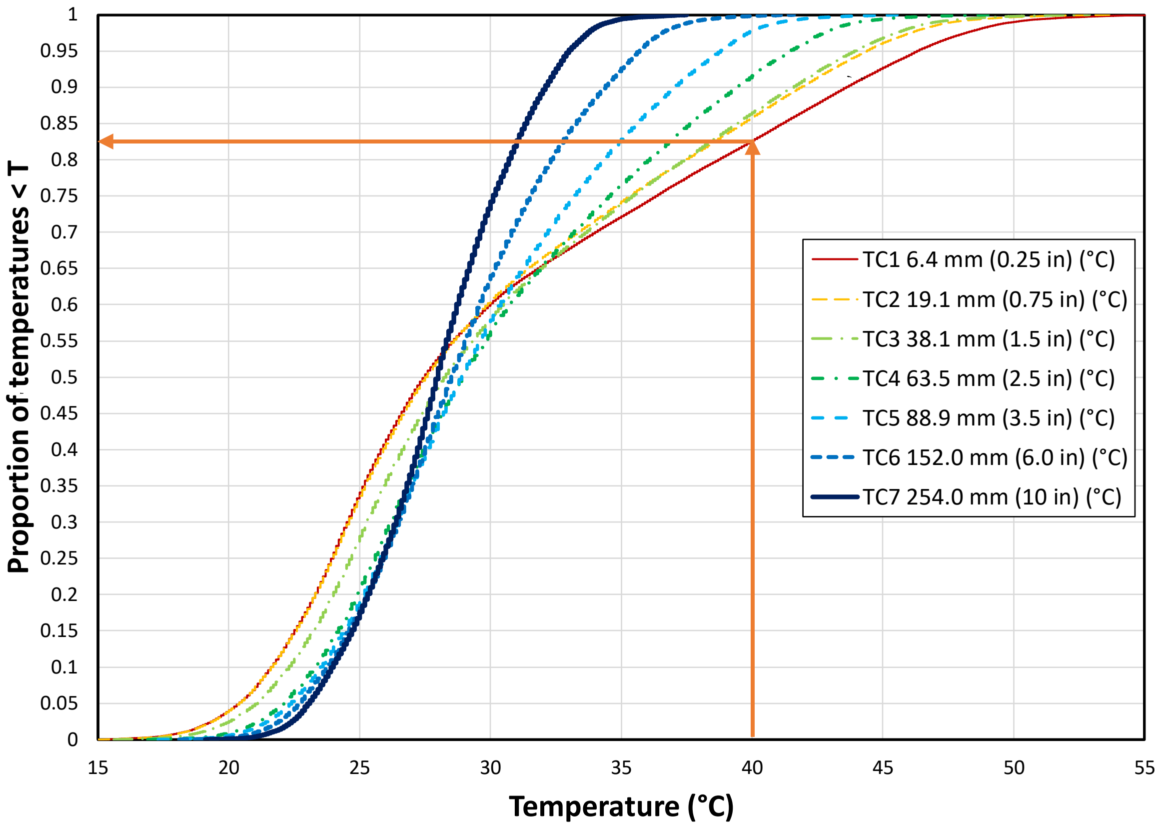


Figure 5-9 Empirical cumulative probability distributions of pavement temperatures.

5.2.3 Conditions Leading to Critical Inverted Moduli Profiles

Traditional fatigue cracking analysis relies on the prediction of an allowable number of repetitions to failure and the use of Miner's law. However, for a given load magnitude, the number of repetitions to failure is a direct indicator of the potential for cracking. The following expression is used by the MEPDG to compute the allowable number of repetitions to failure for a given tensile strain (*12*):

$$N_f = k_{1f}(C)(C_H)\beta_{f_1}(\varepsilon_t)^{k_{f2}\beta_{f2}}(|E *_{HMA}|)^{k_{f3}\beta_{f3}} \tag{5.1}$$

where:

N_f	=	Allowable number of axle-load applications for a flexible pavement and HMA overlays,
ε_t	=	Tensile strain calculated at critical locations, in/in,
$\lvert E^*_{HMA}\rvert$	=	Dynamic modulus of the HMA measured in compression, psi,
k_{f1}, k_{f2}, k_{f3}	=	Global field calibration parameters (k_{f1} = 0.007566, k_{f2} = -3.9492, and k_{f3} = -1.281), and
β_{f1}, β_{f2}, β_{f3}	=	Local or mixture specific field calibration constants;

$C = 10^M$

$$M = 4.84\left(\frac{V_{be}}{V_a + V_{be}} - 0.69\right)$$

where:

V_{be} = Effective asphalt content by volume, %,
V_a = Percent air voids in the HMA mixture, and
C_H = Thickness correction term, dependent on type of cracking.

In (*14*), this expression was used to compute the strain distribution caused by a 40-kN (9000-lb) load with a radius of 150 mm (5.9 inches) (as would be if the load were applied with a Falling Weight Deflectometer) on a structure with 305 mm (12 inches) of HMA placed on top of a base with a modulus of 207 MPa (30,000 psi) and Poisson's ratio of 0.35, and a subgrade with a modulus of 82.8 MPa (12,000 psi) and Poisson's ratio of 0.40. Other parameters used to compute the HMA's dynamic modulus, |E*|, and the assumptions used for computing the loading frequency are given in (*14*). The computations were performed for a temperature profile that induced an inverted moduli profile with depth (with lower values near the surface and increasing with depth). The simulations were also performed with $C = 1$ and $C_H = 0.1$ regardless of whether the interest is in top-down or bottom-up cracking.

The distribution of the logarithm of the number of repetitions to failure for the temperature profile corresponding to 16:00 (4:00 PM) in Figure 5-8 is shown in Figure 5-10. In this figure, the smaller the value of $\log(N_f)$, the higher the potential for fatigue cracking. As shown in the figure for the temperature profile modeled, the critical location occurs at the edge of the load near the surface even though at that location the mixture is much softer than at the bottom (much lower |E*|). Note also that the values of C_H for bottom up fatigue cracking are usually about 3000 times those for top-down, thus leading to predictions of much less cracking potential. The analysis in (*14*) does not require such a differential treatment of top-down and bottom-up fatigue cracking (in fact, the use of different factors for the same mechanism is not advocated in this report).

The main reason for these results is the existence of inverted moduli profile. Thus, an important issue is finding what temperature profiles lead to inverted moduli profiles causing critical conditions near the surface. To explore this, the previous analysis was repeated for many of the measured temperature profiles looking for those where the number of repetitions to failure were nearly the same at the edge of the load near the surface and at the bottom of the HMA layer. These conditions indicate the points at which the critical condition flips from the bottom of the HMA to near the surface at the edge of the load. This was done only for a 305 mm (12 in) HMA layer thickness and with the same pavement characteristics described above.

In (*14*), all the simulations were performed adjusting the asphalt moduli to account for aging over a 3-year period. In addition, the frequency calculations were done strictly according to the MEPDG. In the following analysis, the conditions were extended to include the four combinations of no aging or three years of aging with the frequencies calculated following the MEPDG or with the adjustments proposed by Al Qadi et al. (*18*). These adjustments lead to lower frequencies with depth, and thus to larger inverted moduli gradients.

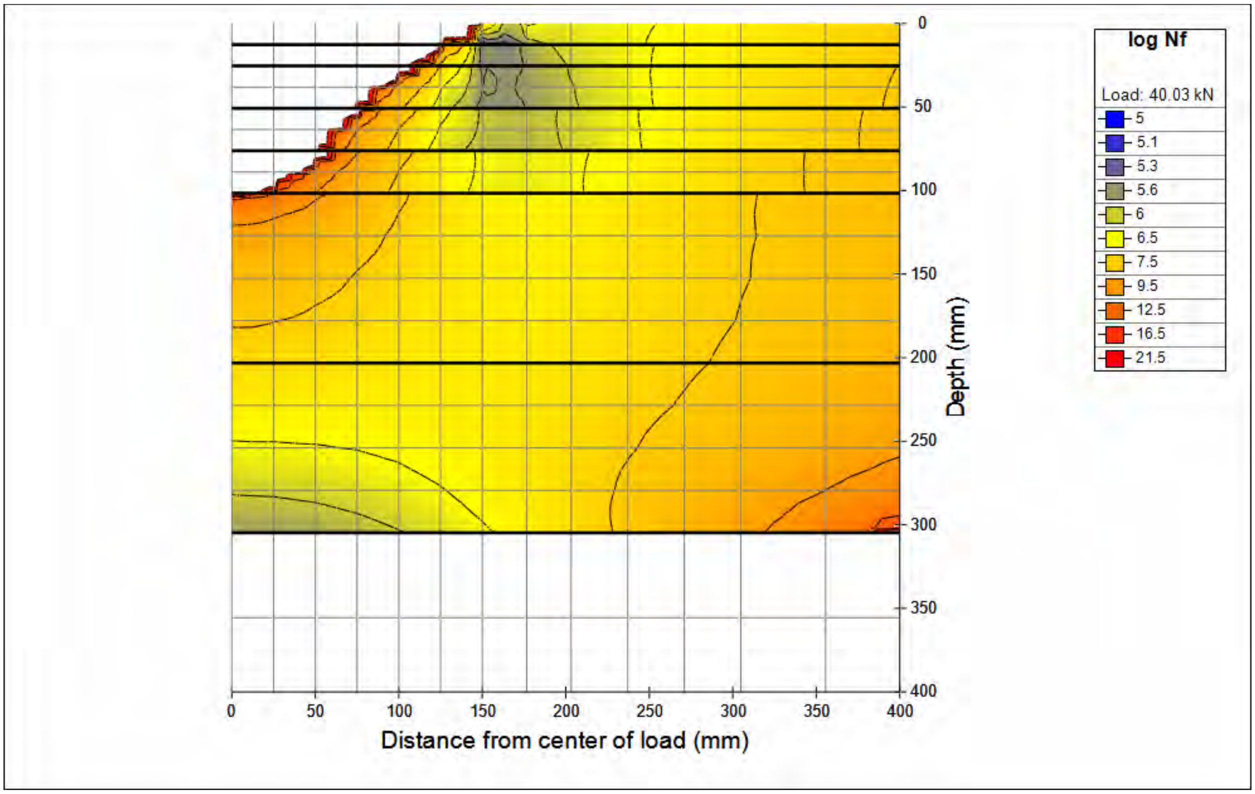


Figure 5-10 Distribution of the logarithm of the number of repetitions to failure for the temperature profile corresponding to 2/14/2016 1:40 PM.

Figure 5-11 shows the estimated critical temperatures at 6 mm depth (note that all the profiles were taken with temperatures monotonically decreasing with depth, as opposed for example, to the profile shown for 3:00 PM on 7/23/2015 in Figure 5-8).

Figure 5-11 illustrates that the critical conditions depend on HMA aging and traffic speed. Furthermore, the predictions are quite different depending on the method used for calculation. Nevertheless, it is seen that temperatures at a 6 mm depth between 40ºC and 45ºC encompass a large set of situations where these inverted moduli can lead to critical strains occurring at the edge of the load near the surface of the pavement. These results also indicate the need for paying more attention to high temperature conditions for fatigue cracking, at least in states with high pavement temperatures during a considerable portion of the year.

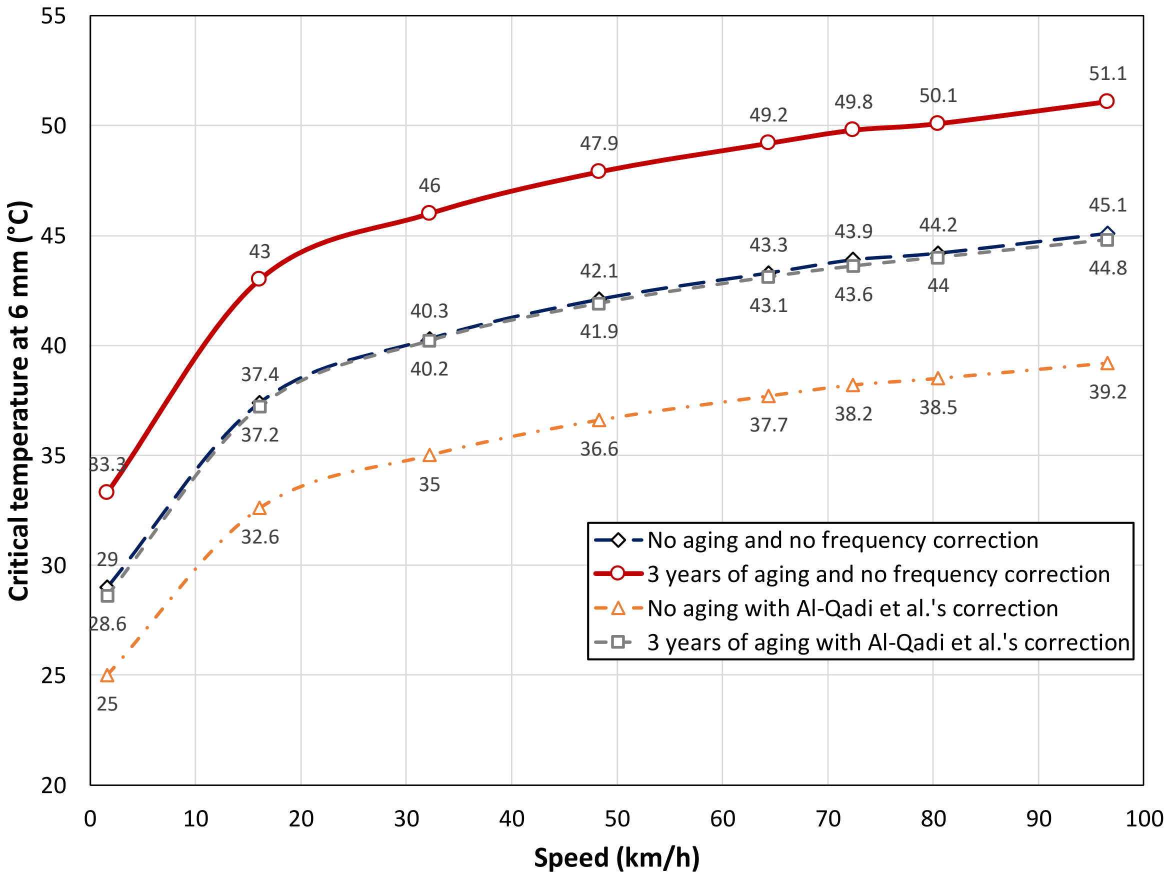


Figure 5-11 Principal and shear strain distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

5.2.4 Stress and Strain Distributions

This section presents an example of the consequences of temperature profiles that cause an inverted moduli profile. The analysis is identical to that presented in (*14*) except that instead of an estimated profile, a measure profile was used. Specifically, the temperature profile measured on 2/14/2016 at 1:40 PM was used. This profile, already shown in Figure 5-8, was used as representative of the profiles where the location of the critical strain is about to change.

Figure 5-12 shows the estimated stress distributions by computing the HMA moduli using the same approach as in (*14*). To generate these plots, once again, the loading area of a 40-kN (9000-lb) load was assumed to have a radius of 150 mm (5.9 inches) and being applied to a structure with 305 mm (12 inches) of an HMA layer that was sub-layered for modeling the effects of changes in temperature and frequency of loading with depth (the same sub-layering used in the MEPDG was used). As in (*14*), the HMA was modeled on top of a granular base 305-mm (12 in.) thick with modulus of 207 MPa (30,000 psi) and Poisson's ratio of 0.35 and a subgrade with modulus of 82.8 MPa (12,000 psi) and Poisson's ratio of 0.40. The parameters used to compute the HMA's dynamic modulus, |E*|, and the assumptions used for computing the loading frequency were identical to those in (*14*). Although the color palettes for each plot are the same, care should be taken to read the scales since they change from plot.

In terms of principal stresses, there is nothing extraordinary about these results. The maximum principal stresses are mostly compressive whereas the minimum principal stresses show some of the bending action with compressive stresses at the top and tensile at the bottom of the HMA (compressive stresses are positive in these plots.) However, note that the largest predicted compressive stress is about twice the value of the largest predicted tensile stress. Also, the minimum principal stresses beyond 200 mm (4 inches) at a depth of about 50 mm (2 in.) are all tensile and nearly vertical, thus having some potential for inducing debonding of thin HMA lifts.

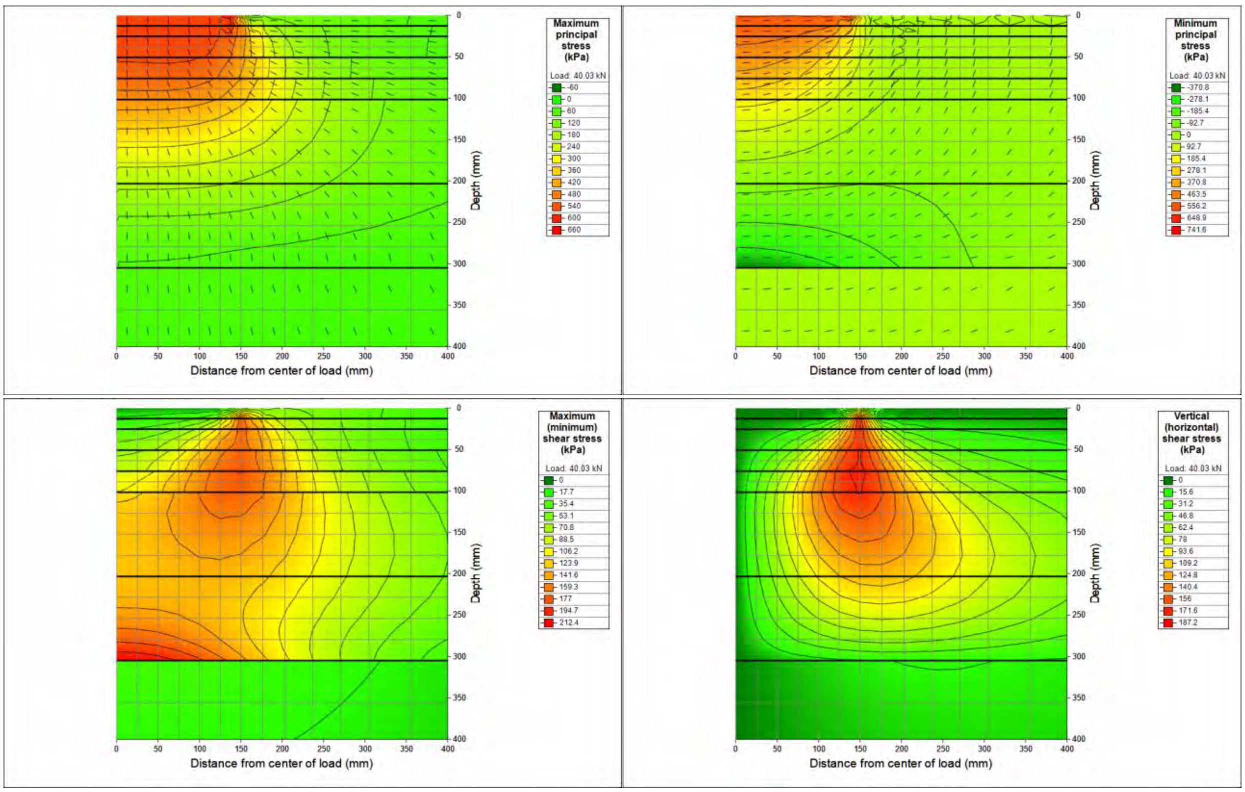


Figure 5-12 Principal and shear stress distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

In terms of shear stresses, while the maximum still occurs at the bottom of the HMA, the maximum of the vertical/horizontal shear stresses occur at the edge of the load between 50 to 100 mm (2 to 4 inches). Again, an interface with a tack coat in this area will be subjected to high horizontal shear stresses, but at these high temperatures the tack coat shear strength will be low.

Figure 5-13 shows the corresponding strain distribution plots. Again, there is nothing extraordinary about the maximum principal strain plot except that the strains are higher near the edge of the load because of the larger differences between the maximum and minimum principal stresses together with the higher shear stresses. For the same reasons, note that now the minimum (tensile) principal strains are largest at the edge of the load and substantially larger than that at the bottom of the HMA. In terms of shear strains, now both maximum and vertical/horizontal shear strains indicate that the critical location is at the edge of the load near the surface. All these plots indicate a high potential for cracking in that area simply because of the moduli induced by the temperature profiles. Note that this may be complementary to other theories, but an important point here is that these conditions occur frequently enough to have an important potential to cause top-down fatigue cracking, even when the temperatures are relatively high. Finally, in terms of the performance of the tack coat, these plots show that interfaces located between 25 and 50 mm (1 to 2 inches) are subjected to the highest strains.

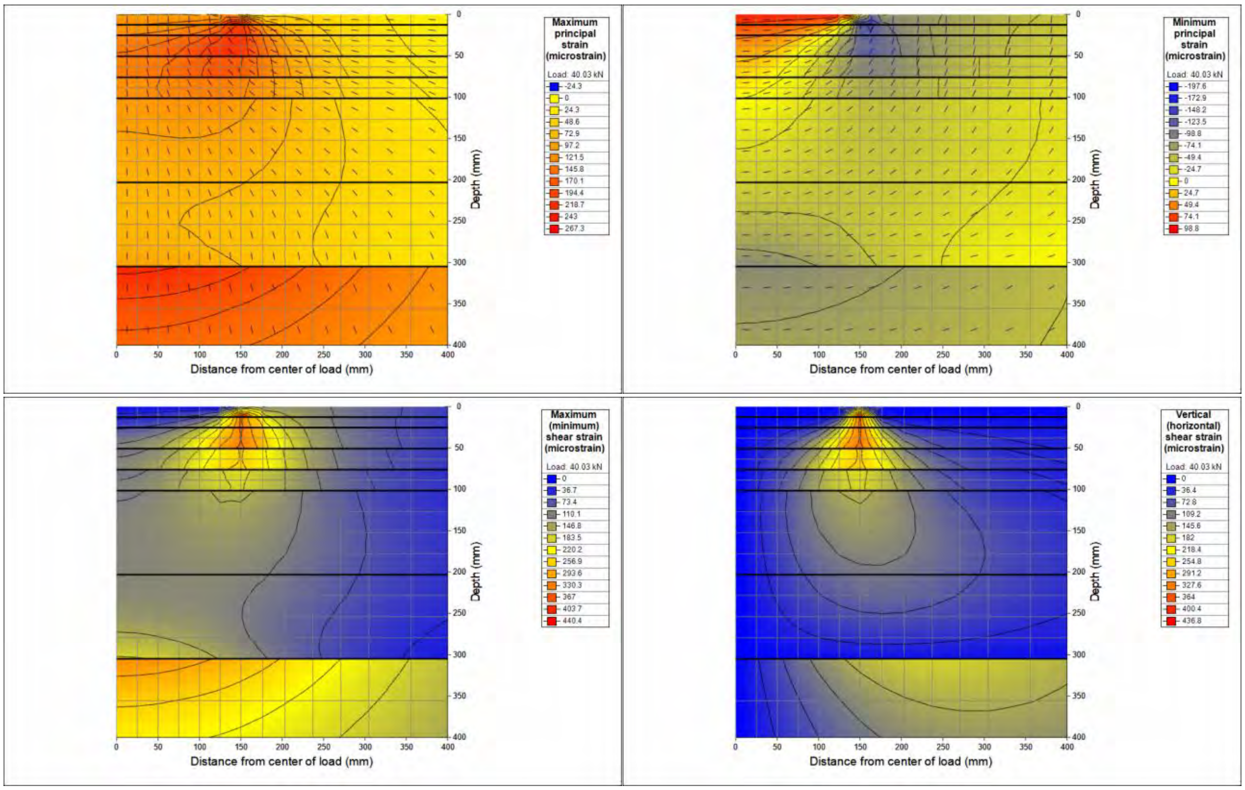


Figure 5-13 Principal and shear strain distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

5.2.5 Evidence Consistent with the Inverted Moduli Predictions

This section presents evidence consistent with inverted moduli predictions leading to high tensile and shear strains on the wheel paths near the surface. Specifically, Figure 5-14 to Figure 5-20 show photographs from the H-1 freeway in Honolulu from around mile points 22 to 24. This section of highway has been in service for a long time and it is due for rehabilitation soon. However, sometime around 2015, the extensive cracking in the section was crack sealed. This clearly highlighted the fact that the conditions under the bridges in terms of cracking were substantially better than either the before or after conditions. With rare exceptions, in general, the extensive cracking virtually stops underneath the bridge and resumes after it.

Note that the cracking occurs mostly in the wheel paths with random transverse cracks. Thus, it appears to be for the most part load related.

Figure 5-14 Principal and shear stress distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

What happens under the bridges is that for a large portion of the day, the pavement is shielded from exposure to the sun and thus the temperatures can never reach elevated values. In other words, those inverted moduli conditions never occur under the bridge. The consistency of the pattern from bridge to bridge is quite remarkable, which indicates that this is not an isolated event (in fact, the same has been observed under another bridge on the H-1 freeway several miles away).

Figure 5-15 Principal and shear stress distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

In some cases, there was no cracking on the right lane. This is seen in Figure 5-15 but in this case, note that this lane is also shielded substantially from the sun. In other cases, there were indications that the right lane may have been rehabilitated at some point. Another effect of the shade provided by the bridges is that the binder in the mixture suffers less aging. However, it is not clear what mechanism would lead to less "load related" cracking because of this.

Figure 5-16 Principal and shear stress distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

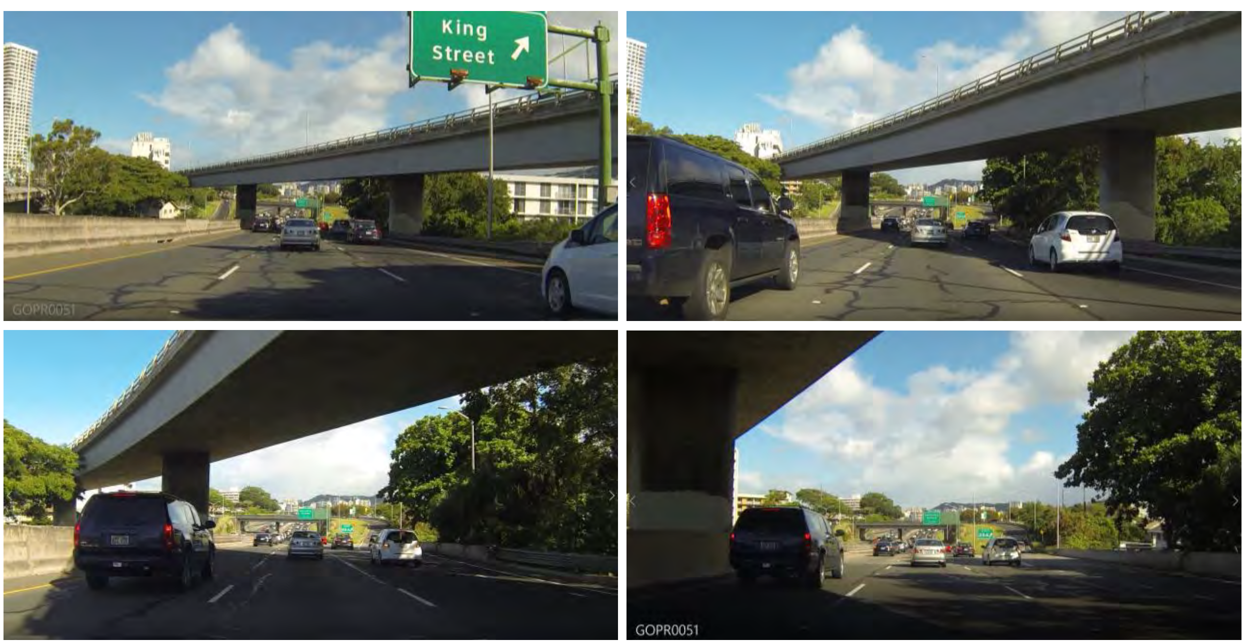


Figure 5-17 Principal and shear stress distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

Figure 5-18 Principal and shear stress distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

Figure 5-19 Principal and shear stress distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

Figure 5-20 Principal and shear stress distributions for the temperature profile corresponding to 2/14/2016 1:40 PM.

6 DEVELOPMENT OF ASPHALT CONCRETE DOGBONE SHAPE SPECIMENS FOR UNIAXIAL TENSION TESTING

6.1 INTRODUCTION

The efforts of this part of the study were directed at developing a test specimen configuration for uniaxial fatigue testing that avoided end breaks. The original intent was to use performance tests to evaluate the design of potential thin lift overlays mixes for Hawaii, particularly for fatigue cracking. The capabilities for fatigue testing at the UH Pavement laboratory included beam testing with a beam fatigue apparatus and uniaxial fatigue testing with proper attachments for the Asphalt Mixture Performance Tester (AMPT). Previous experiences with the fabrication of HMA beams discourage the use of the beam fatigue apparatus. In particular, the creation of slabs requires large amounts of material and the control of aid voids is difficult. On the other hand, there was no experience with uniaxial fatigue testing with the AMPT. Early attempts at performing this test with conventional mixes resulted in end failures that rendered the test results useless. The only difference from conventional testing was that a different testing temperature was targeted, specifically 40ºC. Consequently, the goal of this part of the study morphed into developing a test specimen configuration for uniaxial fatigue testing that avoided end breaks.

A key assumption in uniaxial fatigue testing is that the cylindrical specimen is subjected to a uniform distribution of stresses. Provided the assumption is reasonable, the specimen is equally likely to break at any height. Nevertheless, for use with continuous damage mechanics, the break needs to occur within the middle zone where the Linear Variable Differential Transducers (LVDT) are located so that the computed strains used in the analysis are representative of the strains in the area where the failure occurs. However, a common situation observed during fatigue testing is that samples break at a section near one of the loading platens away from the middle of the sample. This has been attributed to uneven distribution of air voids within the sample (*19*) and to eccentricity of the load (*20*). The two sample sizes most commonly used (diameter × height = 100 mm × 150 mm or 75 mm × 150 mm) have been selected to minimize the effects of an uneven distribution of air voids (*19*). To minimize the effects of eccentricity, Kutay et al. (*20*) designed a specialized platen gluing jig and a ball-jointed top platen to eliminate bending even with non-perfectly parallel specimen ends. Based on information presented in the literature (*21*, *22*), it appears that breaks near the platens are still common. This should not be surprising given that neither of the above precautions eliminate the end failure risks under a uniform distribution of stresses. Furthermore, while a gluing jig is already commercially available for the IPC Global Asphalt Mixture Performance Tester (AMPT) used in this study, the use of a ball-jointed platen is not currently an option. Thus, any small play on the axis of the gluing jig or imperfections in the parallelism of the gluing jig and the loading platens result in some load eccentricity when using the AMPT.

The chances for end failures are increased not only by an uneven air voids distribution (higher near the ends) but also by stress/strain concentrations caused by the restraining effect of the steel putty used to glue the specimen to the loading platens. This restraining effect also plays a large role in the breaks near the platens, particularly at high temperatures. In fact, because of the end restrains and the limited height of the specimens, there is no cross section on the specimen with an entirely uniform stress/strain distribution. Thus, it is the objective of this part of the study to develop a specimen configuration that induces the maximum strain to occur within the deformation measurement zone and to make its distribution within this zone more uniform than that obtained in tests with cylindrical samples.

6.2 MOTIVATIONS

6.2.1 Motivation for Testing at High Temperatures

This part of the study was motivated in great part by the desire to evaluate the cracking performance of Hawaiian mixes given the substantial evidence of longitudinal cracking seen in thick Hot Mix Asphalt (HMA) pavement structures in Hawaii. Some of the evidence was discussed in the previous chapter, which also showed why this longitudinal cracking is believed to be mostly top-down fatigue cracking generated by loading applied during periods with high temperature profiles that result in moduli values increasing with depth. Those inverted moduli profiles result in the highest tensile and shear strains occurring at the edge of the load near the top of the HMA. As seen previously, in Hawaii, minimum pavement temperatures at a depth of 6 mm are rarely below 20°C. Furthermore, since those situations happen mostly at night, they occur with no or minimum traffic loadings.

As shown in Chapter 5, temperature measurements performed from August 2015 to August 2016 on a 12-inch HMA sample on top of a 6-in granular material (properly insulated laterally to observe one directional heat flow) showed that at a 6-mm (0.25-inch) depth, less than 4% of the temperatures obtained every five minutes throughout the year were less than 20°C and no measurements were observed below 20°C for the whole year at a depth of 10 inches. Instead, between 4 to 6 hours a day, the pavement temperatures were above 40°C on the top 1.5 inches of HMA.

6.2.2 Motivation for New Specimen Geometry and Testing Conditions.

Because of the motivation to perform fatigue testing at higher temperatures, initial efforts were directed at testing cylindrical samples at 40°C in uniaxial fatigue. Specimens with a mix evaluated for the Honolulu International Airport were tested for this purpose. The mix is dense graded with 6.1% asphalt content and its gradation can be classified as a 12.5 nominal maximum aggregate size (NMAS). More details about the mix design are described in (*23*).

Two significant problems were encountered during this initial effort. First, although the UTS032 IPC software for collecting data for Simplified-Viscoelastic Continuous Damage (S-VECD) analysis could maintain the average of the strains computed from the three on-specimen LVDTs within a narrow range in a strain-controlled test, the strains from each LVDT could be quite different from each other because of eccentricity of the load. Under these conditions, maintaining the average strain constant is not always satisfactory since it may result in the strain from one LVDT decreasing while the other two strains are increasing (this was observed in a portion of a test). Although minimizing the load eccentricity could resolve this problem, it was decided that it was easier to use a stress-controlled test in which the strains increase monotonically, though not necessarily at the same rate when there is load eccentricity. Therefore, a stress-controlled repeated tensile load creep-recovery test with a 400 kPa, 0.1 s haversine load and 1.9 s rest period was configured using the UTS019 IPC software. The 400 kPa loading stress was selected to achieve reasonable testing times after experimenting with incremental tests (i.e., in tests where the stress level was incremented by 100 kPa after 1000 cycles and 2000 s rest periods between different load levels.) Notice that since this is not purely a fatigue test, the use of the term fatigue is avoided herein in the test name. Nevertheless, the stress-controlled situation may be representative of conditions inducing cracking at high temperatures in thick pavements. For illustration of strain distributions under these conditions see (*14*) and the previous chapter. The second problem was that, as shown in Figure 6-1, the specimens tested in either the strain-controlled fatigue test or the repeated tensile load creep-recovery test broke consistently on a section close to the platen (~5-10 mm from the platen).

After testing several specimens, these breaks were so consistent from specimen to specimen that an uneven air voids distribution or an eccentric load were unlikely to be the sole reason for their occurrence. Instead, it was suspected that because of the higher Poisson ratio and lower modulus of HMA at 40°C, there is a larger radial contraction that is restrained by the plates at the sample ends (to which the specimen is glued with steel putty) and that this effect is high enough to induce an early failure.

Figure 6-1 Break occurring consistently 5 to 10 mm from the loading platen.

6.3 FINITE ELEMENT SIMULATIONS

6.3.1 Cylindrical specimen.

To confirm that strain concentrations at the specimen ends could be a significant factor in the breakage of cylindrical samples, axisymmetric and 3-dimensional finite element simulations of 150-mm height × 100-mm diameter samples were performed based on information from tensile moduli for 40°C and 10-Hz frequency obtained from master curves (not shown here) developed for specimens prepared with different binders (PG64-22 and PG76-22) tested in tension. For ease of comparison, every simulation was performed with a static load that would produce a nominal strain of 100 $\mu\varepsilon$ (i.e., 100 microstrain or 1×10^{-4}). Simulations performed with different programs (Abaqus Standard and Plaxis) were in general consistent for similar meshes. Several configurations were modeled for the steel putty gluing the specimen ends to the steel plates on the circumference of the sample. Figure 6-2 shows the maximum principal strain results of two simulations with moduli and Poisson ratios of 690 MPa and 0.40 for HMA, 5,860 MPa and 0.32 for the steel putty, and 193,000 MPa and 0.28 for the steel plates, respectively.

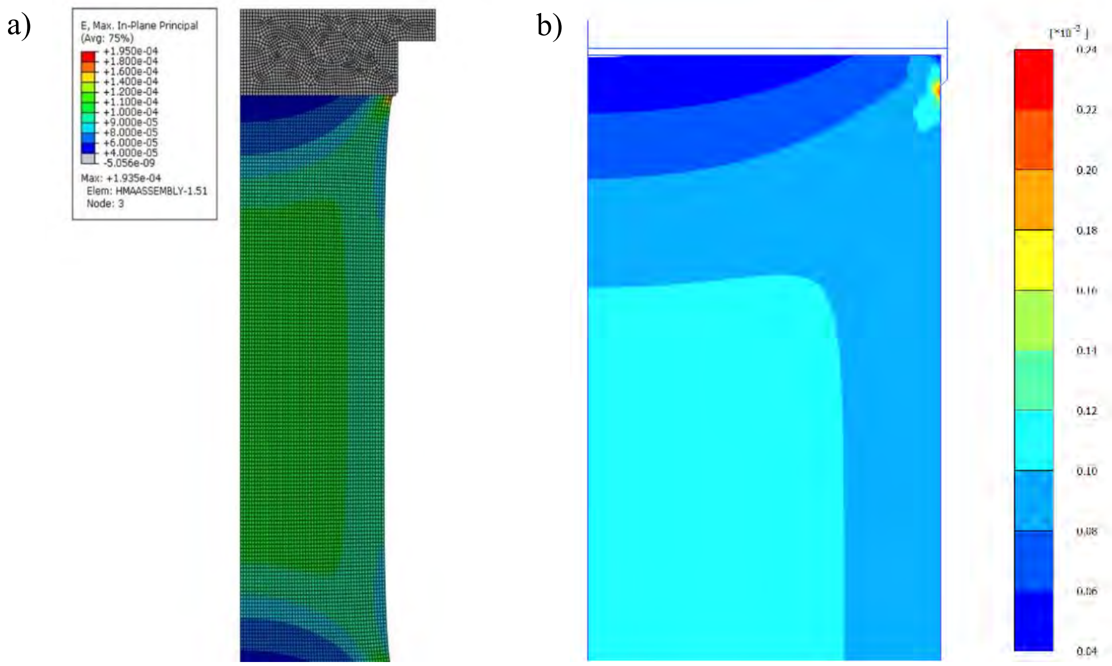


Figure 6-2 Finite element simulations of cylindrical specimens (target strain = (target strain = 100 με) a) Results with Abaqus Standard with glue flush with the sample (left) and b) Results with Plaxis with glue over sample.

The modulus of 690 MPa for the HMA is lower than the dynamic moduli obtained from the master curves to account in part for the pulse loading in the test versus the cyclic loading in the dynamic modulus test and for the fact that at higher strains, like those observed in the test, the dynamic modulus is further reduced. In fact, this value was selected based on the resilient strains observed on some of the preliminary repeated load tests performed in this study. The plot on Figure 6-2 a) (the left plot) was obtained with Abaqus Standard with the steel putty left flush with the specimen and the one on Figure 6-2 b) (the right plot) was obtained with Plaxis with the steel putty covering part of the specimen. Note that while the strains on the steel plate and the steel putty are shown for the Abaqus Standard results, these have been omitted for the Plaxis results (right plot). In both cases, the maximum strain is about twice the nominal (target) strain, with larger strain concentrations when the steel putty covers part of the sample. The figure also illustrates that the strains are not uniform on any cross section. The numerical results for these simulations indicate that variations from +6% at the center to -2% on the outside circumference could be expected. Similar observations can be made for vertical strains. These results imply that the average strain within the measurement zone is slightly underestimated in tensile tests on cylindrical samples.

In summary, the finite element analysis confirms that strains in restrained cylindrical samples can almost double the target strains and that therefore strain concentrations are indeed a big factor in the end-failures at 40°C.

6.3.2 Trimmed Specimen (Dog-bone Shape).

Many finite element simulation runs were performed to develop a trimmed specimen configuration in the form of a dog-bone by means of a staircase transition to obtain a strain distribution with the following characteristics: 1) a more uniform distribution in the middle of the specimen, 2) maximum strain located within the strain measurement zone, and 3) no concentration of strains on the trimmed edges. It must be noted at the outset that the last characteristic is impossible to be achieved with a staircase transition (and thus, so is the second characteristic). However, given other sample imperfections and the fact that HMA is not a homogeneous material, it was hoped that if no such concentrations could be predicted with a relatively small mesh then the resulting configuration could be more successful at inducing middle breaks than the cylindrical samples.

Figure 6-3 shows the trimmed configuration that was finally selected. The results in this section correspond to a slightly different configuration that was used while developing this trimmed configuration. The plot in Figure 6-4 a) shows the results with one of two of candidate configurations analyzed. Again, a load was selected so that the target strain in the middle of the sample was 100 με. The moduli and Poisson ratio information are the same used for the cylindrical specimens. The results on the left and center of the figure (parts a) and b), respectively) were obtained with Abaqus Standard and show a maximum strain that is less than 4.4% higher than the target strain. Thus, the lateral variation of strain along a horizontal cross-section is slightly smaller than the corresponding strain variation in cylindrical specimens.

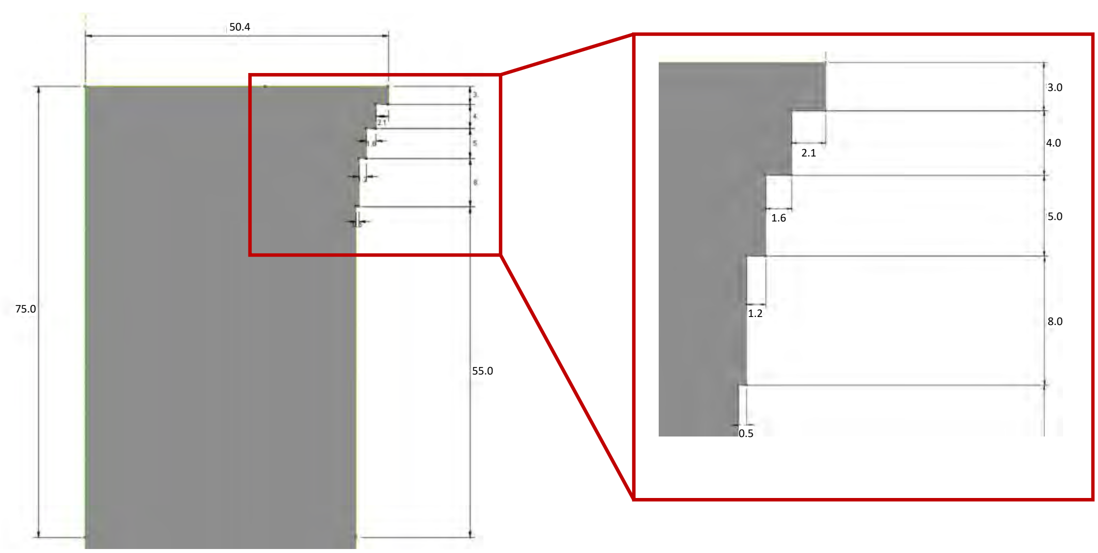


Figure 6-3 Trimmed specimen upper-right quarter geometry (dimensions in mm).

Notice that sharp edges of the trimmed configuration always result in some strain concentration. The results shown in part b) of Figure 6-4 were obtained with Abaqus Standard with the same inputs as before but with a finer mesh. In this case, the maximum strain occurs near one of the cuts and is more than 20% larger than the nominal strain. The results shown on Figure 6-4 c), obtained with a fine triangular mesh but with Plaxis, also predict strain concentrations of the same order near some of the trimmed edges (the finer the mesh the higher are the predicted strain concentrations).

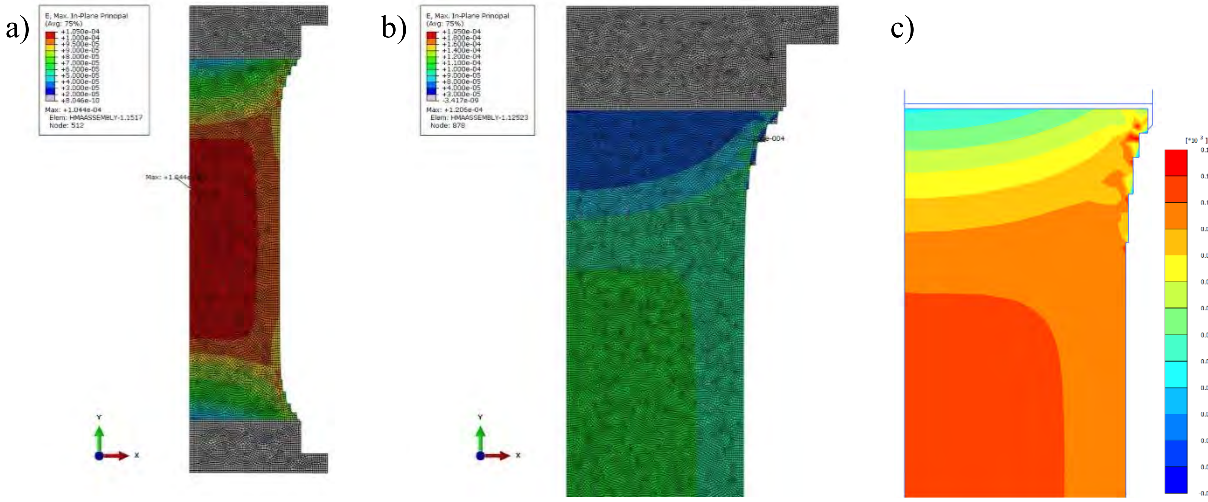


Figure 6-4 Finite element simulations of trimmed specimens (target strain = 100 με). Results with: a) Abaqus Standard – coarse mesh (left), b) Abaqus Standard - fine mesh (center), and c) Plaxis - fine mesh (right).

6.4 SAMPLE TRIMMING

After the finite element modeling showed a potential advantage in terms of slightly more uniform stress distributions in cross-sections near the middle of the specimen and potentially smaller maximum strains, it was necessary to develop a trimming procedure.

In this study, cylindrical specimens were first obtained following standard practice (i.e., compacting gyratory specimens, taking cores from them, and then cutting the top and bottom to obtain the cylindrical samples). Then, the trimming was performed with a circular saw with the help of an attachment developed to hold the sample horizontally. As shown in Figure 6-5, the attachment was designed so that it can slid on the guides of the circular saw and it can be fixed in a desired position for trimming. The sample is sustained by two rollers that allow rotating it over its axis without lifting it. Once an initial cut with the desired depth is obtained, the specimen can be pushed very slowly horizontally to expand the cut. With the trimming completed for a small strip, a small rotation can be applied, and the process repeated. Very small rotations are needed to create a smooth cylindrical surface for each trimming depth. Care must be taken to create four initial cuts at the appropriate depths to serve as reference and, for the shallower cuts, make sure they are on locations with zones not affected by deeper cuts. This allows finishing the shallower cuts once the deeper cuts have been completed by using the initial cut as reference. It is convenient to complete the deeper cuts first since the sample can rotate over the roller with wider contact surfaces between the sample and the rollers.

Getting the approximate desired depths is one of the more challenging aspects of the procedure. A caliper may be used for controlling the depths and distances from the top and bottom of the specimen. However, it was also found practical to use a straight edge with appropriately placed marks to control these distances. Markings parallel to the top and bottom drawn on tape around the sample was another procedure explored for controlling the lateral displacement of the sample. However, although this produces better guidance for the operator, it also creates some problems since the tape tends to create lumps that may lift the sample while rotating it.

The whole cutting process takes 3 to 4 hours; therefore, for practical use some automated procedure would need to be developed. Additional time is also needed to dry the sample (relatively small if a device such as the CoreDry© is used) and for smoothing the sample with epoxy. The latter task is not very time consuming, but it typically requires overnight waiting for the epoxy to set and harden.

6.5 TESTING OF TRIMMED SAMPLES

Most of the breaks discussed in this section for trimmed specimens were obtained with repeated-creep and recovery tests with 0.1 s haversine loading with a peak stress of 400 kPa (in the middle of the specimen) and 1.9 s rest periods. However, a few of the specimens were fractured with the exploratory ramping stresses discussed earlier.

a) b)

Figure 6-5 Specimen trimming set up.

The initial results were very encouraging since the first four specimens tested, shown on Figure 6-6 a), broke in the middle region (the crack on the rightmost specimen is not clearly visible since the specimen was reheated to remove the platens). However, after these initial successes, the following eight specimens tested broke near the ends as shown on Figure 6-6 b). Although these experiences were unsuccessful, they were valuable in that they indicated the middle portion of several samples were being substantially stretched to the point that in several occasions it was believed the sample was failing in the middle until a couple of minutes before the sample failed near one of the sample ends.

a) b)

Figure 6-6 Successful middle breaks (left) and unsuccessful end breaks (right).

These unsuccessful tests also pointed to the need to pay more attention to load eccentricity. In this study, the plates were glued with the help of the IPC gluing jig. However, careful inspection of the jig showed some play on the rod which is connected to the top plate of the gluing jig that in turn sustain the top platen being glued to the specimen. Any play on this rod may result in lack of parallelism between the faces of the top and bottom platens. Although this problem was solved by machining a replacement part on the gluing jig, the faces of the bottom of the gluing jig and the top are machined within a tolerance that though very small can still result in some eccentricity. The platens themselves and the loading mechanism in the AMPT can introduce some additional small lack of parallelism. Careful observation of this issue showed that for most specimens, when the first load was detected while raising the ram, one side of the top platen contacted the loading plate while on the other side there was a small gap. To minimize the effect of the load eccentricity caused by this small lack of parallelism, shims made with aluminum foil were placed inside the gap using an appropriate number of plies depending on the gaps size (1 to 3 plies were sufficient in most cases). In addition, all the screws used to secure the platens were tighten with the same torque using a torque-wrench. These two precautions together with the smoothing of the staircase pattern discuss next eliminated end breaks in the rest of the tests.

6.6 SOLVING THE STRAIN CONCENTRATION PROBLEM

Clearly, for the dog-bone shape specimen to be useful, there was a need to smooth out the staircase transition. Since no practical solution could be found using mechanical means, instead it was decided to restore part of the trimmed material. For practical reasons, HMA cannot be used for this purpose. Instead, a material compatible with HMA at the temperature of interest was needed. Although, the modulus of the epoxy cement used for gluing the gage points was not known at 40°C, the experience with this material indicated that it could be a good candidate. Consequently, additional finite element simulations were performed by filling the steps in the transition with wedges of epoxy cement. These simulations showed that if the modulus of the epoxy cement is of the same order of magnitude as that of HMA, the strain concentrations could be eliminated, and the maximum strain could be made to occur in the middle of the sample. Figure 6-7 a) shows how the wedges were used to create a smooth transition for the trimmed configuration shown in Figure 6-3 from a 100.8-mm diameter at the specimen ends to a 90.0-mm diameter in the middle portion. The rest of the figure illustrates the strain distributions obtained using a modulus of 3,500 MPa and a Poisson ratio of 0.32 for the epoxy cement. The moduli and Poisson ratios for the other materials are the same as before.

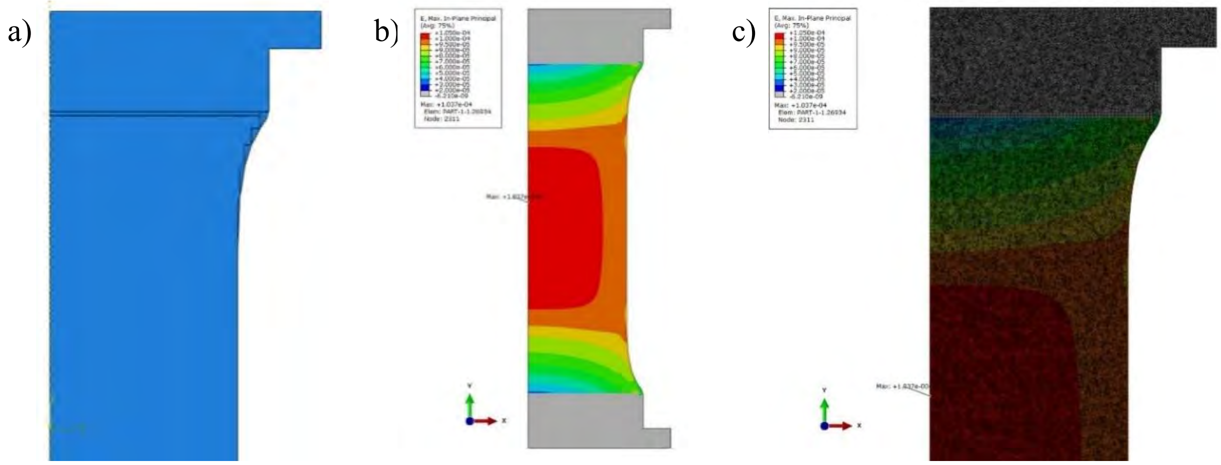


Figure 6-7 Finite element simulations of the trimmed-epoxy smoothed specimens (target strain = 100 με).

The strain distribution results indicate that the maximum strain occurs in the center of the sample, slightly above or below the mid height of the specimen. They also show that the distribution of strains is not uniform even in the cross-section at mid height. Nevertheless, the maximum strain in this simulation is below 4% higher than the nominal (target) strain in the middle cross-section. Of course, the values and the location of the maximum vary with the assumed epoxy cement modulus and Poisson ratio but even with a simulated epoxy modulus more than 5 times higher than that of HMA, the maximum strain occurs at the axis of symmetry slightly above or below the middle of the sample. Furthermore, even with the use of the very fine mesh shown on Figure 6-7 c), no concentration of strains is predicted.

6.7 TRIMMED-EPOXY SMOOTHED CONFIGURATION VALIDATION

To validate the finite element simulation results, additional specimens were trimmed, smoothed, and tested. Nine specimens were tested with this configuration and all of them fractured within the on-specimen LVDT zone. Table 2-1shows the type of binder, whether the sample contains polyolefin/aramid fibers, whether the sample was smoothed, the air·voids, the number of cycles until a crack propagated through a complete cross-section, and the type of break for eight of the nine specimens and a few other tested with the repeated creep and recovery test with a haversine stress of 400 kPa and 0.1 s loading and 1.9 s rest period. The epoxy smoothed specimen not included in this table was tested with a ramping load. Figure 6-8 a) shows eight of the 9 epoxy smoothed specimens. Figure 6-8 b) shows one of those specimens still in the AMPT chamber.

Figure 6-9 shows the curves of cumulative axial deformation at the end of each cycle for 8 of the nine specimens tested with the trimmed-epoxy smoothed configuration. As seen in this figure, the curve for specimen FPMA F3 has a slight discontinuity in slope. This is because the software froze during that test. Thus, the test was interrupted and re-started. The curve shown for this specimen is the best match that could be found between the two parts of the test. All the curves show an initial portion where the cumulative deformation (unrecovered viscoelastic plus plastic) increases very rapidly but at a decreasing rate, followed by a region where the strain increments are relatively constant, and then followed by a zone where the strain increment per cycle gets progressively higher until failure. The inflection point of the curve is somewhere within the middle portion. This behavior is similar to that overserved in compressive permanent deformation tests.

Table 6-1 Trimmed specimen characteristics.

Specimen	Binder type/Fibers	Epoxy smoothed	Air voids (%)	Number of cycles to crack separation	Type of Break	Notes
HMA-F4	PG64-22/No	No	7.11	4765	End	
HMA-F6	PG64-22/No	Yes	7.07	5010	Middle	
FHMA-F5	PG64-22/Yes	Yes	7.27	3340	Middle	
FHMA-F6	PG64-22/Yes	Yes	7.07	3942	Middle	
FHMA-F7	PG64-22/Yes	Yes	7.15	4422	Middle	
PMA-F1	PG76-22/No	No	6.91	14413	End	
PMA-F2	PG76-22/No	No	6.99	11012	End	
PMA-F3	PG76-22/No	Yes	7.07	27020	Middle	
PMA-F4	PG76-22/No	Yes	6.99	26460	Middle	
FPMA-F1	PG76-22/Yes	Yes	7.03	15355	Middle	Substantial eccentricity
FPMA-F3	PG76-22/Yes	Yes	7.23	25068	Middle	Computer froze

a) b)

Figure 6-8 Effectiveness of specimen configuration to induce mid-specimen fracture.

The first three curves (for specimens FHMA F5, FHMA F6, and FHMA F7) are for specimens prepared with an unmodified PG64-22 binder and polyolefin/aramid fibers. The next curve is for specimen HMA F6, which is a specimen prepared with unmodified PG64-22 binder without fibers. Unfortunately, not much can be said with a single specimen with unmodified binder without fibers in comparison with three unmodified specimens with fibers. However, it is important to point that the fact that the single HMA specimen lasted longer than any of the FHMA specimens is consistent with the analysis of dynamic modulus testing results obtained with the same mixes in compression (*24*). The following four curves are for four specimens prepared with polymer modified binders with and without fibers. Specimens FPMA F1 and FPMA F2 were prepared with polyolefin/aramid fibers and specimens PMA F3 and PMA F4 were prepared without fibers. There is a significant difference in performance of specimen FPMA F1 relative to the other three polymer-modified specimens. This specimen had a noticeable lack of parallelism and was tested prior to the adoption of aluminum foil shims and tightening of screws with a torque-wrench to minimize load eccentricity. In addition, the deformations measured by the three LVDTs before going out of range were substantially different from each other, confirming a problem with load eccentricity. Therefore, it is not surprising that this specimen lasted much less than the other three.

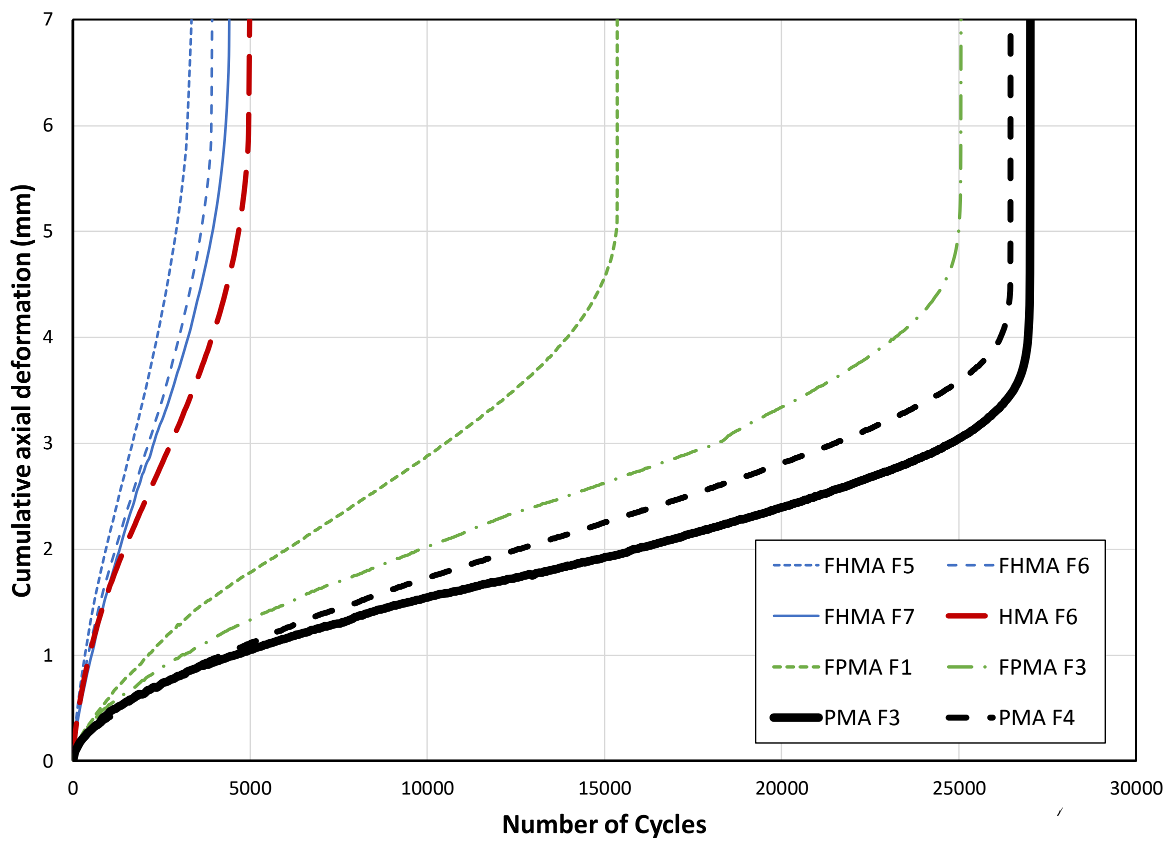


Figure 6-9 Cumulative axial deformation at the end of each cycle for specimens with mid height failures.

Once again, consistently with dynamic modulus findings with these mixes, the two PMA specimens (without fibers) displayed a better performance than the specimen FPMA F3 with fibers. An important observation from these experiments is the extremely large difference in performance between the mixes prepared with unmodified binders and with polymer modified binders. In general, the polymer modified mixes outperformed the unmodified mixes by a factor of about 5.

Figure 6-10 shows some of the same curves in Figure 6-9 for mid-specimen breaks together with results for trimmed specimens with end breaks tested before the use of epoxy to smooth out the sharp edges and shims and a torque-wrench to minimize load eccentricity. For both, the HMA and PMA mixes, the performance was substantially reduced without smoothing and the use of shims to minimize load eccentricity. In this figure, the performance reduction because of end breaks is seen more clearly for the specimens prepared with polymer modified binder. Specifically, the number of cycles until complete fracture of specimen PMA F2 is less than half of those specimens PMA F3 and PMA F4. The reduction for specimen PMA F1 was not as large but was still close to 50%. These results stress the importance of minimizing load eccentricity to obtain meaningful results.

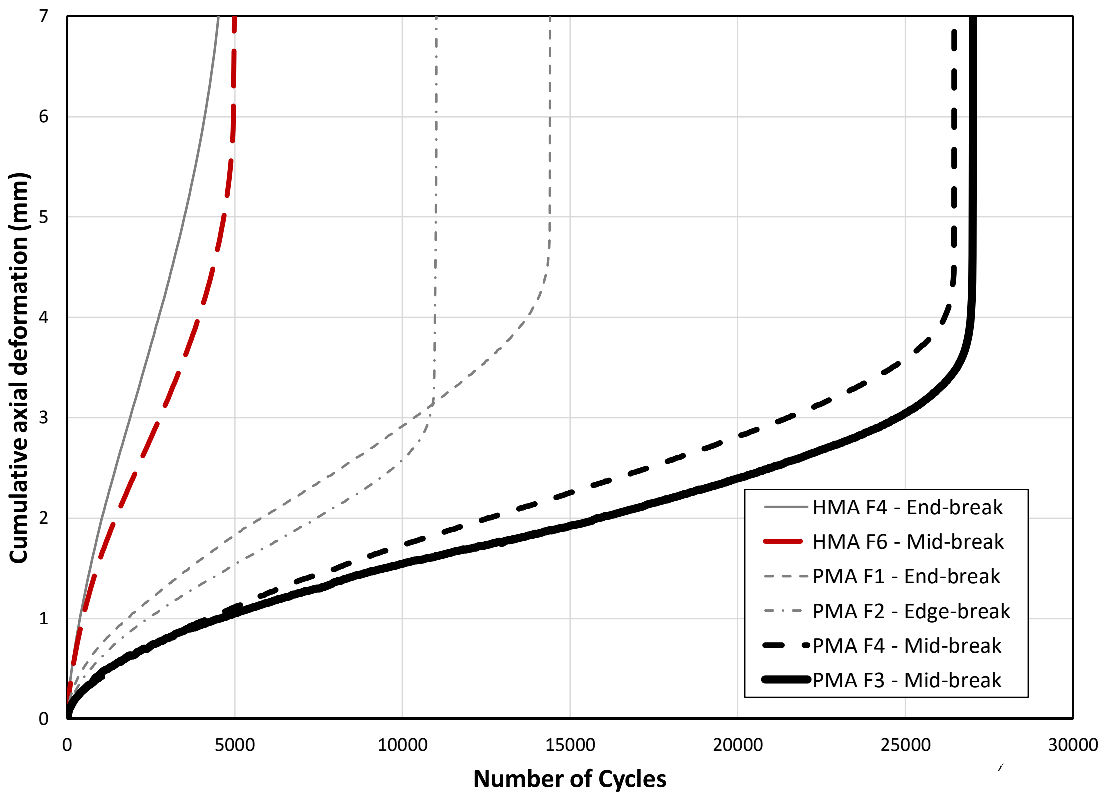


Figure 6-10 Cumulative axial deformation at the end of each cycle for specimens with mid height failures.

It is apparent that the combination of the specimen configuration (trimmed geometry and epoxy smoothing) together with the precautions used to minimize load eccentricity have been effective at inducing the mid-specimen failures even in the potential presence of an uneven air voids distribution.

All samples stretched between 4 to 6 mm before breaking. Consequently, the on specimen LVDT typically used for fatigue testing (which have only 1 mm range) have limited applicability. For this type of test, a larger range is required. Nevertheless, it is interesting to note that consistently with the finite element simulations most of the deformation accumulated on the specimen originates between the LVDTs. In general, it was found that just before the on-specimens LVDTs went out of range, their displacement was about 70 to 80% of the actuator displacement even though their initial gage length (70 mm) is less than half the specimen height (~150 mm).

Dynamic finite element analysis with pulse loading and HMA viscoelastic properties (Prony series derived from the master curve) show that the maximum strain within the HMA occurs at a similar location as predicted by the static analysis. However, it also shows a higher strain within the last epoxy wedge in contact with the steel plate (about 30% higher than the target strain in the sample). Nevertheless, considering the successes with testing, this may indicate that the epoxy is able to withstand larger strains than the HMA without failure.

6.8 CHAPTER CONCLUSIONS AND RECOMMENDATIONS

The dog-bone shape configuration developed in this study combined with epoxy smoothing and the use of aluminum foil shims to reduce the effects of load eccentricity has shown to be effective at inducing mid-specimen breaks and avoiding undesirable strains concentrations. Thus, its use could result in more representative prediction of the material performance. Further improvements such as the use of larger range on-specimen LVDTs are needed to make the data analysis of this test configuration more useful. Development of an automated trimming procedure is recommended to make it practical. It is recommended to further validate these results for strain-controlled fatigue tests and different temperatures.

Clearly, the process of trimming the specimens with the pattern shown in Figure 6-3 and using epoxy cement to smooth out the transition provides excellent results in terms of the location of the break occurring in a desirable location. Other interesting results include the following. First, the number of cycles at which the samples with both trimming and epoxy smoothing broke were always larger than the number of cycles at which the samples with trimming without epoxy broke. As shown above, for the PMA specimens, the number of cycles until crack separation with epoxy smoothing and the use of aluminum shims were about doubled the ones with just trimming. It is important to note that specimen FPMA-F1 and the specimens without epoxy smoothing were tested before the use of shims to minimize load eccentricity was implemented. This may explain the substantially poorer performance of specimen FPMA-F1 compared to the almost identical specimen FPMA-F3. The master curves (not presented here) for trimmed and untrimmed specimens were similar for mixes of the same type.

When using the trimmed-epoxy smoothed configuration, a very large difference was noted between the average number of repetitions until the specimens broke for the mixes prepared with unmodified PG64-22 binder (generally below 5,000 cycles) and the mixes prepared with PG76-22 binders (more than 25,000 cycles). This indicates that the test has great potential to differentiate mixes with substantially different performance. The shape of the permanent deformation curves in tension is similar to that obtained in the flow number test (compressive permanent deformation). Thus, similar procedures may be used to discern its inflexion point.

Despite these successful results, it is recommended to explore other test configurations to overcome a few of shortcomings. First, while aluminum shims were used with success in this study to reduce the problems with load eccentricity, it is difficult to provide guidance of how to use them successfully. Other mechanical approaches involving the steel ball typically used between the top loading platen and the AMPT loading plate and set screws can provide more consistent and effective results. Second, the specimen preparation is too long for practical purposes. While fatigue testing in general is impractical for routine testing, the trimming and epoxy smoothing operations add a significant amount of time to the specimen preparation. Third, it is not possible to test field specimens.

Successful results have already been obtained with respect with all the above limitations with a different test specimen configuration obtained from laboratory or field cylindrical slices of a follow up study. These will be presented in a different report. Nevertheless, the results and experiences in this study provided in great part the ideas for success in the follow up study.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

A main goal of this study was to quantify the benefits of different pavement preservation treatments to facilitate their adoption and use in pavement preservation programs in a tropical environment such as Hawaii. For this purpose, the University of Hawaii (UH) partnered with the City and County of Honolulu (C&CH) in the Island of Oahu, Hawaii and with the Hawaii Asphalt Pavement Industry (HAPI) and its members to apply preservation treatments on a sample of sections to monitor their performance. The treatments included crack sealing, a fog seal, different proprietary seal coats, and slurry seal. All but one of the treatments were applied in a straight section and a cul-de-sac section between November 2014 and December 2014. The exception was a seal coat that was applied only on a cul-de-sac section in January 2015.

The treatments were monitored by observing their application and following over time the cracking progression on the surface of the treated sections and control sections and any other issues such as wearing off the surface, delamination, and aggregate loss (mostly observed in the controlled sections). Cracking lengths were monitored for about three years. Other issues were also inspected after 4.5 years.

In addition, two other efforts of this study included the measurements of pavement temperatures with depth over time and the development of an asphalt concrete specimen configuration for uniaxial fatigue testing that avoids or minimizes end breaks. Both efforts were directed at addressing the common occurrence of the top-down fatigue cracking in Hawaii. The measurement of pavement temperatures provides some validation of assumed temperature profiles that have been used to study the potential causes of top-down fatigue cracking in high temperature environments. The special fatigue testing configuration was developed with high temperature testing in mind since given the measured temperatures, top-down fatigue cracking in Hawaii must occur at much higher pavement temperatures than those assumed in most analytical studies.

The following are the main findings of the study in each of its three main themes.

Pavement Preservation Treatment Performance:

- In straight sections, crack sealing was found to reduce the rate of cracking progression with respect to the control section even when the cracking was clearly mostly environmentally induced. The results in cul-de-sacs were less conclusive because of factors that could not be controlled but they were still consistent with a slight reduction in the rate of the cracking progression.
- The sealant in cracks sealed with the “rout and seal” procedure was in general still performing adequately after 4.5 years and effectively sealing the cracks.
- For cracks approximately 10 mm (3/8 inch) wide or larger and sealed with the “clean and seal” procedure, the sealant was in general still performing adequately after 4.5 years and effectively sealing the cracks.

- The performance of crack sealing in thinner cracks sealed with the “clean and seal” procedure varies widely depending on the width of the crack. For very thin cracks about less than 3 mm (1/8 inch), only a very small amount of the sealant penetrates the crack, providing mostly a short-lived temporary bridge that is quickly broken because of the high strains created by the crack movement. In this type of cracks, it was often observed that no sealant was present in less than a year. Better performance was observed as the crack widths increased but for cracks less than about 10 mm (3/8 inch) the sealant and the crack wall often separated on one side of the crack.
- All the seal coats evaluated, and the slurry seals were very effective at arresting the occurrence of raveling, but the durability of the seal coats varied, with one starting to wear off in less than 2 years and others still providing a nice wearing surface after 4.5 years.
- The cracking progression rates in all the sections treated with seal coats were higher than the rate on the corresponding control sections. This happened for both, straight sections and section in cul-de-sacs.
- The cracking progression rate in the two sections treated with fog seal/rejuvenator, one in a straight section and the other in a cul-de-sac, were lower than the rates on the corresponding control sections.
- The fog seal application started fading after about two years in the straight section with more traffic and in some small areas after more than three years in the cul-de-sac section.
- None of the preservation treatments studied will prevent the additional environmental cracking that would eventually had occur without the treatment. As indicated before, the fog seal is the only treatment that decreased the cracking rate. The results for the slurry seals were more difficult to interpret but they did not appear to alter them much. The seal coats appear to consistently increase the rate of cracking progression.
- Significant aggregate loss was observed on some of the slurry seals.

Measurements of pavement temperatures:

- The measured pavement temperatures near the surface were rarely below 20ºC (68ºF). since these values are representative of most conditions of interest in Hawaii, top-down fatigue cracking must occur at higher temperatures.
- Pavement temperature profiles leading to inverted moduli profiles that create high tensile and shear strain levels near the surface occur often. The results depend on frequency of loading and binder aging, but they can easily occur on about 15% of the time.
- Passing rains can cause sudden temperature drops of the order of 15ºC within short periods (15-min). For Hawaii, this happens quite often.

Uniaxial fatigue cracking test configuration (dog-bone shape) to avoid end breaks

- The dog-bone shape configuration developed in the study, combined with epoxy smoothing and the use of aluminum foil shims to reduce the effects of load eccentricity, was effective at inducing mid-specimen breaks and avoiding undesirable strains concentrations.

7.2 RECOMMENDATIONS

The following are conservative recommendations for programming pavement preservation work on low volume city streets:

- Standard seal coats with 2 lb. of sand: 4 years,
- Liquid Road: 5 years,
- Slurry Seal: 6 years.

An interval of 2 to 3 years is recommended to revisit sections that were previously crack sealed to seal new cracks and reseal any previously sealed cracks that had reopened. Considering the cracking rates observed in seal coats, this may be even more important in sections with these treatments to protect the pavement preservation investment and truly extend the pavement life.

In addition to be a waste of natural resources, large aggregate losses in the slurry seals can lead to shorter life cycles. Given the success of seal coats and the fog seal in arresting raveling, the application of a seal coat shortly after the application of the slurry seal should be considered as an alternative to minimize the loss of aggregate in the slurry seal. Similar solutions have been found effective with chips seals and this may extend the slurry seal performance substantially.

The City and County of Honolulu should continue its efforts toward a stronger pavement preservation program. As part of that program, pavement thicknesses on reconstructed pavement sections should be looked at carefully..

In this report, some arguments were provided for the increase in the cracking progression rates on the seal coats used in Hawaii, but these were speculative arguments about the treatments inducing higher surface temperatures and thus higher temperature ranges on each day. This argument should be verified or refuted with another study.

The study of the consequences of inverted moduli profiles from high pavement temperatures at the pavement surface should be continued and validated with field experiments and including the performance of tack coats under these conditions.

In uniaxial fatigue cracking studies with the AMPT, other test configurations to overcome end breaks should be studied to reduce the problems with load eccentricity, to reduce specimen preparation times, and to be able test field specimens. Some advances have already been made in this area, but they still need improvement.

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APPENDIX A LOCATIONS OF STRAIGHT SECTIONS

A.1 HOOLAUNA STREET – CRACK SEALING CONTROL SECTION

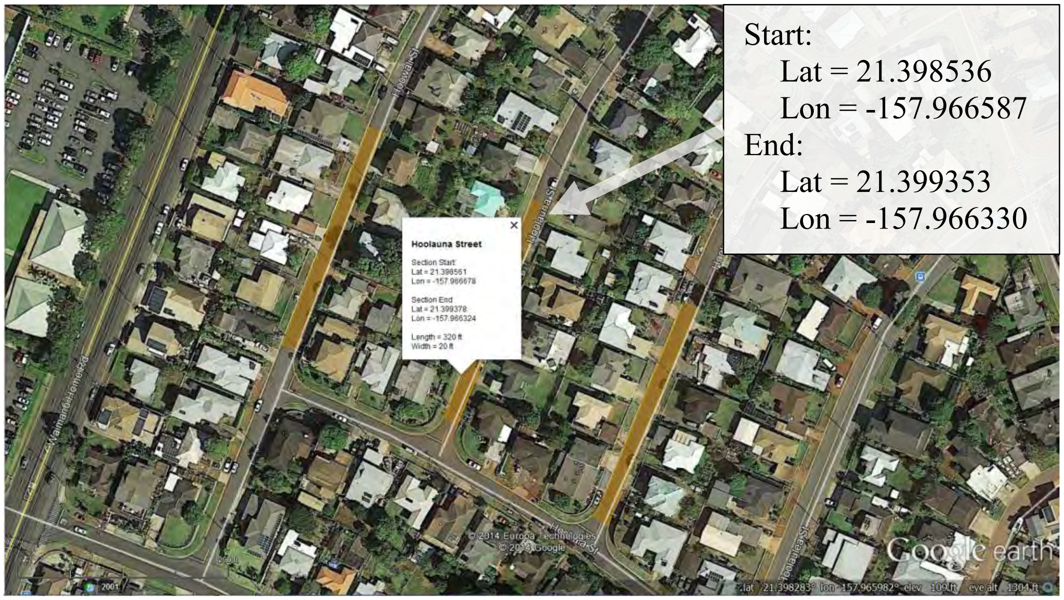

Figure A-1 Location of Hoowali Street - Crack Sealing Control Section.

A.2 HOOKANO STREET – CRACK SEALING

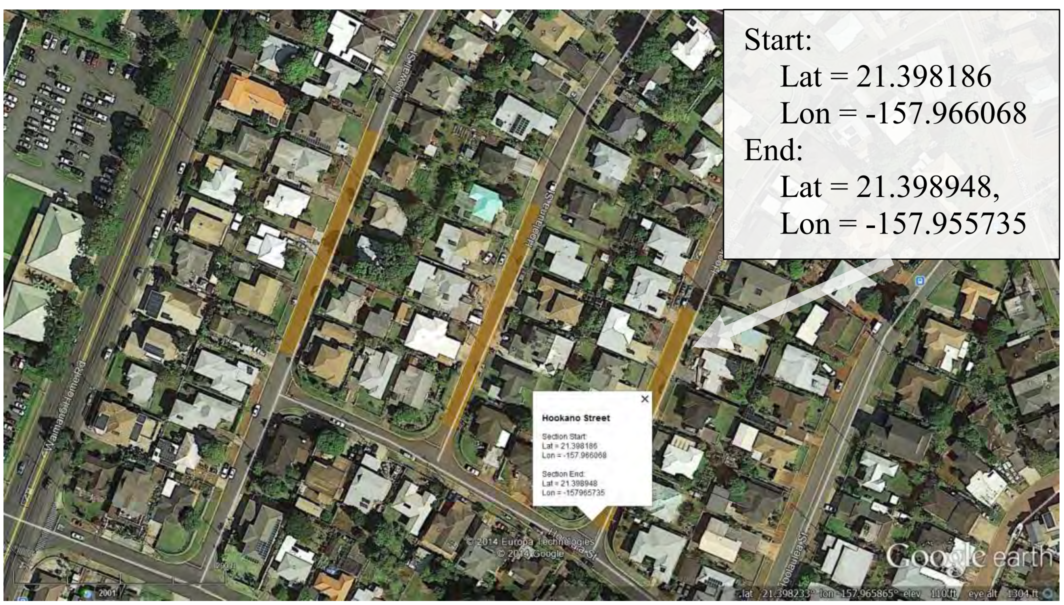

Figure A-2 Location of Hookano Street – Crack Sealing with “Roadsaver 211 by Crafco” - GP Roadway Solutions and Goldwins Supply Service Inc.

A.3 HOOWALI STREET – CRACK SEALING

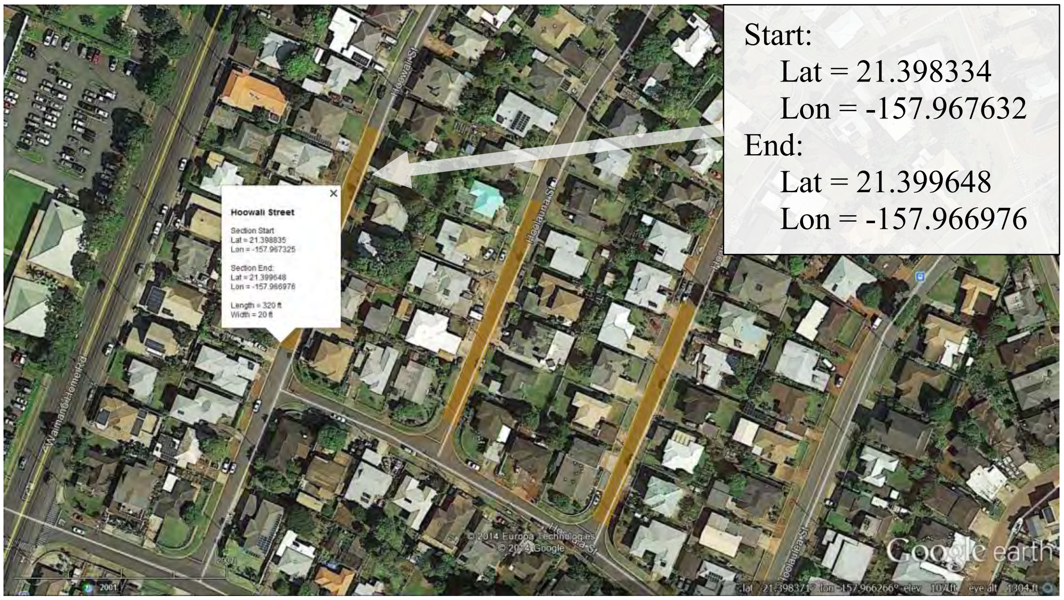

Figure A-3 Location of Hoowali Street – Crack Sealing with “CrackMaster™ Supreme-HT (Hot Pour Crack Sealant)” - SealMaster®/Hawaii.

A.4 SECTION 1 ON KAWELOKA STREET – FOG SEAL (PLASTI-PAVE)

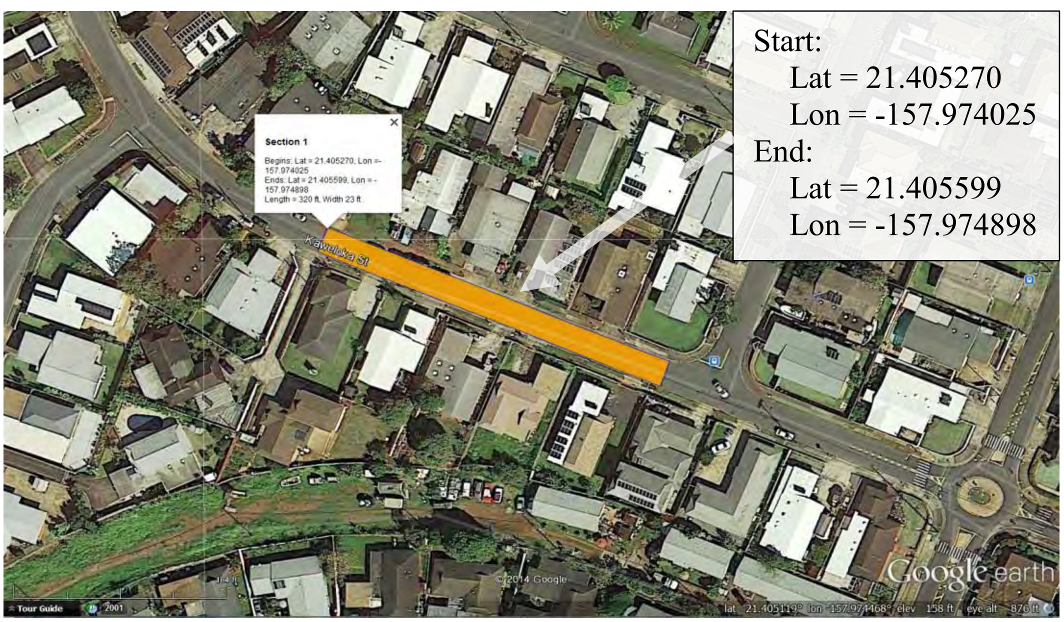

Figure A-4 Location of Section 1 on Kaweloka Street - Fog Seal with “Plasti-Pave (Pavement Rejuvenator)” - SealMaster®/Hawaii.

A.5 SECTION 2 ON KAWELOKA – SEAL COAT

Figure A-5 Location of Section 2 on Kaweloka Street – Seal Coat with "Liquid Road™ (Bituminous Surface Treatment)" by SealMaster®/Hawaii.

A.6 SECTION 3 ON KAWELOKA STREET – SEAL COAT

Figure A-6 Location of Section 3 on Kaweloka Street – Seal Coat with "MasterSeal™ Ready to Use (Asphalt Based Pavement Sealer Fortified with Gilsonite)" by SealMaster®/Hawaii.

A.7 SECTION 4 ON KAWELOKA STREET - SEAL COAT

Figure A-7 Location of Section 4 on Kaweloka Street – Seal Coat with “OptiPave Plus™ Ready to Use (Asphalt Based Pavement Sealer Fortified with Gilsonite and TopTuff)” by SealMaster®/Hawaii.

A.8 SECTION 5 ON KAWELOKA STREET – FOG SEAL:

Figure A-8 Location of Section 5 on Kaweloka Street – Seal Coat with “CarbonSeal-HF” by GP Roadway Solutions.

A.9 SECTION 6 ON KAWELOKA STREET – CONTROL SECTION

Figure A-9 Location of Section 6 on Kaweloka Street – Control Section for Seal Coats with no bus loading.

A.10 SECTION 7 ON KAWELOKA STREET – CONTROL SECTION

Figure A-10 Location of Section 7 on Kaweloka Street – Control Section for Seal Coats with no bus loading.

A.11 SECTION 8 ON KAWELOKA STREET – CONTROL SECTION

Figure A-11 Location of Section 8 on Kaweloka Street – Control Section for Seal Coats with no bus loading.

A.12 SECTION 3’ ON KAWELOKA STREET – CONTROL SECTION

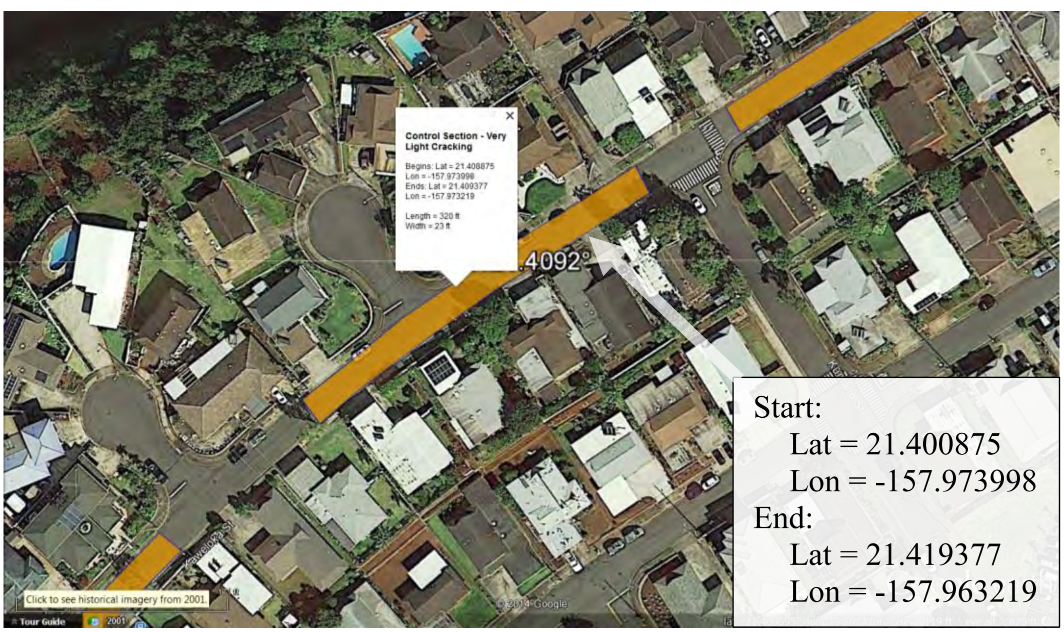

Figure A-12 Location of Section 3’ on Kaweloka Street – Control Section for Seal Coats with bus loading.

A.13 HULAHE STREET – SLURRY SEAL

Figure A-13 Location of Hulahe Street section – Slurry Seal by Alakona Corporation.

APPENDIX B LOCATIONS OF CUL-DE-SAC SECTIONS

B.1 PALAMOI STREET – CRACK SEALING CONTROL SECTION

Figure B-1 Palamoi Street section – Crack Sealing Control Section.

B.2 PAAAINA PLACE – CRACK SEALING

Figure B-2 Paaaina Place section – Crack Sealing with “Roadsaver 211 by Crafco” by GP Roadway Solutions.

B.3 KAWELOKA PLACE – CRACK SEALING

Figure B-3 Kaweloka Place section – Crack Sealing with “CrackMaster™ Supreme” (Hot Pour Crack Sealant)” by SealMaster®/Hawaii.

B.4 KAUMOLI PLACE – CONTROL SECTION

Figure B-4 Kaumoli Place – Control section for Seal Coats and Slurry Seal.

B.5 HOOLAWA PLACE – FOG SEAL

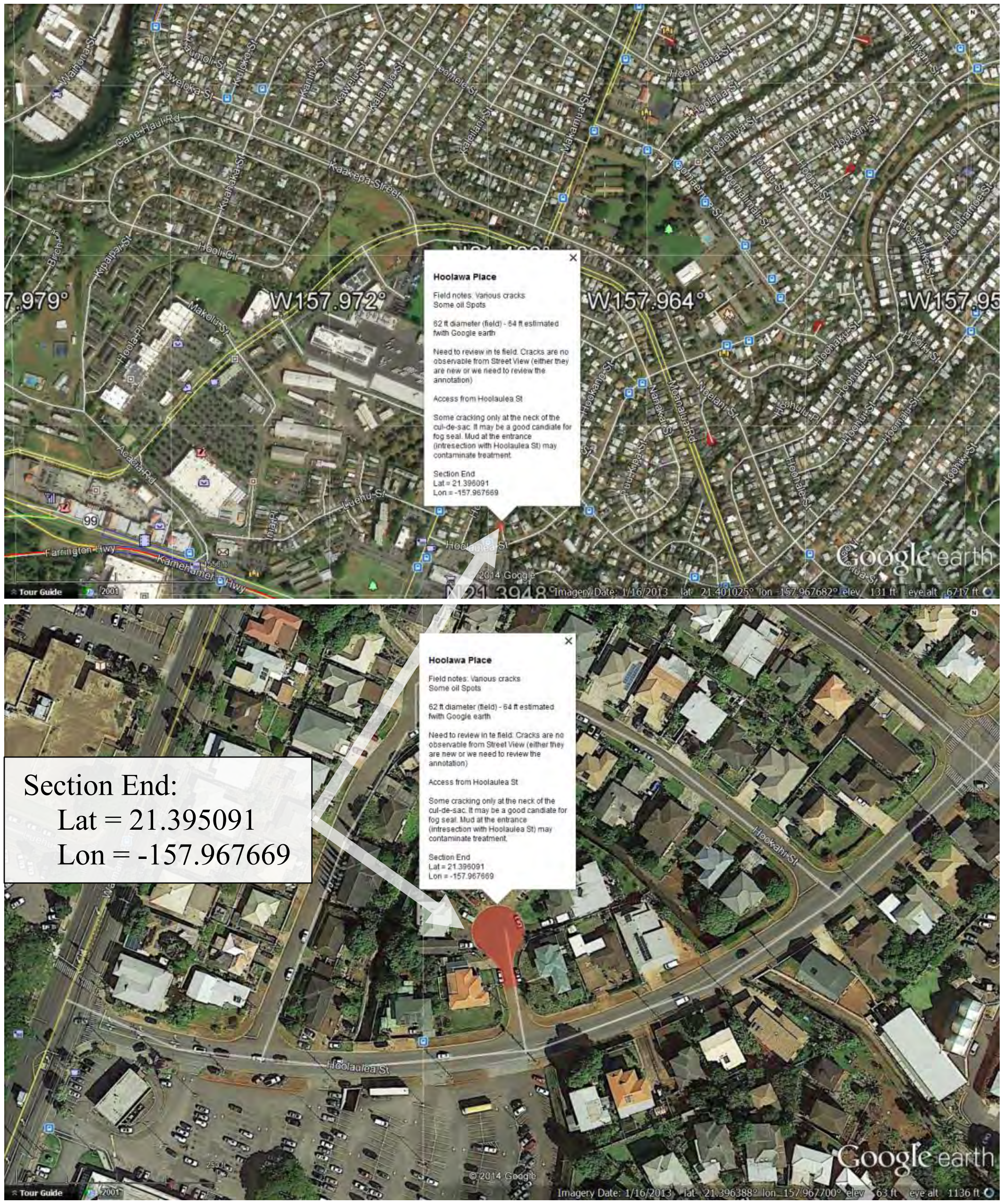

Figure B-5 Hoolawa Place section – Fog Seal with “Plasti-Pave (Pavement Rejuvenator)” by SealMaster®/Hawaii.

B.6 KANIHI STREET – SEAL COAT

Figure B-6 Kanihi Street section – Seal Coat with "Liquid Road™ (Bituminous Surface Treatment)" by SealMaster®/Hawaii.

B.7 KALAUIPO PLACE – SEAL COAT

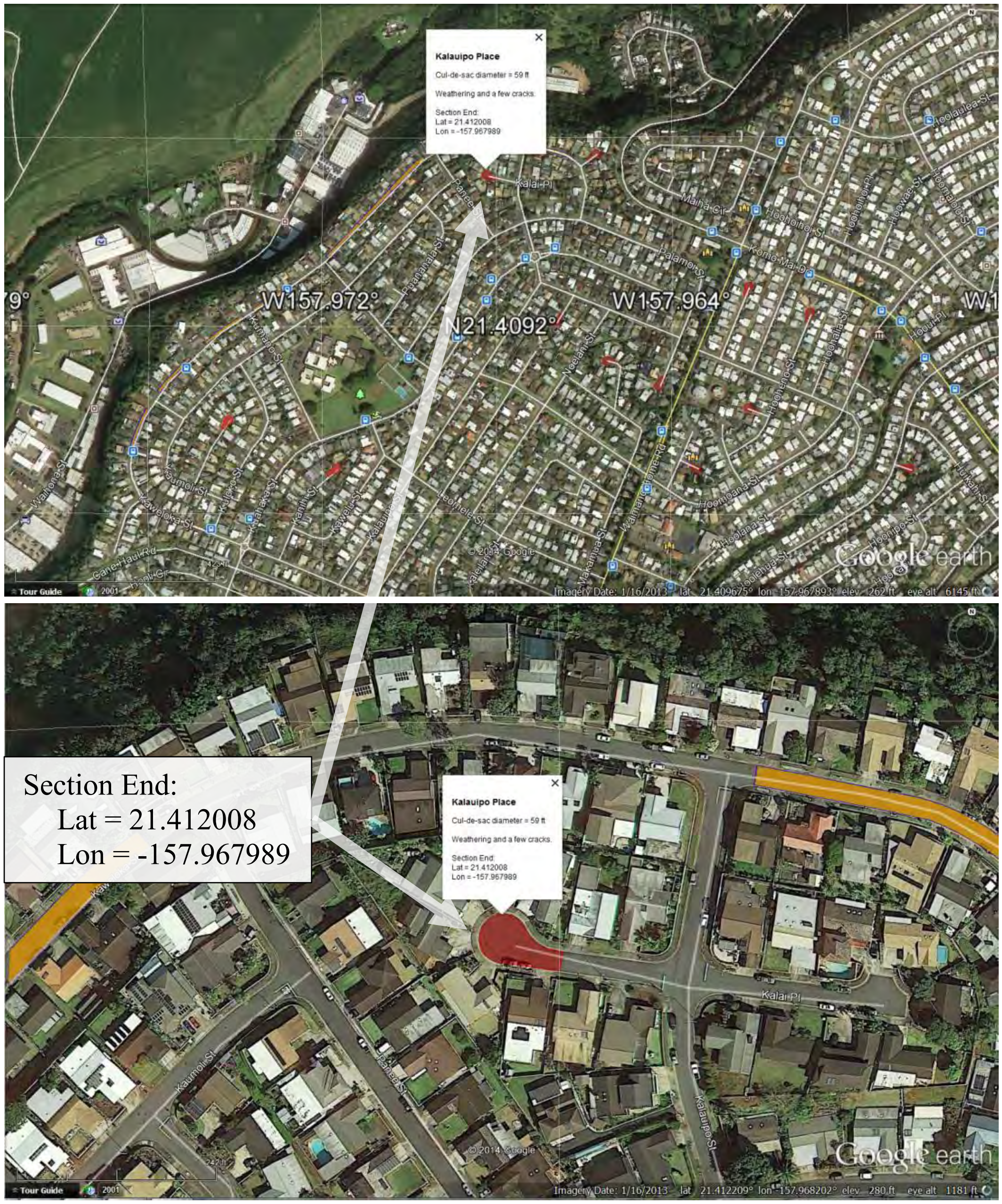

Figure B-7 Kalauipo Place section – Seal Coat with “MasterSeal^{TM} Ready to Use (Asphalt Based Pavement Sealer Fortified with Gilsonite)” by SealMaster®/Hawaii.

B.8 HOOLANA STREET – SEAL COAT

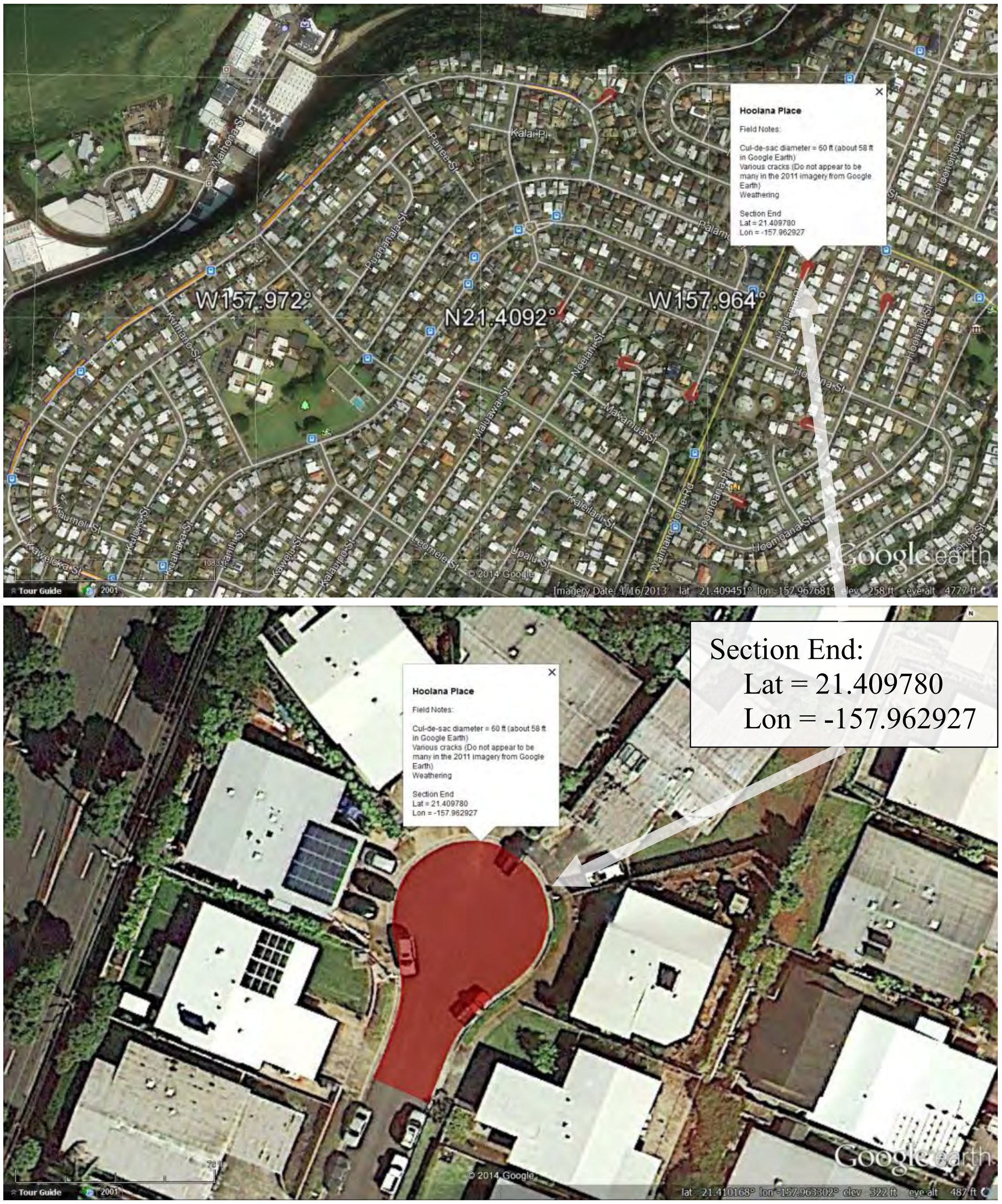

Figure B-8 Hoolana Place section – Seal Coat with “OptiPave Plus^{TM} Ready to Use (Asphalt Based Pavement Sealer Fortified with Gilsonite and TopTuff” by SealMaster®/Hawaii.

B.9 HOOHENO STREET – SEAL COAT

Figure B-9 Hooheno Street section – Seal Coat with "Resurfacer by Brewer Cote" by Oahu Sealcoating & Paving LLC.

B.10 HOOHENO PLACE – SEAL COAT

Figure B-10 Hooheno Place section – Seal Coat with “CarbonSeal-HF” by Grace Pacific Roadway Solutions.

B.11 HIANA PLACE – SLURRY SEAL

Figure B-11 Hiana Place section – Slurry Seal by Alakona Corporation.

B.12 HAPAPA PLACE – SLURRY SEAL

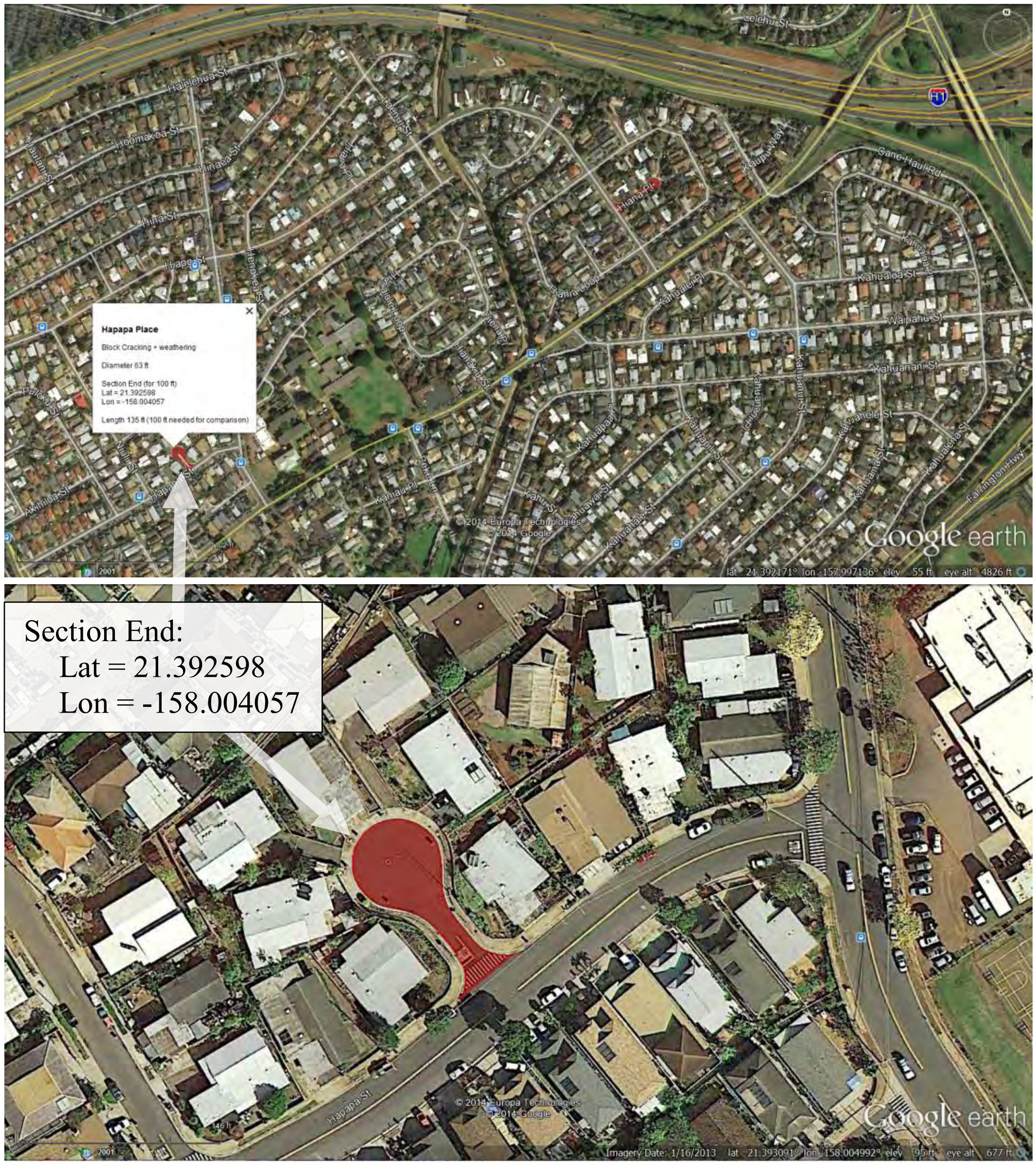

Figure B-12 Hapapa Place section – Slurry Seal by Alakona Corporation.

APPENDIX C CHRONOLOGICAL OBSERVATIONS

The following subsections provide evidentiary photographs of the progression of cracking and other issues difficult to quantify in all these sections studied.

C.1 CRACK SEALING PERFORMANCE IN STRAIGHT SECTIONS

C.1.1 Hoolauna St. - Control section for crack sealing in straight segments.

Figure C-1 shows the condition of this section near the beginning of the study. Cracking was composed mostly of large blocks (block cracking). One side of these blocks was typically part of a longitudinal crack along the construction joint. Sometimes the blocks were large enough that the opposite side was the joint with the gutter, but oftentimes other longitudinal cracks appeared between the centerline and the joint with the gutter.

Figure C-1 Cracking patterns observed on the Control Section on Hoolauna Street on 01/03/2015.

Clearly, not much change could be observed visually from survey to survey. This is illustrated on the photos in Figure C-2, Figure C-3, and Figure C-4, which show the same patterns. After three years, the pattern looks very similar, though as shown by the quantities in Figure 4-3, the total cracking had increased by about 20%. As discussed before, the cracking increase was relatively gradual with the error in measurements being of the same magnitude as the average change between surveys.

Figure C-3 also shows some of the degradation observed on the surface (loss of mastic and aggregates, some of which can be seen loose in the cracks). Figure C-4 shows raveling developing near the center lane joint and in the joints with the gutter.

Figure C-2 Cracking patterns observed on the Control Section on Hoolauna Street on 03/03/2015.

Figure C-3 Cracking patterns observed on the Control Section on Hoolauna Street on 06/27/2016.

Figure C-4 Cracking patterns observed on the Control Section on Hoolauna Street on 12/14/2016.

C.1.2 Hoowali Street (Pearl City) - “CrackMaster™ PL-HT” (Hot Pour Crack Sealant) – SealMaster®/Hawaii

Figure C-5 to Figure C-9 show examples of the condition of the section over time. Figure C-5 shows the condition on 08/29/2015, nine months after the section was crack sealed. As seen on the top two photos in the figure, there is full contact between the sealant and the crack walls. Thus, the sealant is indeed preventing the infiltration of water through the cracks. The photo on the bottom of the figure illustrates that a large part of this section had not developed a longitudinal crack, as seen in the other two sections. This may explain in part the lower cracking observed on this section. This photo also illustrates that a new crack was developing close to the center of the lane.

Figure C-6 illustrates that 16 months after the treatment application, the crack sealing on routed cracks was still performing well (on only a small portion of this section the cracks were routed). The bottom photo in that figure shows the development of another new crack. Unlike the untreated section, these were initially easier to identify.

Figure C-7 shows the conditions after 19 months. The top left photo shows the condition of a crack that was not routed. As shown, the sealant was still filling the crack fully. It is also seen that the crack was propagating longitudinally. The photo on the top right shows the same crack that was shown on the top left of Figure C-6. Some loose aggregate incrustations can be seen together with some wrinkles in the surface of the sealant. This was quite common as the sealants aged in all the crack sealing jobs, but it has no consequence as long as the sealant does not stiffen. The bottom left photo shows another common situation in this study. A new crack is formed adjacent to where the sealant was poured with no obvious crack visible. This is typically observed with low severity cracks that are not always visible while sealing. It is likely that the portion of the crack where no sealant was poured had already formed before the sealing operation but that it was not visible to the operator.

Figure C-5 Cracking patterns observed on Hoowali Street on 08/29/2015 (sealed with CrackMaster^{TM} PL-HT).

Figure C-8 and Figure C-9 show the conditions after more than 3 years (after about 38 months). The two photos on the left of Figure C-8 show again the typical wrinkles developed on the surface of the sealant. The photos on the right show that the cracking pattern continues developing between the sealed cracks. The top left photo in Figure C-9 shows what happens on low severity cracks where the sealant is subjected to high strains with the crack movement. It is apparent that there are portions were the crack has reopened. The figure also shows further examples of crack propagation and water infiltration through the joint with the gutter, as highlighted with the vegetation growth. Finally, the bottom right photo on Figure C-9 shows that the binder is still soft enough that can be imprinted with a finger.

The condition of the sealer on 5/24/2019 is shown in Figure C-10. In routed cracks or in wide cracks, the crack sealer is still performing well after 4.5 years. Although no photo was taken, it can still be indented.

Figure C-6 Condition of crack sealing observed on Hoowali Street on 03/03/2016 (sealed with CrackMaster^{TM} PL-HT).

Figure C-7 Condition of crack sealing observed on Hoowali Street on 06/27/2016 (sealed with CrackMaster^{TM} PL-HT).

Figure C-8 Condition of crack sealing observed on Hoowali Street on 01/26/2018 (sealed with CrackMaster^{TM} PL-HT).

Figure C-9 Condition of crack sealing observed on Hoowali Street on 01/26/2018 (sealed with CrackMaster^{TM} PL-HT).

Figure C-10 Condition of crack sealing observed on Hoowali Street on 5/24/2019 (sealed with CrackMaster™ PL-HT).

C.1.3 Hookano Street (Pearl City) – Grace Pacific Roadway Solutions - Crack Sealing with Roadsaver 211 by Crafco

Figure C-11 shows examples of routed cracks soon after they were crack sealed. The sealant in these photos appears to be in perfect contact with the crack walls. The top right photo shows that parts of this section were experiencing significant raveling.

Figure C-11 Condition of crack sealing observed on Hookano Street on 03/27/2015 (sealed with Roadsaver 211).

The photo in Figure C-12 shows another example of a crack meandering outside the sealing overband. In this case, the sealed crack is visible. Again, since no such cracks were observed immediately after sealing, it is most likely that they were not formed yet or if they were, they were not yet visible. The photo in Figure C-13 shows that after a year, the sealant in routed cracks was performing as expected.

Figure C-12 Condition of crack sealing observed on Hookano Street on 08/29/2015 (sealed with Roadsaver 211).

Figure C-13 Condition of crack sealing observed on Hookano Street on 01/24/2016 (sealed with Roadsaver 211).

When this section was selected and assigned for the crack sealing study, it was not realized the level of raveling that it was experiencing. In fact, the raveling in this section was widespread. This is illustrated on Figure C-14, which shows the condition in a particularly bad spot. In that area, a pound of aggregate was swept from the marked squared yard shown on the top-right photo. This is common on streets with on-street parking and where some vehicles are parked regularly in the same spot. Vehicles with oil leaks parked regularly on the same spots contribute significantly to this problem. Raveling on other sections was not this obvious, but usually loose aggregates in the gutter were a good indicator of aggregate loss for other sections as well.

Figure C-14 Raveling observed on Hookano Street on 03/03/2016 (sealed with Roadsaver 211).

The photos on Figure C-15 show new cracks forming despite the relatively large level of cracking in the section. Notice that most of these are completely new and unrelated to the crack sealing in the section. The photo on the bottom right of the figure is another example of the true path of a crack being exposed after it was sealed.

Figure C-16 is more relevant to the performance of the crack sealing. The top left photo in the figure, illustrates a problem with the sealing of relative thin cracks that have not been routed. In this case, the crack sealing is not performing its job after only slightly more than a year. In addition to the high strains induced by the short distance between the crack faces, the crack may have been too thin for the sealer to penetrate it. Thus, any crack movement will simply break the thin film of sealant and expose the crack again. The photo on the top right shows a less severe case but where still the sealing is not performing adequately. In this case, the sealant has penetrated the crack, but its width is too small to absorb the crack movements, thus leading to strain levels that are too high for the sealant or the bond between the sealant and the crack face. Note that the sealer in wider cracks with an adequate reservoir (i.e., not very shallow cracks where the material can be easily pull out), even when not routed, tend to perform quite well, as illustrated in the bottom left photo of Figure C-16. The bottom right photo shows another example of a crack manifesting adjacent to where the operator probably thought there was a thin/hairline crack.

The top left photo of Figure C-17 shows another example of a crack where the sealant is not performing its function after only a year and half. Note that the overband appears worn out and the crack is exposed. In most of these cases, the cracks were originally thin when sealed and they widen afterwards. The top right photo shows a crack that is for the most part still sealed but with a circular defect where the sealant had been lost. This is likely related to tracking combined with a dirty interface. Given the large area of the defect, even with a clean interface, it would be difficult to avoid the sealer been pulled out of the crack. The two photos at the bottom of the figure show again the substantial raveling in this section. This may have prevented good bonding of the sealant at the joint, as manifested by the vegetation growth seen on the photo on the left.

The top left photo in Figure C-18 shows that in places where the sealant at the gutter joint had stayed in place, no vegetation is observed and thus there is no ingress of water into the pavement through the joint. Still, several spots with vegetation growth are seen. As indicated before, this lackluster performance may have been related to the significant raveling of the pavement surface (easily dislodged aggregates leave part of the sealant exposed) together with the tracking produced by parking operations. The other photos in Figure C-18 and in Figure C-19 provide further illustrations of the performance issues about thin cracks that were not routed.

Figure C-15 Condition of crack sealing observed on Hookano Street on 03/03/2016 (sealed with Roadsaver 211).

Figure C-16 More on the condition of crack sealing observed on Hookano Street on 03/03/2016 (sealed with Roadsaver 211).

Figure C-17 Condition of crack sealing observed on Hookano Street on 06/27/2016 (sealed with Roadsaver 211).

Figure C-18 Condition of crack sealing observed on Hookano Street on 01/26/2018 (sealed with Roadsaver 211).

Figure C-19 Condition of crack sealing observed on Hookano Street on 01/26/2018 (sealed with Roadsaver 211).

Figure C-20 shows that in the cracks that were routed and/or were wide enough when sealed, the sealant is still performing well. Although on occasion one may find an example like the one in the bottom left photo, where part of the sealant had been lost, for the most part the sealant on routed or wide cracks was performing quite well after three years. As for the other crack-sealed straight section, the binder is still soft to the touch after three years (see the finger indentation in the bottom right photo).

Figure C-21 provides an overall view of the section about three years after having been crack sealed.

Finally, Figure C-22 shows that as of 5/24/2019, 4.5 years after the cracks were seal, the sealer is still performing well. Note again how it can still be indented.

Figure C-20 Condition of crack sealing observed on Hookano Street on 01/26/2018 (sealed with Roadsaver 211).

Figure C-21 Condition of crack sealing observed on Hookano Street on 01/26/2018 (sealed with Roadsaver 211).

Figure C-22 Condition of crack sealing observed on Hookano Street on 5/24/2019 (sealed with Roadsaver 211).

C.2 CRACK SEALING PERFORMANCE IN CUL-DE-SACS SECTIONS

C.2.1 Palamoi Street - Control section for crack sealing in cul-de-sacs.

Figure C-23 shows the condition of this section near the beginning of the study. Cracking was composed mostly of large blocks (block cracking) with some of the cracks accompanying the curvature of the cul-de-sac. This pattern is typical of what was observed in all cul-de-sacs included in the study. As shown in Figure C-24, little had changed after more than a year (which is also a reflection of the slight increase in cracking noted on Figure 4-7).

Figure C-23 Condition of the Palamoi Street section on 03/20/2015 (three months into the study period) used as control for crack sealing.

Figure C-24 Condition of the Palamoi Street section on 06/27/2016 (sixteen months into the study period) used as control for crack sealing.

C.2.2 Kaweloka Place (Pearl City) - CrackMaster™ PH-HT (Hot Pour Crack Sealant) – SealMaster®/Hawaii.

Figure C-25 shows the condition of the section on 08/29/2015, about 10 months after the crack sealing application. The top left of the figure illustrates the pattern on this section, which is quite typical of the pattern observed in other cul-de-sac sections. The other photos in the figure show that the pavement surface already had a coarse texture because of some binder and aggregate loss.

Figure C-26 and Figure C-27 show the condition of the crack sealing on 03/03/2016. These figures illustrate that the overband after about a year and four months showed significant loss of material because of tracking. This, in part, may have been helped by the coarse texture, which makes dislodging of aggregates easier and bonding of the crack sealant with the existing surface more difficult.

Figure C-25 Condition of the Kaweloka Place section on 08/29/2015.

Figure C-28 and Figure C-29 show little change four months later, but it is also clear that the overband material was barely visible in some cracks. Also, as shown on the top right photo in Figure C-29, some low severity cracks were exposed either because of straining of the sealer or its complete loss inside the crack. In this type of crack, the sealer cannot usually go too deep. Thus, the small vertical cross-sectional area available to transmit a force by adhesion of the sealer to the crack walls together with the large strains on the sealer produced by the daily crack movements facilitates the separation of the sealer with one of the walls or even cracking on the sealer.

As shown in Figure C-30 through Figure C-32, by December of 2016 (six month later) the conditions were again very similar (which is consistent with the cracking progression shown in Figure 4-8).

Figure C-33 and Figure C-34 show the condition after 14 additional months (January 2018). Figure C-33 shows, consistently with the trend shown in Figure 4-8, some additional cracking (top left). There are also thin cracks with hardly any sealer on them (top right and mid left). The other photos show cracks with the sealer exhibiting a considerable wrinkled surface and with loose aggregate incrustations into the sealer. Nevertheless, the sealer may still be helping to reduce the amount of water infiltration. Figure C-34 provides a view of the condition of the section in January 2018, more than 3 years after the treatment application.

Finally, Figure C-35 shows the conditions on 5/24/2019. No significant changes were observed.

Figure C-26 Condition of the Kaweloka Place section on 03/03/2016.

Figure C-27 Condition of the Kaweloka Place section on 03/03/2016.

Figure C-28 Condition of the Kaweloka Place section on 06/24/2016.

Figure C-29 Condition of the Kaweloka Place section on 06/24/2016.

Figure C-30 Condition of the Kaweloka Place section on 12/14/2016.

Figure C-31 Condition of the Kaweloka Place section on 12/14/2016.

Figure C-32 Condition of the Kaweloka Place section on 01/26/2018.

Figure C-33 Condition of the Kaweloka Place section on 01/26/2018.

Figure C-34 Condition of the Kaweloka Place section on 01/26/2018.

Figure C-35 Condition of the Kaweloka Place section on 5/24/2019.

C.2.3 Paaaina Place – GPRS and Goldwins Supply Service Inc. - Roadsaver 211 by Crafco

Figure C-36 and Figure C-37 show the condition of the section on 03/30/2015, about 4 months after the crack sealing application on 11/19/2014. Figure C-36 shows that the pattern on this section conforms to the typical pattern observed in other cul-de-sac sections, with a crack running mostly longitudinally near the centerline and blocks radiating from it and becoming approximately parallel to the curves of the cul-de-sac. Clearly, the cracking appears to be for the most part environmentally related.

Figure C-37 shows the texture of the surface, where some loss of aggregates and mastic is noted (note the loose aggregates in the top photos). Some unsealed thin cracks are also seen in these photos.

Figure C-38 shows the condition of the crack sealing on 08/29/2015. It is clear from the four top photos that the overband material had been largely removed by traffic (although the overbands were still visible, the aggregate surfaces were already exposed). It is also seen that loose aggregates had accumulated and had been pushed into the crack sealer in some areas. In some other cases, a portion of the sealer in wide cracks had been removed either because the crack was not properly cleaned before sealing, or because the larger crack width made it easier for the sealer to be pulled out of the crack when tracked, or because of a combination of these factors. Despite these issues, most of the sealed cracks continued to be properly sealed and performing as expected. The rest of the photos in Figure C-38 show that little change in the cracking pattern could be observed nine and a half months after the treatment application.

The top six photos in Figure C-39 illustrate that the crack sealer continued performing well in most of the section (with some occasional loose aggregate accumulation) as of 03/03/2016, fourteen months after the treatment application. The two bottom photos show two locations where the sealer had been removed in part of the crack and loose aggregate had accumulated. As indicated by the trend shown in Figure 4-9, the total cracking length increased slightly. Consequently, the cracking pattern, illustrated in Figure C-40 is virtually unchanged.

Figure C-41 through Figure C-45 document the slow progression of cracking observed on 06/27/2016, 12/14/2016, and 12/14/2016. Figure C-41 shows the progression of new cracks, some sealed cracks with the overband barely visible, and some cracks with a portion of the sealer removed. However, as illustrated in the photos in Figure C-42, the crack sealer for most of the section is still performing its function well since it fully fills the crack and it is in full contact with the crack walls. In addition, the sealer was still soft to the touch. Figure C-43 shows the conditions on 12/14/2016, two years and one month after the treatment application. The observations are basically the same as before.

Figure C-44 shows the conditions on 02/07/2018, three years and two months after the crack sealing application. This figure illustrates that unsealed cracks were getting wider, that cracking continued propagating at the end of sealed cracks, and that the sealer in some cracks was getting wrinkly and probably not in full contact anymore with the crack walls.

Figure C-36 Condition of the Paaaina Place section on 03/30/2015.

Figure C-37 Condition of the Paaaina Place section on 03/30/2015.

Figure C-38 Condition of the Paaaina Place section on 08/29/2015.

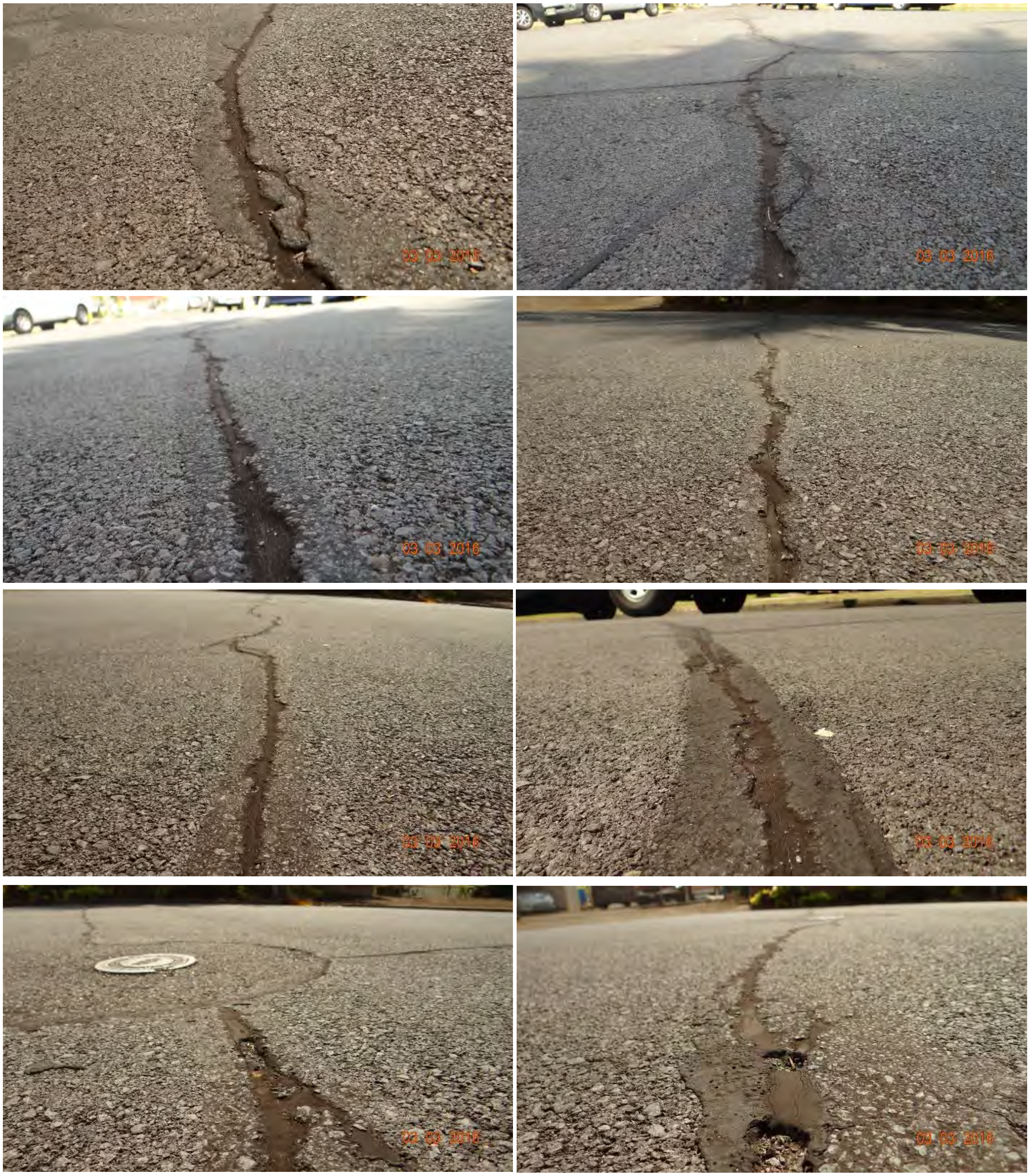

Figure C-39 Condition of the Paaaina Place section on 03/03/2016.

Figure C-40 Condition of the Paaaina Place section on 03/03/2016.

The top four photos in Figure C-45 clearly illustrate the different performance of the sealer in thin, unrouted cracks versus cracks with an adequate reservoir (either routed as shown in this figure or wide enough so that crack movements induce small strains in the sealer). In the thin, unrouted cracks, the sealer often appears to have been squeezed as the crack closes at higher temperatures and to have lost contact with the crack walls as the crack opens at lower temperatures. In very thin cracks, sometimes practically no sealer was seen inside the crack. On the other hand, on wider cracks, the exposed top surface of the sealer was mostly flat, and no spaces were noted between the sealer and crack walls. It is expected that performance of the crack sealer, in terms of minimizing water infiltration into the pavement structure, is quite different in each case, particularly for heavy rain conditions such as those illustrated in the top two photos in Figure C-46. The two middle photos in that figure show a more dull appearance of the surface around an unsealed crack indicating that water was infiltrating the pavement through the crack (in this particular case, the crack was also near the top of the pavement crown, which may have also contributed to that appearance; however, notice that no water was visible on the crack itself). On the other hand, the lower photos in Figure C-46 illustrate how the sealer was not allowing water to infiltrate into the pavement structure through the crack.

Figure C-47 and Figure C-48 show several photos illustrating the differences in surface appearance after the precipitation slowed significantly or shortly after the rain stopped. In all cases, the surfaces of the sealed cracks were still wet, as indicated by their shiny appearance, while at the same time no water was observed in the unsealed cracks and a dull surface appearance was noted on the surface around them. While these observations are expected and probably obvious, it is still considered useful to provide this photographic evidence of the benefits of properly sealing cracks, particularly on a state with so much precipitation as Hawaii.

Figure C-49 shows the condition of the crack sealer on 5/24/2019. After 4.5 years, the crack sealer was still performing its function adequately. Notice that it was still soft enough to be indented. Most existing cracks were still adequately sealed.

Figure C-41 Condition of the Paaaina Place section on 06/27/2016.

Figure C-42 Condition of the Paaaina Place section on 06/27/2016.

Figure C-43 Condition of the Paaaina Place section on 12/14/2016.

Figure C-44 Condition of the Paaaina Place section on 02/07/2018.

Figure C-45 Condition of the Paaaina Place section on 02/07/2018.

Figure C-46 Condition of the Paaaina Place section on 02/07/2018.

Figure C-47 Condition of the Paaaina Place section on 02/07/2018.

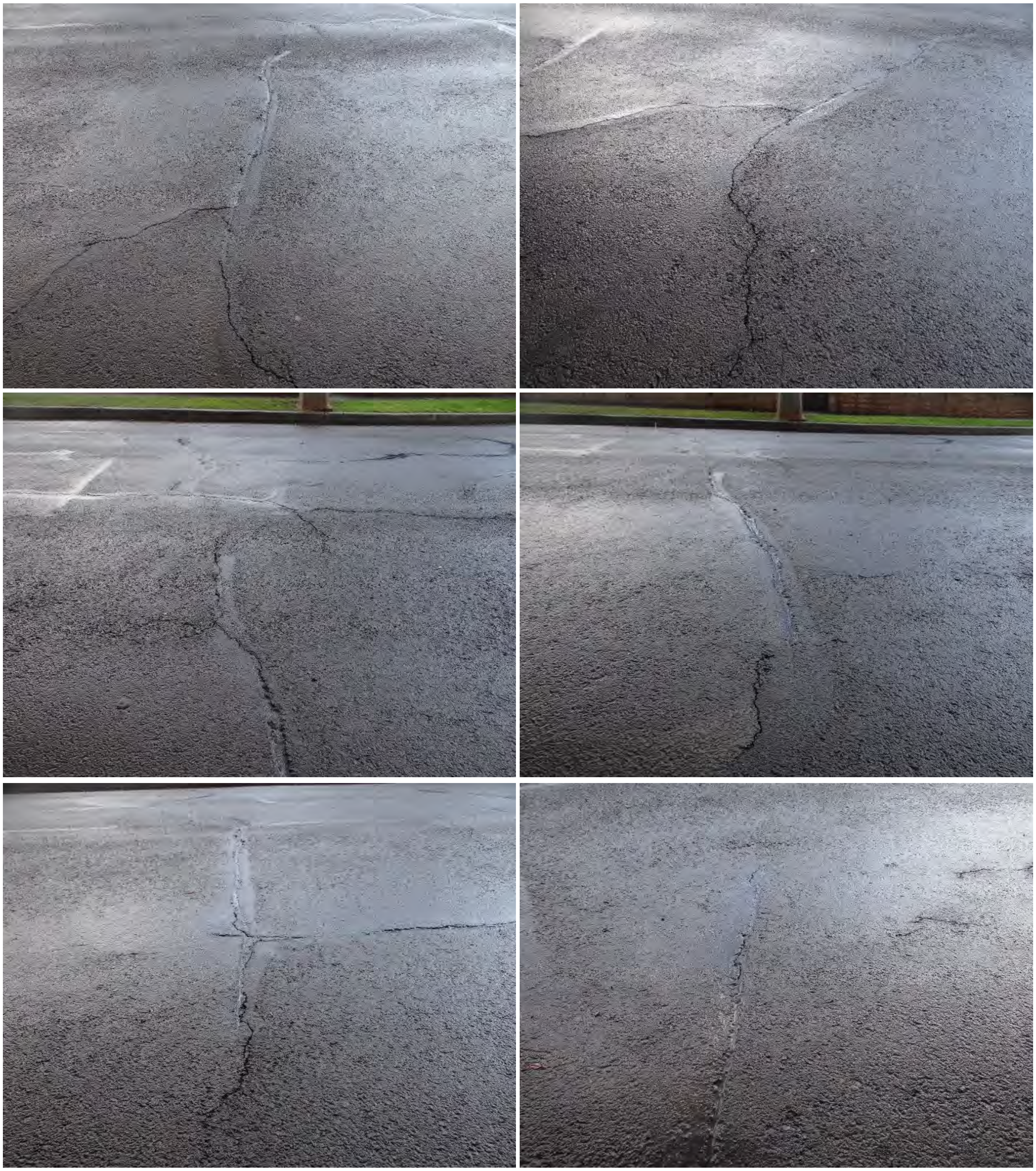

Figure C-48 Condition of the Paaaina Place section on 02/07/2018.

Figure C-49 Condition of the Paaaina Place section on 5/24/2019.

C.3 SEAL COATS IN STRAIGHT SECTIONS

C.3.1 Section 3' – Control Section with Bus Traffic

Figure C-50 shows the condition of the section on 03/30/2015. This figure shows the typical pattern observed in this section throughout the study period, namely, longitudinal cracking along the joint, transverse cracking, and some block cracking. The cracking appeared to be for the most part environmentally related.

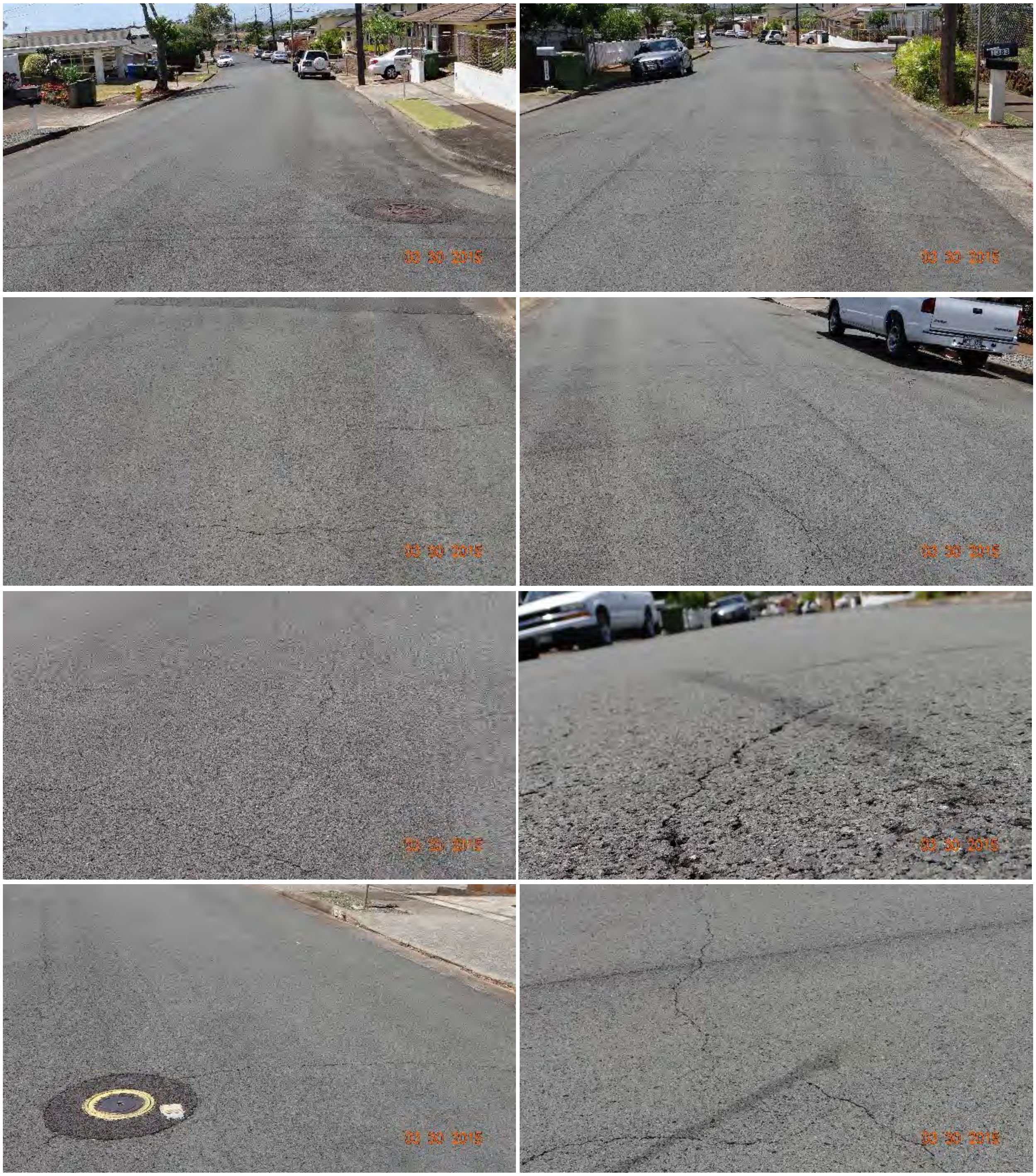

Figure C-50 Condition of Kaweloka Streets control section 3'on 03/30/2015.

However, in some places, the cracking appeared to have been enhanced by loading as illustrated by the crack running parallel to the joint in the photo on the right on the second row of Figure

C-50. The pavement surface was still in good condition, but it was pitted in some places, which is an indication of some incipient raveling. Some small aggregates were loose on the surface.

C.3.2 Kaweloka Street Section 1 - Plasti-Pave (fog seal) by SealMaster®/Hawaii – Bus Traffic

Figure C-51 shows the condition of the section on 03/27/2015, about four and a half months after the treatment application in November 2014. The two photos on the top show that, as expected, the sealed cracks were still in good condition. The left middle photo shows some scaring of the surface caused by traffic probably shortly after treatment application. Some new cracking was also observed, as illustrated in the right middle photo. This and the two photos on the bottom of the figure also show the appearance of some new longitudinal cracks with pumping of fines.

Figure C-51 Condition of Kaweloka Street section 1, treated with Plasti-Pave, on 03/27/2015.

Clearly, this treatment does not alter much the texture of the surface, but it gives the appearance of a much newer road. The four photos on the top of Figure C-52 provide good examples of the contrast between the treated section and the adjacent pavement still provided on 08/29/2015, more than nine months after the treatment application. The two photos on the third row show the sealed cracks were still sealed (even though most were relatively thin). The last two photos show that pumping of fines was still occurring.

Figure C-52 Condition of Kaweloka Street section 1, treated with Plasti-Pave, on 08/29/2015.

As shown in Figure C-53, about 15 months after the treatment application (03/3/2016), the cracks with pumping problems got slightly wider and continued pumping fines. The texture of the pavement looked similar, but with some of the aggregate faces showing some exposure.

The top photo in Figure C-54 shows that a high contrast with the untreated pavement still existed on 06/24/2016, 19 months after the treatment application. The photo on the bottom illustrates the presence of some loose aggregates indicating the possibility of some incipient raveling. However, these were more likely to have come from the adjacent section that exhibited some raveling. The sealer was still filling the depressions, but the aggregate protrusions were a bit more exposed.

The top two photos in Figure C-55 show the general condition of the treatment on 12/13/2016, about 25 months after the treatment application. The photo on the left shows some lack of uniformity whereas the one on the right shows that the pumping problem through some cracks continued.

Figure C-53 Condition of Kaweloka Street section 1, treated with Plasti-Pave, on 03/3/2016.

Figure C-54 Condition of Kaweloka Street section 1, treated with Plasti-Pave, on 06/24/2016.

The photos in second row of Figure C-55 provide a closeup of the cracks with pumping issues. In addition to the fines, moisture in the cracks was evident. The other photos in the figure show how the sealed cracks continue propagating and the coexistence in the bottom right photo of load related cracks (longitudinal with pumping) and transverse cracks.

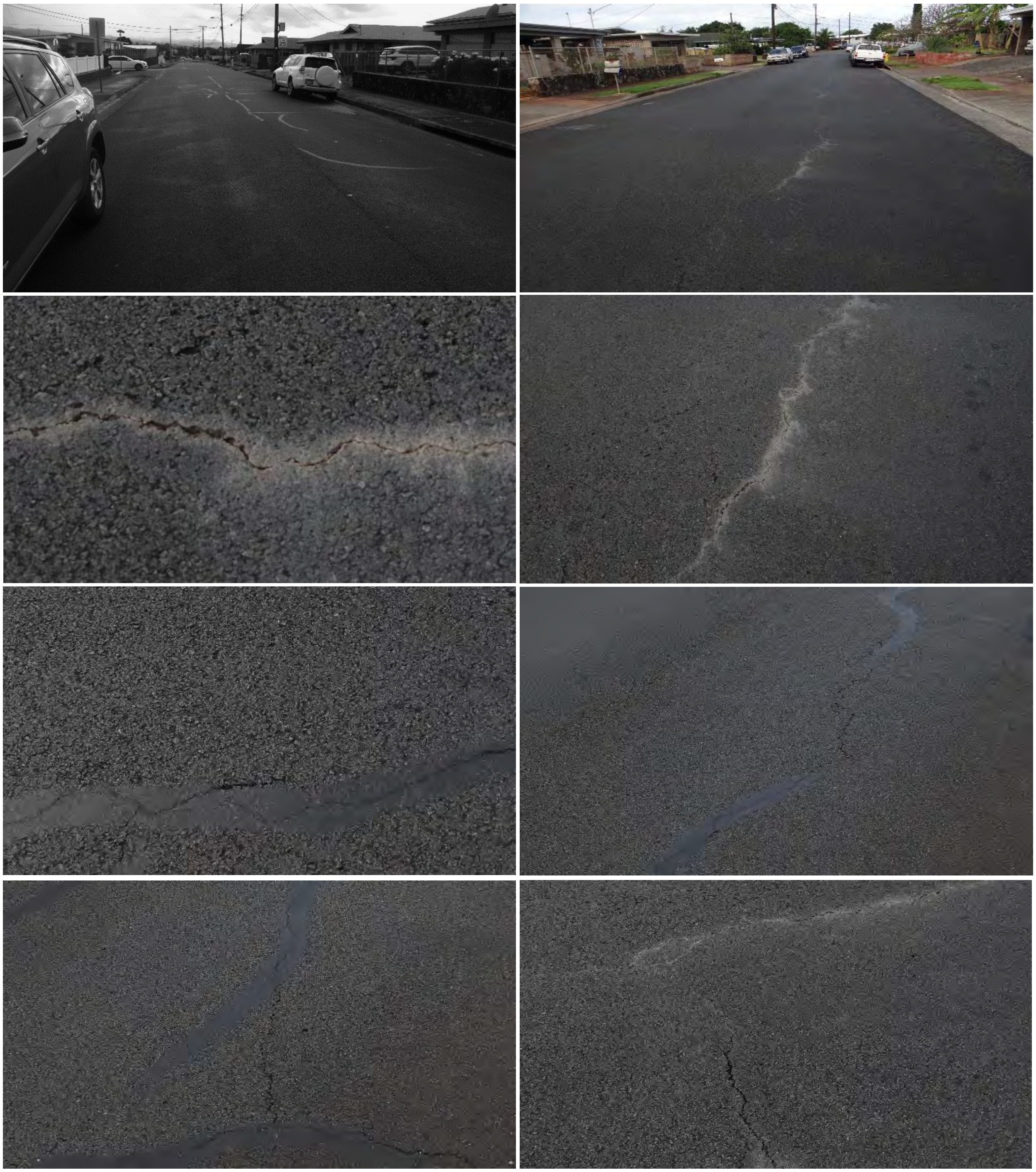

Figure C-55 Condition of Kaweloka Street section 1, treated with Plasti-Pave, on 12/13/2016.

The photos in Figure C-56 show that on 1/26/2018, 38 months after the treatment application, there was significant and uneven fading of the fog seal. Although there is less contrast with the untreated pavement, this was still quite visible. This indicates that the seal is still covering the depressions between aggregates. The figure also shows that some of the cracks with pumping were starting to develop the typical fatigue cracking pattern. It is important to note that during the more than three years with the seal coat very limited loss of aggregate was noted.

Figure C-56 Condition of Kaweloka Street section 1, treated with Plasti-Pave, on 1/26/2018.

Finally, Figure C-58 shows that on 5/24/2019, 54 months after the treatment application, the sealer had continued fading though there was still enough contrast with the untreated section to be noticeable. At this point, it was difficult to see if the sealer was still helping to arrest raveling. The treated surface looked a little better than the untreated, but this assessment was quite subjective. Pumping of fines from some cracks had continued helping the development of a fatigue cracking pattern

Figure C-57 Condition of Kaweloka Street section 1, treated with Plasti-Pave, on 5/24/2019.

C.3.3 Kaweloka Street Section 2 - Liquid Road by SealMaster®/Hawaii – Bus Traffic

Figure C-58 shows the appearance of the treatment immediately after its application on 11/21/2014. Since the material in the first coat was spread with a spreader box and contained a relatively large amount of sand, this treatment typically had an uneven appearance immediately after its application. However, as shown later, once the material dried, the marks became less noticeable. The photo on the bottom left shows that sealed cracks were still identifiable, despite this treatment being thicker than the other seal coats used in this study. The photo on the bottom right shows that Liquid Road has a texture coarser than the other seal coats (this becomes clearer when compared with similar photos for the other treatments).

Figure C-59 shows the treatment visual appearance after drying on the same day (11/21/2014). Some of the photos clearly illustrate the higher sand content, as many partially coated sand particles are clearly visible. The two photos on the third row show the contrast between the existing pavement surface and the treated surface. This treatment does a good job at filling the pits created by loss of aggregates and provides more surface texture than the other seal coats used in Hawaii. The last two photos, which show the treatment near the gutter, illustrate the thickness of the material.

Figure C-60 shows the conditions on 3/27/2015, about four months after the treatment application. The top two photos show the general condition of the section. As illustrated by the photo on the left, the original spreading marks were now more inconspicuous. The photo on the right shows a considerable amount of sand still available on the surface. The two middle photos show that the treatment still provided a high contrast with the existing pavement while the two photos on the bottom show that some cracks had already started to develop. As discussed earlier, this is to be expected since the larger amount of sand is likely resulting in the binder being subjected to much higher strains within the seal coat.

The top two photos in Figure C-61 show that on 8/29/2015, nine months after its application, Liquid Road still provided the appearance of a new road. The top middle photos show the appearance of many new very thin cracks. On the other hand, the two photos on the bottom show existing cracks that continue propagating.

The conditions in Figure C-62 illustrate that on 12/4/2015, almost a year after its application, this treatment still provided a general new surface like appearance. However, additional thin new cracks continued appearing and some other cracks started to get wider. The two photos at the bottom illustrate that the seal coat often cracked on top of a sealed crack and in other cases the cracks diverged from a sealed crack. At this early stage, it was believed no water could infiltrate through these cracks. However, it is difficult to ascertain when that occurs.

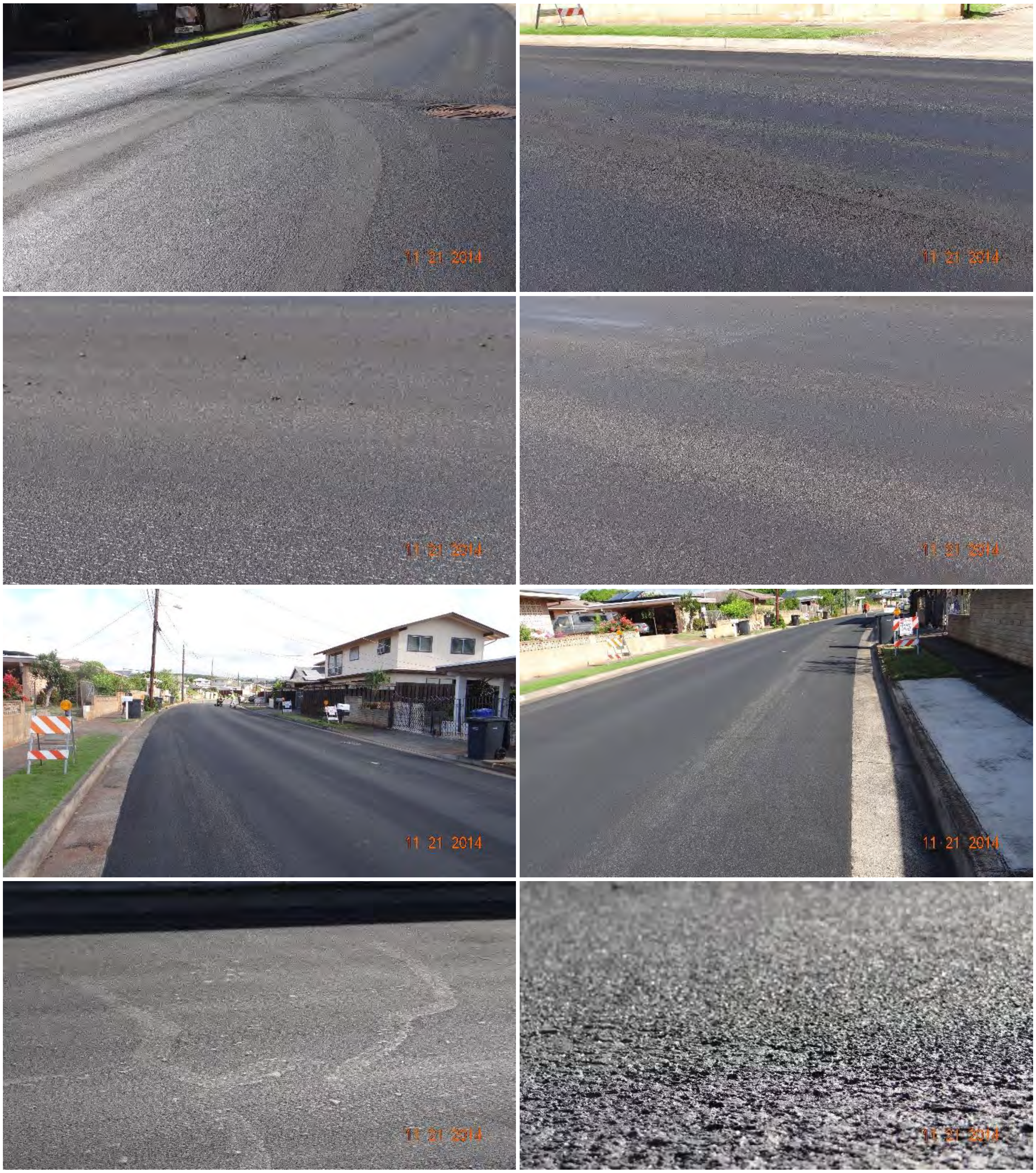

Figure C-58 Surface appearance on Kaweloka Street section 2, treated with Liquid Road, immediately after the second coat application on 11/21/2014.

Figure C-59 Surface appearance on Kaweloka Street section 2, treated with Liquid Road, after further drying on the date of the second coat application, 11/21/2014.

Figure C-60 Condition of Kaweloka Street section 2, treated with Liquid Road, on 3/27/2015.

Figure C-63 shows the Liqui Road condition on 3/3/2016, 15 months after its application. The two photos at the top still show a high contrast with the untreated section and an overall good appearance. The two photos on the second row show the condition of the treatment at the joint with the gutter. It is seen that if the joint is not sealed with a crack sealer, any excess seal coat material left on top of the joint will be broken off eventually, exposing the joint to moisture, as indicated by the vegetation growth. The photo on the left on the third row illustrate how the seal had cracked on top of sealed cracks and how those cracks continued propagating beyond the sealed crack portion. This is common to all seal coats in this study, which indicates that none of them would prevent the additional cracking that would eventually occur with or without seal coat. The photo on the right shows the appearance of new longitudinal load related cracks. Finally, the last two photos in Figure C-63 show some of the cracks getting wider and developing some spalling.

Figure C-61 Condition of Kaweloka Street section 2, treated with Liquid Road, on 8/29/2015.

Figure C-62 Condition of Kaweloka Street section 2, treated with Liquid Road, on 12/4/2015.

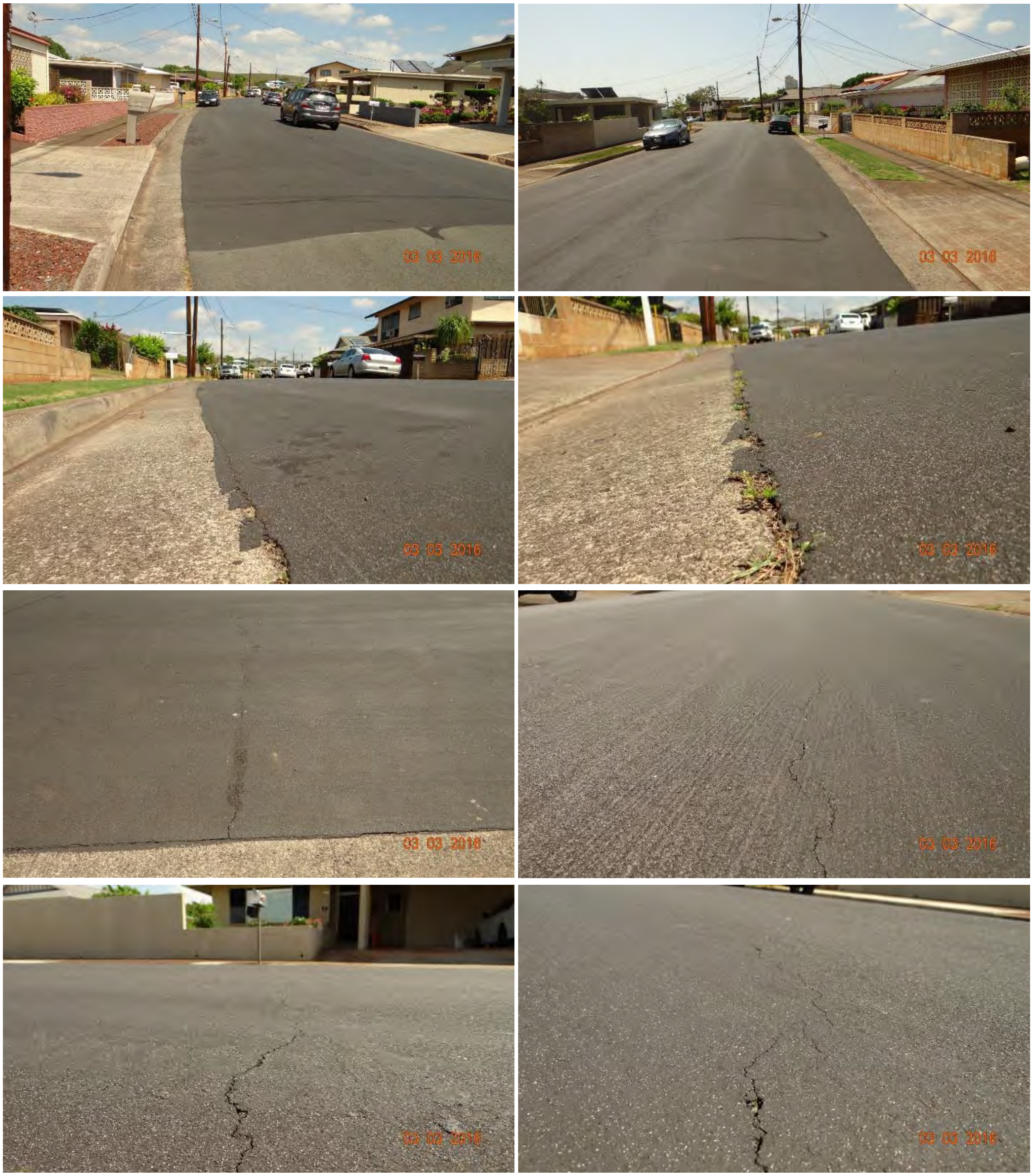

Figure C-63 Condition of Kaweloka Street section 2, treated with Liquid Road, on 3/3/2016.

Figure C-64 shows that not much had changed by 6/24/2016. The general appearance was still distinct from the existing sections and the treatment was still holding large amounts of sand, which provides some micro texture. However, some spots that were originally blotchy had started to show some loss of material, as illustrated in the middle left photo. The bottom photo shows the difference in texture with the adjacent untreated section. This clearly illustrates the major contribution of the seal coat, which is arresting any pitting and raveling of the surface and avoiding further oxidation of the binder, which leads to more raveling and eventually disintegration of the mix if left untreated. The last photo illustrates once again that any cracks developing in the existing pavement will simply go through the treatment.

Figure C-64 Condition of Kaweloka Street section 2, treated with Liquid Road, on 6/24/2016.

The same observations can be made for the conditions shown on Figure C-65 on 12/13/2016, slightly more than two years after treatment application.

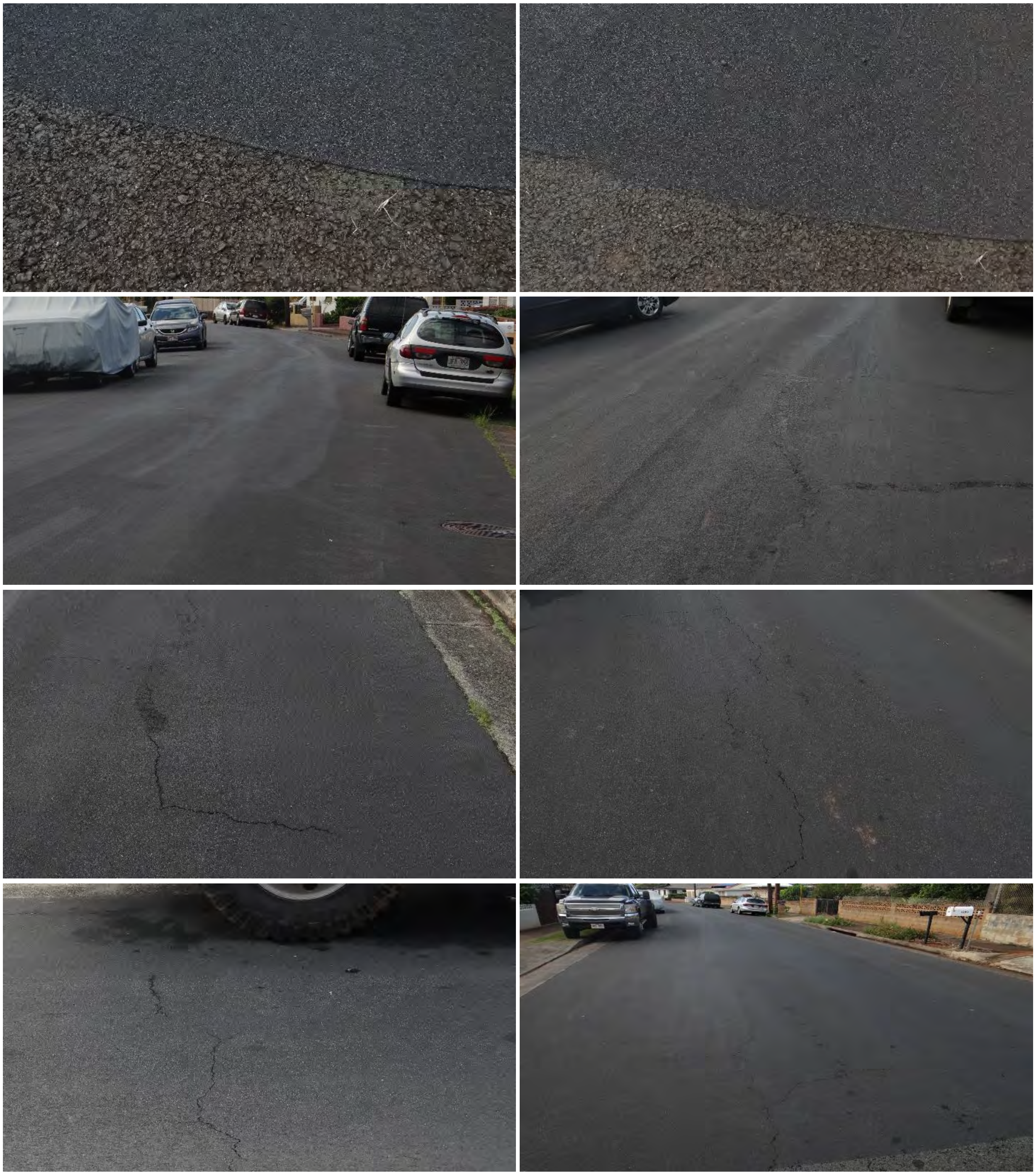

Figure C-65 Condition of Kaweloka Street section 2, treated with Liquid Road, on 12/13/2016.

Figure C-66 and Figure C-67 show the conditions on 1/26/2018, 38 months after the treatment application. The two photos at the top of Figure C-66 show an overall good appearance of the treated section. Although the surface was starting to show signs of oxidation, there was still a very high contrast with the existing untreated section, as shown in the second row. The differences in texture between the treated and untreated sections were basically the same as those illustrated in Figure C-64.

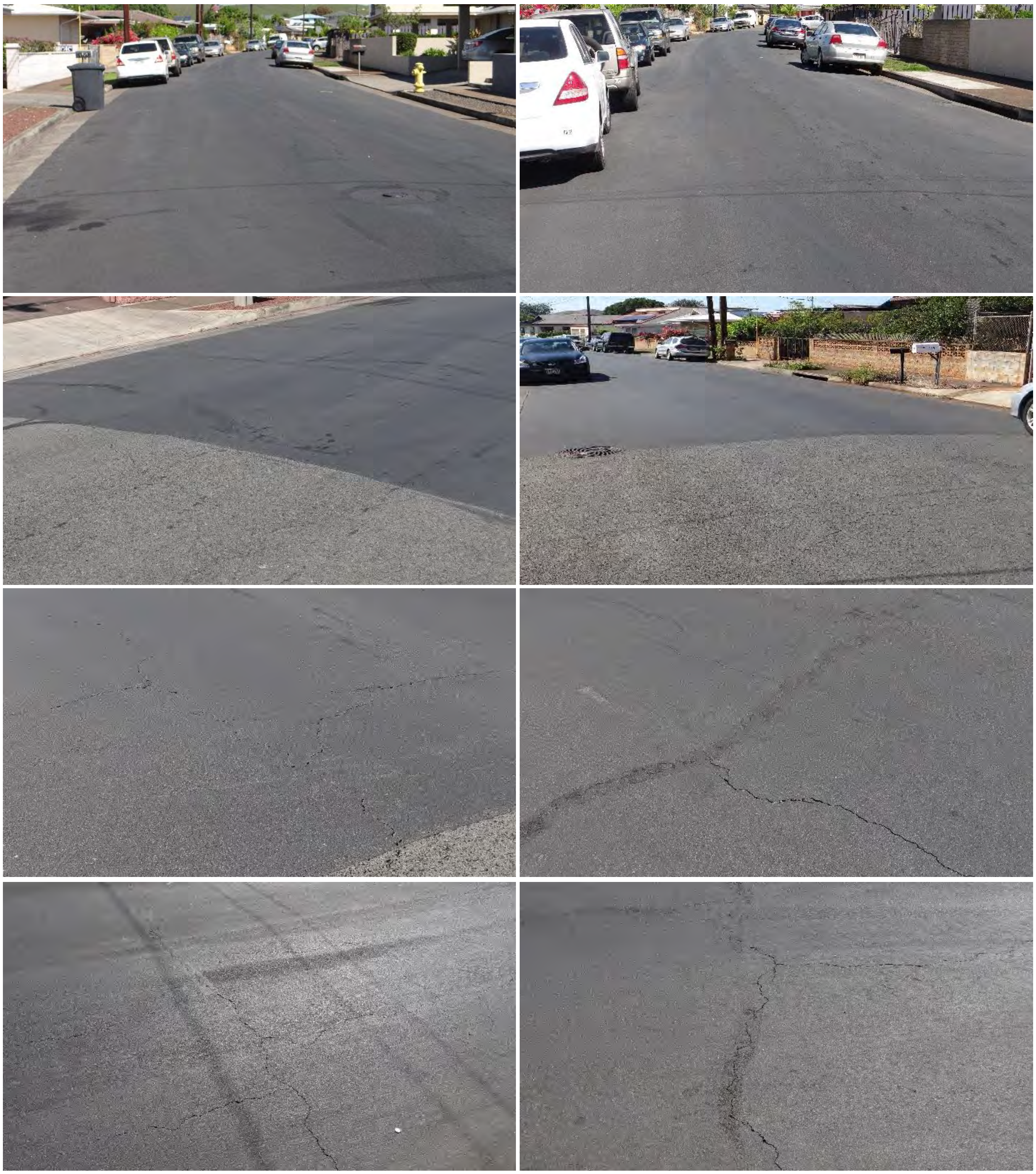

Figure C-66 Condition of Kaweloka Street section 2, treated with Liquid Road, on 1/26/2018.

The last four photos in Figure C-66 show the cracking that developed on the treatment. Notice that is not possible to judge visually whether the crack sealing was still preventing infiltration when the seal coat on top had cracked, particularly on cracks that were thin when the crack sealer was applied. As discussed earlier, in those conditions, the period over which the crack sealer can perform its function is limited. The cracking generally had a block pattern, indicating that most of the cracking was environmentally induced but there were certainly longitudinal cracks that were induced or enlarged by traffic loading. It is important to point out that traffic on these streets was not as channelized as that on highways with lane striping. In this case, drivers in both directions often load the same spots depending on vehicles parked and opposing traffic.

The top two photos in Figure C-67 show examples of the longitudinal cracks believed to be load related. The photos on the second row illustrate a defect that occurred in an originally blotchy area and cracks emanating from a manhole. The latter was a very common occurrence with any treatment around manholes.

The last four photos in Figure C-67 show how the width of many cracks and the spalling had increased to a level deserving renewed attention for crack sealing. This emphasizes the need to have a crack sealing program that is continuous or recurrent within short periods to ensure its effectiveness.

Finally, Figure C-68 shows the conditions of the treatment on 5/24/2019, 4.5 years after the treatment application. Although not measured, it is apparent that cracking had continued growing slowly in length and severity. Some of the cracking was now changing into a fatigue cracking pattern. There were also areas where the material was starting to show signs of wearing. Nevertheless, as seen in some of the photos in this figure, the pavement texture was still substantially better than the texture of the untreated section. Clearly, the material was still helping to arrest aggregate losses.

Overall, the above chronology shows that despite the increase in the cracking rate on this section relative to the control section, Liquid Road clearly extends the life of the surface. During the 54 months that were monitored, not only did the surface of the treatment had minor aging changes but it also prevented the continuous deterioration (pitting and raveling) observed on adjacent sections. Notice that the cracking would have eventually reached a similar level within a relatively short time had the section not being seal coated and that the cracks are typically wider on the untreated sections. Furthermore, the surface would have continued deteriorating on the untreated sections.

It is also important to point out that the sections with bus traffic monitored in this study appear to be too thin. This leads to higher environmental cracking (the cross section is too small to resist the frictional forces generated with the base) and in turn, these unsealed new environmental cracks lead to additional higher load related cracking as they are subjected to heavy loads, particularly if additional water infiltrates through these additional cracks. It is believed that with a more appropriate thickness, these issues would be minimized. It is important to note that the sections monitored had about 3 inches of Hot Mix Asphalt (HMA) whereas current guidelines require a minimum of 5 inches. This emphasizes that appropriate pavement design is an integral part of an effective pavement preservation program.

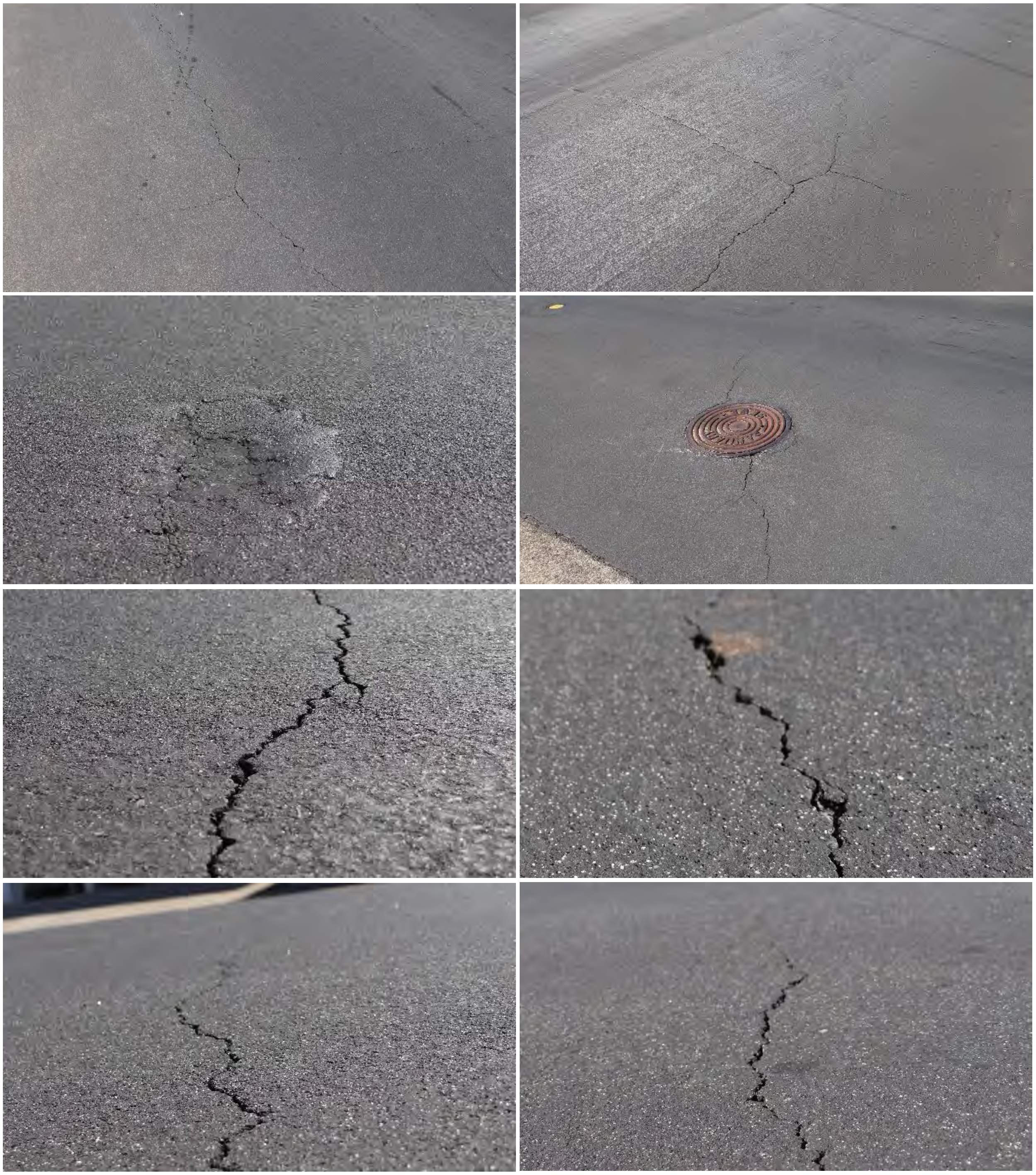

Figure C-67 Condition of Kaweloka Street section 2, treated with Liquid Road, on 1/26/2018.

Figure C-68 Condition of Kaweloka Street section 2, treated with Liquid Road, on 5/24/2019.

C.3.4 Kaweloka Street Section 3 - MasterSeal™ RTU by SealMaster®/Hawaii – Bus Traffic

Figure C-69 shows the appearance of the treatment on 3/27/2015, fourth months after its application. This treatment exhibited a uniform appearance. The two top photos show the high contrast and different textures of the treated and untreated surfaces (later photographs provide a better illustration of the differences in texture). The two photos on the bottom illustrate that this treatment does not hide existing defects on the pavement. This is also better illustrated in later photographs. Note that this is common to the other seal coats monitored in this study ("seal coats" as used in Hawaii, which does not include treatments such as Chip Seals), except for Liquid Road that to a certain extent has a better ability to hide defects because of its thicker application.

Figure C-70 shows the section condition on 8/29/2015, about 10 months after the treatment application. Again, the top two photos show the high contrast between the treated and untreated surfaces, with the treated surface having a much closer appearance to a new pavement. Unfortunately, as illustrated in the middle four photos, the Board of Water Supply apparently had to patch an area affected by a water main break. As shown in some of these photographs, significant cracking was developing around that area. Therefore, as explained earlier, the portion around this area believed to be affected by the water main break was excluded from the measurements in the section and compensated with measurement on a portion on one of its ends that had been treated with a single coat only. The two photos at the bottom illustrate sealed cracks that were still sealed and some new cracks (outside the area affected by the patching).

Figure C-69 Condition of Kaweloka Street section 3, treated with MasterSeal™ RTU, on 3/27/2015.

Figure C-70 Condition of Kaweloka Street section 3, treated with MasterSeal^{TM} RTU, on 8/29/2015.

The photo on the top left of Figure C-71 shows that substantial differences in texture and appearance between the treated and untreated surfaces was maintained as of 6/24/2016, 18 months after the treatment application. This is highlighted in the closeup photo on the top right of the figure. The photo on the left of the second row shows the development of a new load related longitudinal crack upstream of the patched area, whereas the photograph on the right illustrates that this type of treatment cannot hide existing pavement defects. Finally, the bottom photograph shows that a more permanent set of patches had been performed around the water main break area.

Figure C-71 Condition of Kaweloka Street section 3, treated with MasterSeal^{TM} RTU, on 6/24/2016.

Figure C-72 shows that similar conditions were observed on 12/13/2016, slightly more than two years after the treatment application. As illustrated by the four top photos, except for the patched area, the section still had a new appearance without the pitting and raveling of the untreated surfaces. Nevertheless, as shown in the four bottom photos, cracking was still progressing relatively quickly. However, at this stage, most of the cracks were very thin.

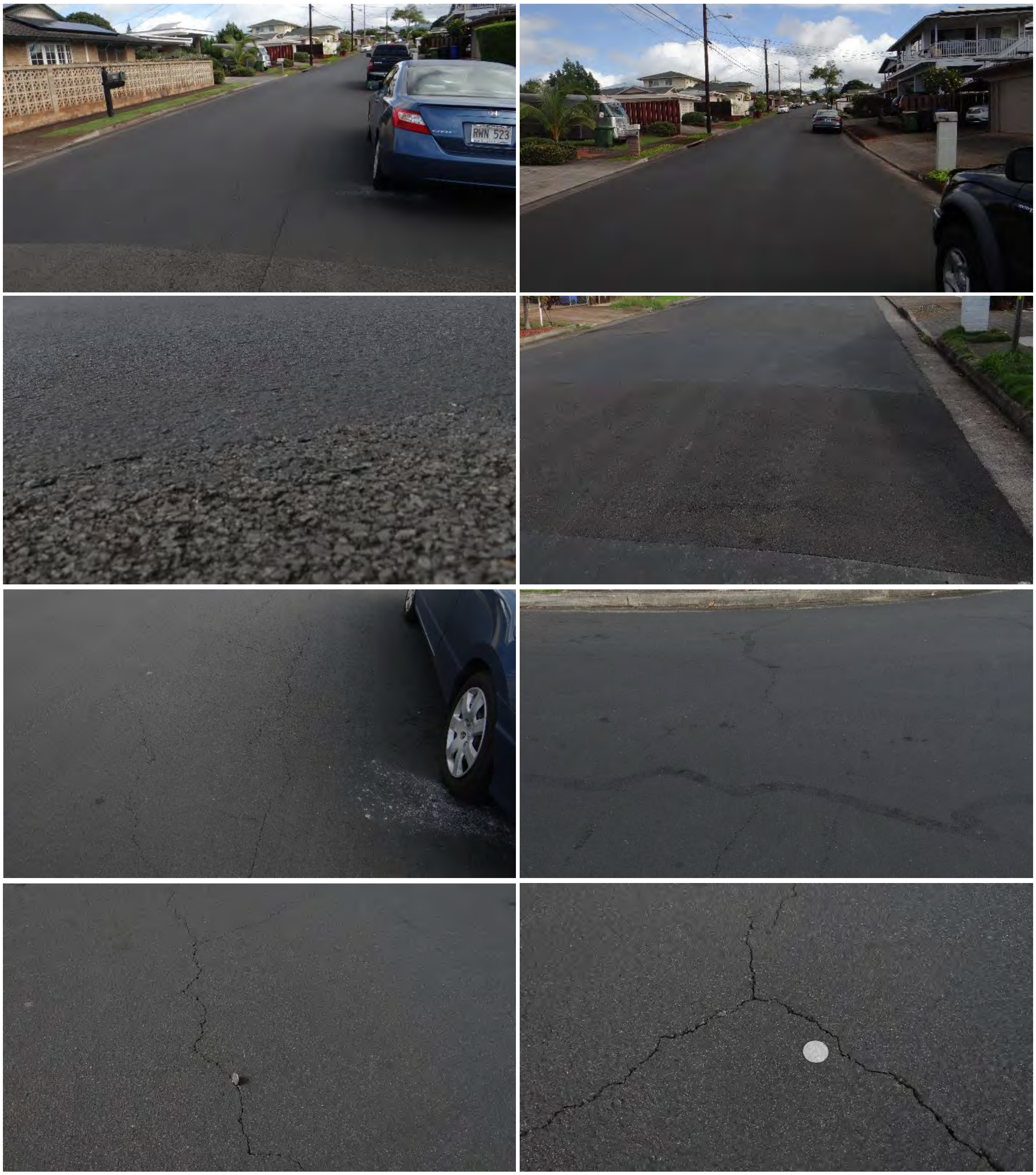

Figure C-72 Condition of Kaweloka Street section 3, treated with MasterSeal^{TM} RTU, on 12/13/2016.

Figure C-73 and Figure C-74 show the conditions on 1/26/2018, 38 months after the treatment application. The top left photo of Figure C-73 clearly shows that there was still a sharp contrast between the treated and untreated surfaces. This is not the case on the photo on the top right, where some fading of the treatment is observed. It is important to note that, at the request of neighbors, this was the portion that was extended from the original plan but was treated with a single coat. The closeups in the photos of the second row show more clearly how the treatment was being washed out in some places, most likely by large amounts of water running down the gutter and the adjacent pavement at high speed. This was an unplanned experiment, but it clearly highlights the benefit of the application of two coats. However, as shown on the left photo on the third row of Figure C-73, some fading of the seal coat was also noted upstream of the patched area. While the patched area itself showed no cracking (right photo on the third row), the last two photos show that the treated area around it show some incipient fatigue cracking. However, this may not be attributable solely to the patch, since as shown in Figure C-74, fatigue cracking was starting to develop throughout the treated section. Recall from Figure 4-14 that the cracking length on this section was large, but as seen in these photographs they were still generally thin. Nevertheless, some signs of pumping were noted, which again brings into question the appropriateness of the design HMA thickness.

Figure C-75 shows the conditions on 5/24/2019, 4.5 years after the treatment application. There was still contrast between the untreated and treated surfaces. There were further signs of wearing off the treatment in the areas with two coats, but the texture still showed much less loss of aggregate and/or mastic. As noted earlier, fatigue cracking had continued its development. Only one photo is shown but it was now much more widespread (again, on this survey, cracking was not quantified). The figure also shows an example of the consequences of some type of solvent leaked into the surface. In the small area shown, the treatment was all but gone (of course, the problem was not the seal coat but whatever was pour on top of it).

Figure C-73 Condition of Kaweloka Street section 3, treated with MasterSeal^{TM} RTU, on 1/26/2018.

Figure C-74 Condition of Kaweloka Street section 3, treated with MasterSeal^{TM} RTU, on 1/26/2018.

Figure C-75 Condition of Kaweloka Street section 3, treated with MasterSeal™ RTU, on 5/24/2019.

C.3.5 Kaweloka Street Section 4 - OptiPave Plus^{TM} RTU by SealMaster®/Hawaii – Bus Traffic

Figure C-76 shows the appearance of the treatment on 3/27/2015, fourth months after its application. The top photo shows a nice and uniform appearance of the treatment shortly after its application. As with other treatments, this makes the pavement look more like a new road. However, the photo on the bottom shows that new cracking was already happening. Recall that this section exhibited the largest increase of cracking over the study period. Figure C-76 also illustrates that the grade of the untreated pavement upstream of the section was even higher than the one on the section. Thus, if water running under the pavement was indeed an issue, this may have created the potential for water to be running under pressure on this section.

Figure C-77 shows that although the overall appearance of the treatment was maintained on 8/29/2015, 9 months after its application, several new cracks were occurring in several places. The cracking continued to get worse with time, as illustrated in Figure C-78, which shows the conditions on 3/3/2016, 15 months after the treatment application. Some of the photographs in this figure show the cracks getting wider, exhibiting some spalling, and developing a typical fatigue cracking pattern.

Note that the surface of the treatment itself was still in good condition even after 25 months from its application (12/13/2016). These is illustrated by the top four photos in Figure C-79, which shows the untreated pavement exhibiting pitting, raveling, and binder stripping while none of these problems were seen on the treated section. The right photo on the second row also shows significant loose aggregate on the surface of the untreated section, indicating that substantial raveling was occurring there while none of this was observed in the treated section. The last four photos in Figure C-79 are examples of the cracking observed on this date, which is basically similar to what was discussed before.

Figure C-76 Condition of Kaweloka Street section 4, treated with OptiPave Plus^{TM} RTU, on 3/27/2015.

Figure C-77 Condition of Kaweloka Street section 4, treated with OptiPave Plus^{TM} RTU, on 8/29/2015.

Figure C-80 and Figure C-81 show the conditions of the treatment on 1/26/2018, 38 months after its application. The photos in Figure C-80 were selected to illustrate the condition of the treatment itself. The two photos on the top show that the overall appearance of the section was better than that of the untreated pavement. However, as shown in the following four photos, some fading was starting to occur at the section ends and near the gutters. Another common problem near the gutters were the oil leaks as illustrated in the bottom left photo. Finally, the bottom right photo shows some aggregate being exposed because of the loss of part of the overband of a sealed crack.

The photos in Figure C-81 were selected to illustrate the cracking on the section at the end of the monitoring period. These photos show that some of the cracks were basically a continuation of the cracks occurring on the untreated section, but they also show many locations with fatigue cracking. In fact, this section showed the clearest manifestation of fatigue cracking in all the treated sections.

Figure C-82 shows that the deterioration had continued its course on 5/25/2019. The surface of the treatment shows more signs of fading, though it was still contributing to resist raveling. There were also more areas exhibiting fatigue cracking.

Figure C-78 Condition of Kaweloka Street section 4, treated with OptiPave Plus^{TM} RTU, on 3/3/2016.

Figure C-79 Condition of Kaweloka Street section 4, treated with OptiPave Plus^{TM} RTU, on 12/13/2016.

Figure C-80 Condition of seal on Kaweloka Street section 4, treated with OptiPave Plus^{TM} RTU, on 1/26/2018.

Figure C-81 Cracking on Kaweloka Street section 4, treated with OptiPave Plus^{TM} RTU, on 1/26/2018.

Figure C-82 Cracking on Kaweloka Street section 4, treated with OptiPave Plus™ RTU, on 5/24/2019.

C.3.6 Kaweloka Street Sections 6, 7, and 8 - control sections without bus traffic

Figure C-83, Figure C-84, Figure C-85, and Figure C-86 are presented to illustrate the conditions of these control sections at four points in time. Specifically, the photos correspond to site visits on 1/26/2015, 6/24/2016, 12/13/2016, and 5/24/2019, respectively. In general, the cracking in the three figures indicate that most of it was environmentally related. The bottom photos in Figure C-83 illustrate a spot with oil leaks (left) and an area with severe raveling/disintegration. This is particularly severe, and it may be a consequence of recurrent oil leaks (with the same vehicle parked on the same spot every day).

On the other hand, the bottom four photos in Figure C-85 show some significant raveling related mostly to environmental effects such as binder oxidation and binder stripping by moisture. These are indicative of what can be expected when sections are left untreated.

Figure C-86 also shows several photos with raveling continuing its slow progress in these sections. Some spots with moisture damage can also be seen.

Figure C-83 Condition of control sections 6, 7, 8 for straight sections without bus traffic on Kaweloka Street, on 1/26/2015.

Figure C-84 Condition of control sections 6, 7, 8 for straight sections without bus traffic on Kaweloka Street, on 6/24/2016.

Figure C-85 Condition of control sections 6, 7, 8 for straight sections without bus traffic on Kaweloka Street, on 12/13/2016.

Figure C-86 Condition of control sections 6, 7, 8 for straight sections without bus traffic on Kaweloka Street, on 5/24/2019.

C.3.7 Kaweloka Street Sections 5 – CarbonSeal-HT by Carbonyte Systems Inc. – No Bus Traffic

Figure C-87 shows the conditions on the day of the application of the first coat (11/19/2014) to illustrate that the cracks on about half of the section were not sealed for some unknown reason. The cracks on the other half were mostly routed and sealed (mid right photo). The bottom left photo also illustrates a small area with some severe raveling whose progression was stopped with the application of the treatment.

Figure C-88 shows the conditions of the treatment on 3/27/2015, almost four months after its application. The treatment had a very uniform appearance. Most of the cracks observed in these photos existed before the treatment application, but the presence of those that were not sealed was essentially highlighted by the application of the seal coat. Although it is difficult to appreciate in these photos, the color of this treatment is dark grey as opposed to the black color of all the other treatments evaluated in this study.

Figure C-87 Condition of section 5 on Kaweloka Street, treated with CarbonSeal-HF, on 11/19/2014 and 11/26/2014.

Figure C-88 Condition of section 5 on Kaweloka Street, treated with CarbonSeal-HF, on 3/27/2015.

As discussed in relation to Figure 4-20, the rate of cracking increase in this section was relatively small because it was not on the bus route. Therefore, in the following discussion, less emphasis is given to the propagation of cracks.

Figure C-89 shows the condition of the seal coat on 3/3/2016. Even though this was only 16 months after the treatment application, there were already some signs that seal coat was fading away. This is illustrated in the top photo in Figure C-89, where an uneven distribution of the color can be seen. It can also be seen that the surface of the top of many aggregates were exposed. The other two photos in the figure illustrate that the crack sealing was performing as expected.

Figure C-89 Condition of section 5 on Kaweloka Street, treated with CarbonSeal-HF, on 3/3/2016.

The top four photos in Figure C-90 show that merely three and half months later, on 6/24/2016, the fading of the seal coat was much more evident and widespread. Nevertheless, as seen by the photo on the left of the third row, the surface with the seal coat did not show the raveling seen on the untreated surface. The other photos illustrate the propagation of some cracks that were sealed as well as the good performance of the crack sealer up to this point.

Figure C-91, Figure C-92, and Figure C-93 show the treatment condition on 1/26/2018, 37 months after its application. The top photos in Figure C-91 show that in several areas the seal coat was practically gone. Still, as illustrated in the two middle photos, during the time of the study, the seal coat was successful at arresting the raveling seen in the untreated surfaces. The last two photos emphasize how much the seal coat had faded. The photo on the left shows a view from further away where the treatment is barely noticeable whereas the photo on the right provides a view from section 4. The difference between the two sections (sections 4 and 5) is substantial.

Figure C-90 Condition of section 5 on Kaweloka Street, treated with CarbonSeal-HF, on 6/24/2016.

Figure C-91 Condition of section 5 on Kaweloka Street, treated with CarbonSeal-HF, on 1/26/2018.

The photos in Figure C-92 show the performance of the crack sealing in the section. In general, the crack sealing performed as expected with some cracks being almost perfectly sealed after three years and with other showing some possible separation with the crack walls. Since most of these cracks were routed, this good performance was expected.

Figure C-93 shows some of the unsealed cracks. These were mostly environmentally induced cracks but even without bus loading some of these showed signs of pumping.

Finally, Figure C-94 shows the conditions on 5/24/2019, about 4.5 years after its application. Further fading of the seal coat was noted with the surface showing some early signs of loss of material. As shown in one of the photos, the crack sealer was soft enough that could still be indented with the finger but at that particular location it appears was not in contact with the crack wall anymore. Once again, in general, the sealer on cracks that were routed or were thick when sealed were still performing well, but those that were thin when sealed were exposed as shown by the last photo in the figure.

Figure C-92 Condition of section 5 on Kaweloka Street, treated with CarbonSeal-HF, on 1/26/2018.

Figure C-93 Condition of section 5 on Kaweloka Street, treated with CarbonSeal-HF, on 1/26/2018.

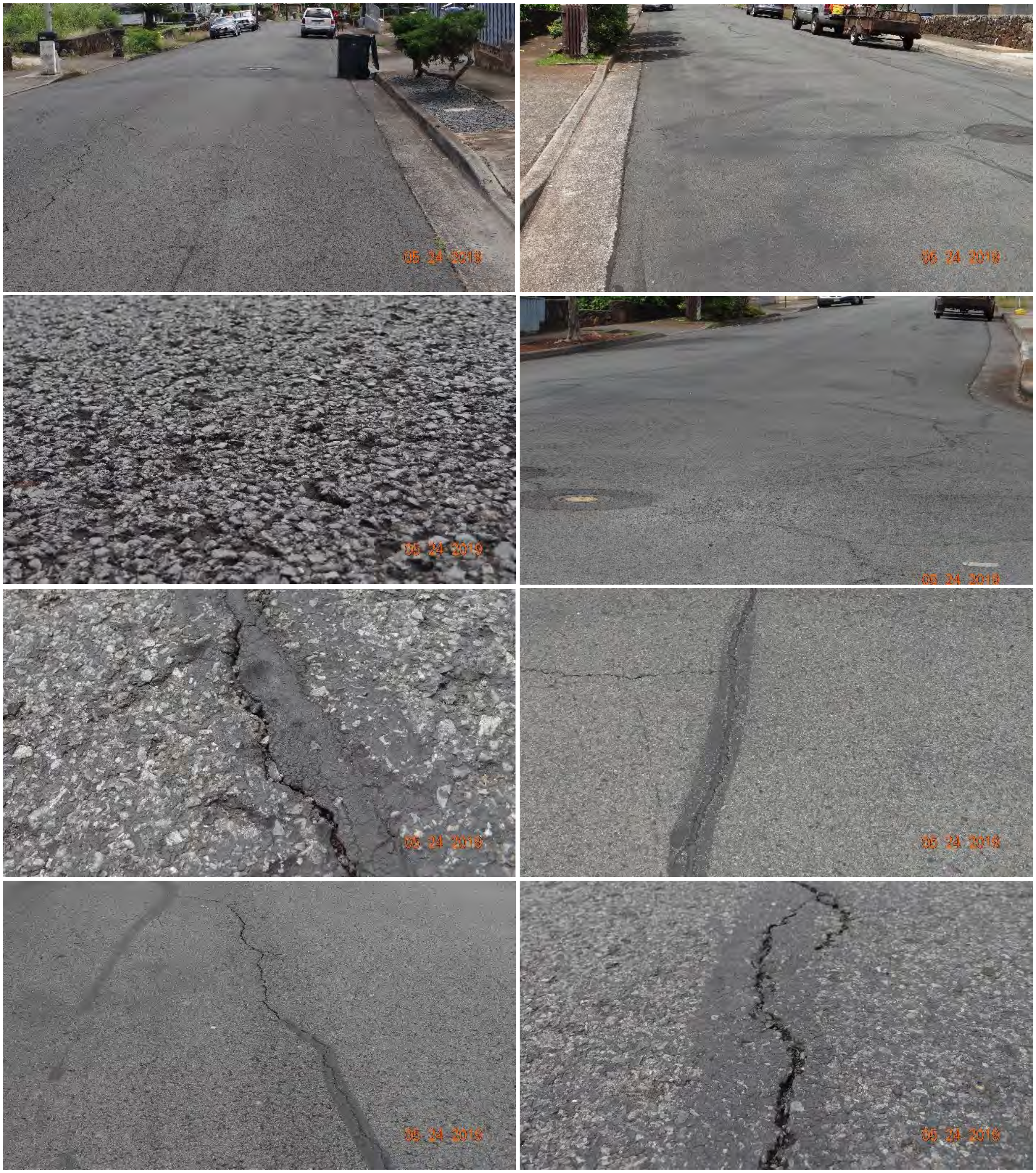

Figure C-94 Condition of section 5 on Kaweloka Street, treated with CarbonSeal-HF, on 5/24/2019.

C.4 SEAL COATS IN CUL-DE-SAC SECTIONS

C.4.1 Kaumoli Place - Control section for cul-de-sacs

Figure C-95 shows the conditions of the control section for cul-de-sacs on Kaumoli street on 3/27/2015. The first six photos show a the typical pattern in cul-de-sacs, with a large longitudidal crack near the centerline and a block cracking pattern with one side of the block accompaning the curvature of the cul-de-sac. The last two photos illustrate that the severity of many cracks could be considered moderate and that the section was already exhibiting some raveling.

Figure C-96 and Figure C-97 illustrate the condition seen on 3/3/2016 and 6/24/2016, respectively. Visually, not much change was noted except that the cracks appeared to be getting wider and the surface a bit more ravelled.

Figure C-98 shows that by 12/13/2016, the section had already been crack sealed. Subsequently, it was also covered with a seal coat. Note that the length of cracking, as seen by the length of the crack sealing overbands on the surface, were measured on that date and included in the trend in Figure 4-21. As noted earlier, the length with sealer usually overestimates the actual length of cracking because of the extension of the overbands at the ends of each crack, which implies that the cracking trend of 0.576 ft/day/10^4ft^2 in Figure 4-21 may be slightly off. Unfortunately, that last observation is very influential and the cracking trend without it drops to 0.260 ft/day/10^4ft^2. Thus, the actual cracking rate should be expected to fall somewhere between these values. As discussed before, this is consistent with the Palamoi Street section used as a control section for crack sealing on cul-de-sacs, for which the rate of 0.416 ft/day/10^4ft^2 was estimated.

Figure C-95 Condition of the control section in cul-de-sacs on Kaumoli Street on 3/27/2015.

Figure C-96 Condition of the control section on Kaumoli Street on 3/3/2016.

Figure C-97 Condition of the control section on Kaumoli Street on 6/27/2016.

Figure C-98 Condition of the control section on Kaumoli Street on 12/13/2016.

C.4.2 Hoolawa Place - Plasti-Pave by SealMaster®/Hawaii.

Figure C-99 through Figure C-102 show the condition of the section over time. Since this section showed the least change in cracking length over time, not many observations can be made in this regard.

Figure C-99 show the condition on 3/27/2015, four months after the treatment application. This section was extremely dirty because of some accumulation of clay material near its entrance due to some apparent drainage problem. The photos on the second row illustrate the overall seal condition and those on the third row show some of the locations where crack sealing had been done prior to the fog seal application. The photos in the last row provide further illustration of the dirty conditions of this section.

Figure C-100 shows the conditions on 8/29/2015. The photos in this figure illustrate that the dirty conditions at times got much worse, depending on the precipitation in the days prior to each survey. Such conditions often made it very difficult to assess the condition of the fog seal itself.

Figure C-101 shows that the surface was cleaner on 6/27/2016, but still quite dirty. Some of the photos show that on several existing thin cracks, the sealer was either gone or not effectively sealing the crack. As discussed before, this was a common observation about the performance of the crack sealing on thin cracks for all sections.

Figure C-102 shows the overall condition of the section on 2/7/2018, 38 months after the treatment application. Despite the dirty conditions, the fog seal still appeared to be performing well.

Figure C-103 show the conditions on 5/24/2019. The sealer was still performing relatively well in most of the cul-de-sac, but it had started to wear off near the gutters, where some raveling was noted.

Figure C-99 Condition of the section on Hoolawa Place, treated with Plasti-Pave, on 3/27/2015.

Figure C-100 Condition of the section on Hoolawa Place, treated with Plasti-Pave, on 8/29/2015.

Figure C-101 Condition of the section on Hoolawa Place, treated with Plasti-Pave, on 6/27/2016.

Figure C-102 Condition of the section on Hoolawa Place, treated with Plasti-Pave, on 2/7/2018.

Figure C-103 Condition of the section on Hoolawa Place, treated with Plasti-Pave, on 5/24/2019.

C.4.3 Kanihi Street - Liquid Road by SealMaster®/Hawaii

Figure C-104 through Figure C-109 show the condition of this section over time. Figure C-104 illustrates the treatment appearance on 11/21/2014, immediately after its application. Similarly to the observation made for the straight section treated with Liquid Road, this treatment can show some uneven appearance shortly after its application. Although the uneven appearance does not completely disapear, it gets substantially less conspicous as the emulsion sets.

The photos in Figure C-105 illustrate the condition of the section on 3/27/2015, after four months of service. As discussed before, this treatment is thicker and provides some more texture than the other seal coats evaluated in the study. Nevertheless, the sealed cracks were still visible. In situations where the crack sealer had been tracked, the cracks appeared a bit unseemly. This was a common problem in sections in residential areas, where traffic could not always be kept out until the sealer cured, despite signage and even policy presence. These photos also show some new hairline cracks and some cracking of the sealer on top of sealed cracks.

The top left photo in Figure C-106 shows that as of 8/29/15, 9 months after the treatment application, there was still a very marked contrast between the treated and untreated surfaces. The other photos in the figure also illustrate that there was still a large amount of sand on the surface of the treatment and that most of the hairline crack had grown in width and they were therefore much more noticeable. However, most of those cracks would be classified as low severity.

Figure C-107 shows that the conditions were similar on 3/3/2016, about 15 months after treatment application, except perhaps that now some cracks were reaching the limit between low and moderate severity. The last two photos in this figure also illustrate the common problem observed in other sections with oil spots created by leaking from parked vehicles.

Figure C-108 illustrates the conditions on 12/13/2016, about 25 months after the treatment application. Clearly, these photos were taken after a rain event, but they are helpful in highlighting the good condition of the surface of the treatment. Of course, the additional cracking developing in the underlying pavement had continued reflecting on the surface. The photo at the bottom of the figure shows a crack that had originally been sealed but that had grown on both ends. It is interesting to see the apparent different moisture levels around most of the sealed crack and its new extensions. The extensions appeared to have more moisture, which may be an indication that even if the crack sealer is not sealing the pavement perfectly it may still be preventing some of the water to infiltrate the crack.

Figure C-109 shows the conditions on 1/26/2018, at the end of the observation period and 38 months after the treatment application. The top photo in the figure shows the overall appearance of the section, which was still good. Note that the photo shows practically no contrast with the "previously untreated pavement" because now that section had been treated as part of existing pavement preservation efforts of the City and County of Honolulu. The fact that it was not easy to detect the difference between the original treatment and the new one attests to the good performance of Liquid Road in this section.

Figure C-110 shows the conditions on 5/24/2019, 16 months after the end of the observation period and 54 months (4.5 years) after the treatment application. The overall appearance of the section was still good, except that the length of cracking appeared to have increased (note that this is just an impression since no measurements were performed for this last survey). The treatment surface still exhibited a texture like the one observed after its application and appears to have significant residual life. Consequently, with a routine crack sealing program that seals these cracks, the surface could be maintained sealed for a while longer.

Figure C-104 Condition of the section on Kanihi Street, treated with Liquid Road, on 11/21/2014.

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Figure C-105 Condition of the section on Kanihi Street, treated with Liquid Road, on 3/27/2015.

Figure C-106 Condition of the section on Kanihi Street, treated with Liquid Road, on 8/29/2015.

Figure C-107 Condition of the section on Kanihi Street, treated with Liquid Road, on 3/3/2016.

Figure C-108 Condition of the section on Kanihi Street, treated with Liquid Road, on 12/13/2016.

Figure C-109 Condition of the section on Kanihi Street, treated with Liquid Road, on 1/26/2018.

Figure C-110 Condition of the section on Kanihi Street, treated with Liquid Road, on 5/24/2019.

C.4.4 Kalauipo Place - MasterSeal^{TM} RTU by SealMaster®/Hawaii

Figure C-111 through Figure C-116 show the condition of this section over time. Figure C-111 illustrates the very uniformly black appearance of this treatment immediately after its application on 11/21/2014. The figure also shows the high contrast with the untreated section. It can also be seen that the crack sealing underneath was still visible though not very conspicous.

Practically no change was observed on 3/30/2015, four month after application of the treatment, with the exception of the appearance of a few harline cracks. The condition is shown in Figure C-112.

Again, as illustrated in Figure C-113, no noticeable changes were observed on 8/20/2015, nine months after application of the treatment.

Figure C-114 shows the conditions on 6/27/2016, 19 months after the treatment application. The two photos on the top show the contrast with the untreated pavement. Note also that the sealer was holding the aggregates in place and avoiding the raveling observed in the untrated pavement. The other photos in the figure show some of the additional cracking and the prior defects that are not hidden well by this type of treatment.

As of 12/14/2016, about 25 months after the application of MasterSeal RTU, the surface of the treatment was still is very good condition. This is illustrated in Figure C-115, which also shows that the length of additional cracking continue growing and that some crack were getting wider.

Figure C-116 shows the condition on 2/7/2018, about 38 months after the treatment application. These photos show that cracking continued getting more extensive and with slightly larger crack widths. Other than that, the seal coat was still protecting the pavement surface.

Finally, Figure C-117 shows the conditions on 5/24/2019. Although the overall condition of the section still looked good, the treatment had started to wear off in some areas near the gutter and in some turning spots. In the latter, there were some loose aggregates dislodge from the exposed surface.

Figure C-111 Condition of the section on Kalauipo Place, treated with MasterSeal^{TM} Ready to Use, on 11/21/2014.

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Figure C-112 Condition of the section on Kalauipo Place, treated with MasterSeal^{TM} Ready to Use, on 3/30/2015.

Figure C-113 Condition of the section on Kalauipo Place, treated with MasterSeal^{TM} Ready to Use, on 8/20/2015.

Figure C-114 Condition of the section on Kalauipo Place, treated with MasterSeal^{TM} Ready to Use, on 6/27/2016.

Figure C-115 Condition of the section on Kalauipo Place, treated with MasterSeal^{TM} Ready to Use, on 12/14/2016.

Figure C-116 Condition of the section on Kalauipo Place, treated with MasterSeal^{TM} Ready to Use, on 2/7/2018.

Figure C-117 Condition of the section on Kalauipo Place, treated with MasterSeal^{TM} Ready to Use, on 5/24/2019.

C.4.5 Hoolana Place - OptiPave Plus™ RTU by SealMaster®/Hawaii

Figure C-118 through Figure C-123 show the condition of this section over time. The top left photo in Figure C-118 shows the whole section and its contrast with the untreated pavement surface on 3/30/2015, after four month of service. The other photos show situations where the crack sealer had been tracked, creating an unpleasant display.

As shown in Figure C-119, most of the changes on 8/29/2015, nine months after the treatment application, were new hairline cracks. The last two photos shown in the figure illustrate how the overband material was wearing off in some cracks.

Figure C-120 shows that on 3/3/2016 the cracking length continued its steady growth. In addition, as shown in the photos in the second row, some new cracks were getting wider and the crack sealer had been removed from some of the sealed cracks.

Figure C-120 also shows that there was a source of dirt in this section that made the pavement surface dirty and less attractive. This is seen more clearly on Figure C-121 showing the conditions on 6/27/2016, after 19 months in service. Some portions of the pavement looked reddish from so much dirt on its surface. Note that the treatment was still showing a high contrast with the untreated surface, which was showing signs of raveling (see the top photos). The photos in the third row show how the propagation of new cracks continued whereas the photos in the last row illustrate further loss of overband material as well as sealer material within sealed cracks.

Figure C-122 shows the conditions on 12/14/2016. Again, the photos on the top show how vehicles using one the driveways were spreading dirt over the pavement surface. The top two rows of photos also show how cracking had propagated with the appearance of new cracks. The last four photos show the sharp contrast in texture between the treated and untreated surfaces. The last two photos in particular show that while the untreated surface displayed significant raveling, with many loose particles, particles that can be dislodge with little effort, and aged binder in the valleys between particles; the treated surface had the valleys between particles still coated with the unaged seal coat material while only the top ridges of the aggregates were exposed. This emphasizes a major benefit of the regular application of this type of treatment.

Figure C-123 shows that by 2/7/2018, the surfaced exhibited a well-developed block cracking pattern with cracks of moderate severity. The contrast between the treated and untreated surfaces was still quite visible, even though the photographs were taken after a rain.

Figure C-124 shows the conditions on 5/24/2019. At this point, it was observed that the treatment was losing its capability to resist raveling, which was now seen on some spots within the section.

Figure C-118 Condition of the section on Hoolana Place, treated with OptiPave Plus™ Ready to Use by SealMasters®/Hawaii, on 3/30/2015.

Figure C-119 Condition of the section on Hoolana Place, treated with OptiPave Plus™ Ready to Use by SealMasters®/Hawaii, on 8/29/2015.

Figure C-120 Condition of the section on Hoolana Place, treated with OptiPave Plus^{TM} Ready to Use by SealMasters®/Hawaii, on 3/3/2016.

Figure C-121 Condition of the section on Hoolana Place, treated with OptiPave Plus^{TM} Ready to Use by SealMasters®/Hawaii, on 6/27/2016.

Figure C-122 Condition of the section on Hoolana Place, treated with OptiPave Plus™ Ready to Use by SealMasters®/Hawaii, on 12/14/2016.

Figure C-123 Condition of the section on Hoolana Place, treated with OptiPave Plus™ Ready to Use by SealMasters®/Hawaii, on 2/7/2018.

Figure C-124 Condition of the section on Hoolana Place, treated with OptiPave Plus™ Ready to Use by SealMasters®/Hawaii, on 5/24/2019.

C.4.6 Hooheno Street - Resurfacer by Brewer Cote – Oahu Seal Coating & Paving

Figure C-125 shows the general condition of the section before treatment. In addition to showing a well-developed moderate severity block cracking pattern, it shows that the surface was already at a point where some rejuvenation was needed. As shown in the bottom right photograph, a small area was already raveling.

Figure C-126 shows the condition on 3/30/2015, two months after treatment (this section was completed on 1/28/2015). As for other treatments dicussed in this report, there was a high contrast (visual and condition) between the treated and untreated surfaces. As it occurred for other sections, tracking of the crack sealing was often an issue, providing an unsightly visual appearance.

The top two photos in Figure C-127 illustrate the contrast between the untreated and treated surfaces, as of 8/29/15 with just seven months in service, was not only visual but also in terms of the condition. The photograph in the top left shows that raveling was occuring on the untreated surface. The other photos in the figure show the development of new heailine cracks as continuation of sealed cracks and the condition of some of the crack sealing.

As illustrated in Figure C-128, not much change could be appreciated visually on 3/3/2016, a year and a month after the treatment application, except that some of the cracks were getting wider. Of course, as indicated by the trend in Figure 4-26, the length of cracking was also increasing.

Figure C-125 Condition of the section on Hooheno Street, before treatment with Resurfacer by Brewer Cote (work performed by Oahu Seal Coating and Paving), on 1/3/2015.

Figure C-126 Condition of the section on Hooheno Street, treated with Resurfacer by Brewer Cote (work performed by Oahu Seal Coating and Paving), on 3/30/2015.

Figure C-129 shows the conditions on 12/14/2016, after about 22 months in service. As seen in the top two photos, the general condition still looked good though there were some signs of wearing off on one of the sides. The four middle photos show that many cracks were becoming moderate. In addition to illustrating the significant different texture between the treated and untreated surfaces, the last two photographs also show some incipient wearing off the treatment near the end of the section.

Figure C-130 show the conditions on 2/7/2018, just about three years of the treatment application. The photos in this figure show that the original cracking pattern had completely reappeared and expanded by additional cracks. Although not shown in these photos, some additional wearing off of the seal coat was noted.

Finally, Figure C-131 shows that the treatment was clearly wearing off. This can be seen when looking outward from the cul-de-sac since the adjacent section had now been treated. Raveling was now clearly seen in parts of the section.

Figure C-127 Condition of the section on Hooheno Street, treated with Resurfacer by Brewer Cote (work performed by Oahu Seal Coating and Paving), on 8/29/2015.

Figure C-128 Condition of the section on Hooheno Street, treated with Resurfacer by Brewer Cote (work performed by Oahu Seal Coating and Paving), on 3/3/2016.

Figure C-129 Condition of the section on Hooheno Street, treated with Resurfacer by Brewer Cote (work performed by Oahu Seal Coating and Paving), on 12/14/2016.

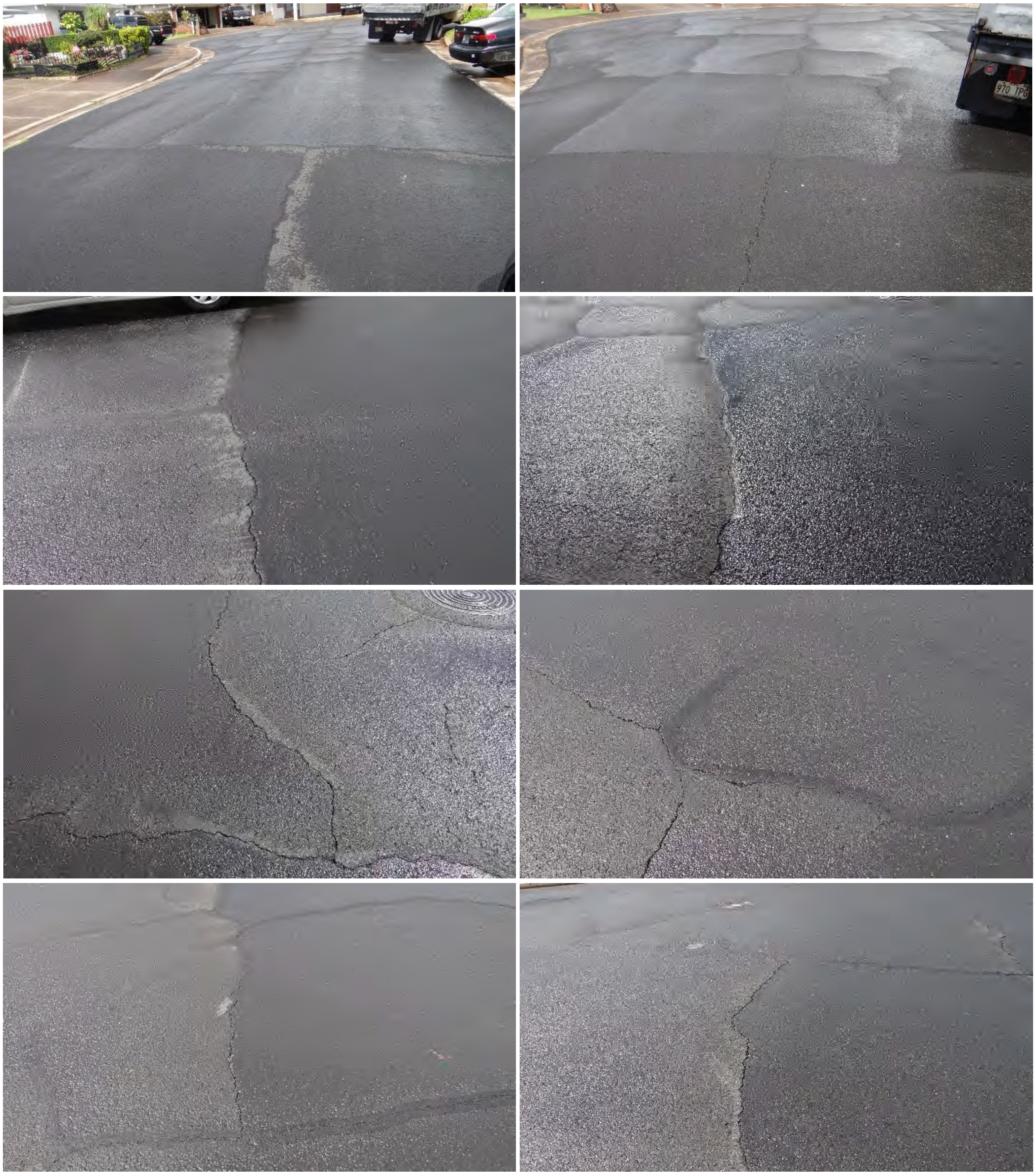

Figure C-130 Condition of the section on Hooheno Street, treated with Resurfacer by Brewer Cote (work performed by Oahu Seal Coating and Paving), on 2/7/2018.

Figure C-131 Condition of the section on Hooheno Street, treated with Resurfacer by Brewer Cote (work performed by Oahu Seal Coating and Paving), on 5/24/2019.

C.4.7 Hooheno Place - CarbonSeal-HF by Carbonyte Systems Inc - GPRS

Figure C-132 shows the condition of the surface before treatment on the date the cracks were sealed on 11/19/2014. The surface had some sign of raveling as seen by some loose aggregates. In addition, the clear stripping of binder between aggregates makes them more easily to dislodge.

Figure C-132 Surface condition on Hooheno Place, before treatment with CarbonSeal-HF by Carbonyte Systems Inc., on 11/19/2014.

Figure C-133 shows the condition immediately after the second coat application on 11/21/2014. As usual, despite some of the crack sealing being visible, the visual appearance of the treated section is much more appealing.

Figure C-133 Condition of the section on Hooheno Place, before treatment with CarbonSeal-HF by Carbonyte Systems Inc., on 11/21/2014.

Figure C-134 shows the condition on 3/30/2015, with four months in service. The bottom photograph in this figure provides a good example of the different textures of the treated and untreated surfaces. Again, several dislodged aggregates can be observed on the untreated surface.

As illustrated in Figure C-135, consistent with the relatively low rate in Figure 4-27, there were a few additional low severity cracks on 6/27/2016, about 19 months after the treatment application. The last two photos illustrate one more time that in general, these seal coats cannot hide or correct severe surface defects.

Figure C-136 shows the condition on 12/14/2016, almost 25 months after the treatment application. The conditions were similar to the ones described earlier. However, some wearing off or fading of the treatment was noticed in turning areas. These fading continued progressing until the end of the study, although it was not as dramatic as the fading that occurred in the straight section treated with the same product. The difference may be related to the fact that the straight section was on a steep grade with water runoff running at high speed.

Figure C-134 Condition of the section on Hooheno Place, before treatment with CarbonSeal-HF by Carbonyte Systems Inc., on 3/30/2015.

Figure C-135 Condition of the section on Hooheno Place, before treatment with CarbonSeal-HF by Carbonyte Systems Inc., on 6/27/2016.

Figure C-136 Condition of the section on Hooheno Place, before treatment with CarbonSeal-HF by Carbonyte Systems Inc., on 12/14/2016.

Figure C-137 illustrates the performance of the section immediately after a rain event on 2/7/2018. The top four photos show that unsealed cracks, or cracks where the sealant was not performing well, allow the ingress of water. The photos in the third row provide a more direct comparison between two sealed cracks, the one on the left where the sealer had lost contact with the crack wall (an unrouted thin crack) that allows the infiltration of water versus the one on the right, which is a routed sealed crack with the sealer performing well. Each of the last two photos provide similar examples, but in these cases, the sealer was performing well in the part of the crack with water on the surface and not well in other parts of the crack.

Figure C-138 shows that on 5/24/2019, the seal coat had worn off substantially, to the point that it was not easily distinguishable anymore. This was also revealed by the noticeable amount of raveling seen on the surface. On the other hand, the crack sealer in this section was performing well. As seen in one of the photos, it was still soft enough that it could be indented.

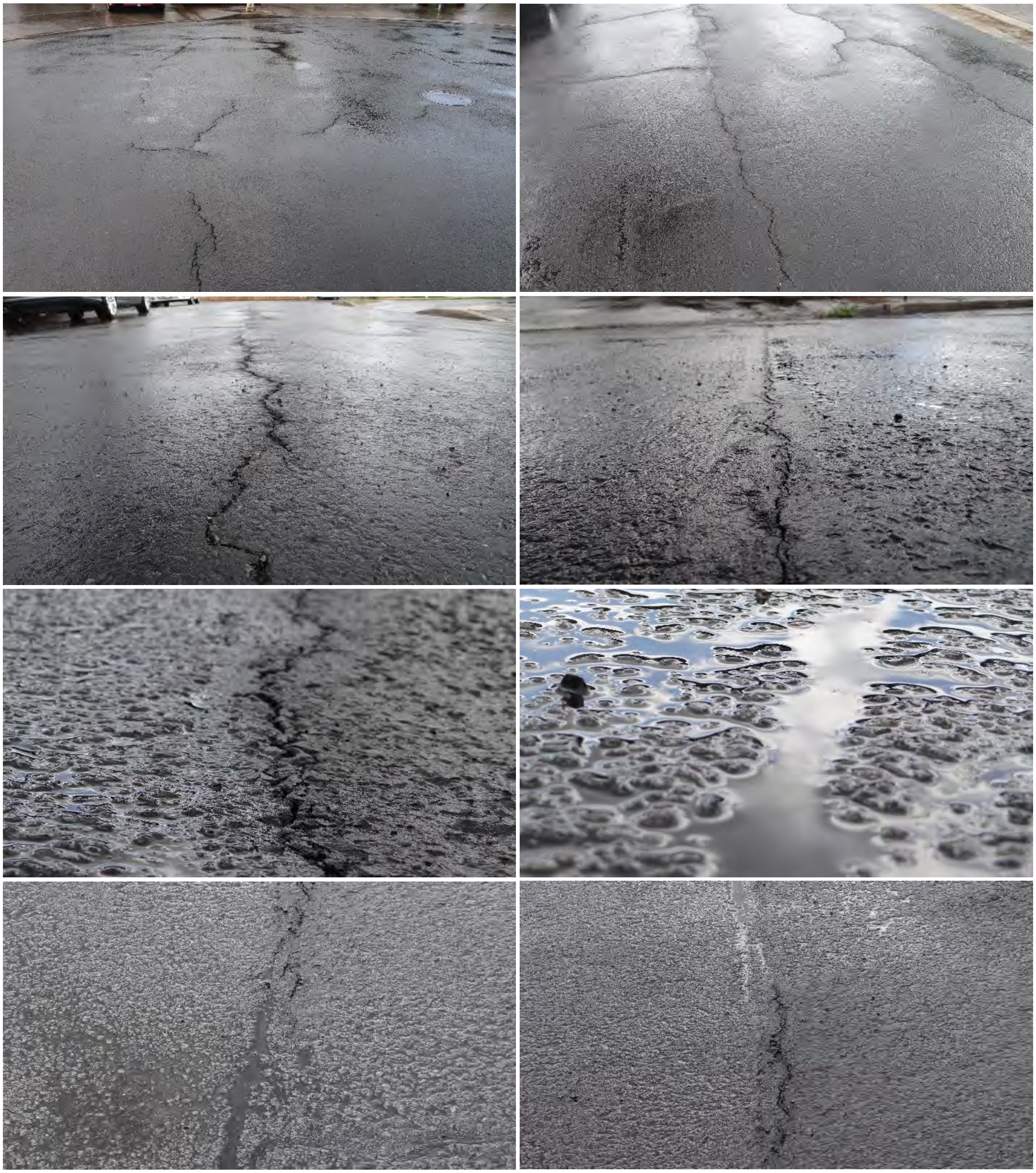

Figure C-137 Condition of the section on Hooheno Place, before treatment with CarbonSeal-HF by Carbonyte Systems Inc., on 2/7/2018.

Figure C-138 Condition of the section on Hooheno Place, before treatment with CarbonSeal-HF by Carbonyte Systems Inc., on 5/24/2019.

C.5 SLURRY SEAL IN STRAIGHT SECTIONS

C.5.1 Hulahe Street section - Slurry Seal - Alakona Corporation

Figure C-139 shows the condition of the section's surface on 8/29/2015, eight and a half months after the slurry seal application. The overall appearance of the section was good, though there were a few defects that are highlighted in the photos corresponding to later surveys. In general, because of its thicker application and some of the hand work required on the joints with the gutter, slurry seals tend to show some uneven appearance. The two photos on the bottom of Figure C-139 show some of the few cracks observed up to this point. Although it can not be appreciated in these photos, a common issue with this treatment is the initial high loss of aggregate depending on the slurry consistency. As shown later, the amount of loose aggregate can be substantial in some cases.

Figure C-140 shows that as of 3/3/2016, about 15 months after the slurry seal application, although the cracking length was growing (not shown in these photos) the overall appearance of the section was still good. The bottom right photo in Figure C-140 illustrates the common problem of oil spills from parked cars. This is not only unsightly but also ends up eventually affecting the condition of those spots.

Figure C-141 shows the condition of the section on 6/27/2016, after slightly more than 19 months of service. Although the overall appearance of the section was still acceptable (top photos), several problems (some unrelated to the treatment) were more noticeable. First, as shown in the photos in the second row, a patch had already been performed within the section and another area had been marked for repair. Both were apparently related to a water main breaks. The photos on the third row highlight the fact that oil spills on this street were quite common. The last two photos show the coarse texture that this treatment often exhibits (when compared with the other seal coats in this study) and the problem of aggregate loss, particularly on parking areas. As shown in the bottom right photo, the amount of loose aggregate can be quite substantial.

The top photos in Figure C-142 illustrate that further loss of material may result in spots with delamination. The four middle photos show some of the cracking observed on 6/27/2016 and the last two photos show a construction defect that persisted over the whole study period.

Figure C-143 shows the conditions on 12/14/2016, with 25 months in service. Once again, as shown on the top left photo, the overall appearance of the section was good even though as shown in the other photos some of the same issues observed in other surveys were still present.

Figure C-144 and Figure C-145 show the condition of the section on 2/7/2018, after 38 months of service. The top photos in Figure C-144 show that the section still had a generally good appearance though the cracking was now more noticeable. The other photos in the figure show different examples of the type of cracks observed.

Figure C-145 highlights other issues discussed before. Namely, the top two photos show the condition of delaminated areas, the photos in the second row show patched areas and another area marked for a new repair by the Board of Water Supply, the photos in the third row show that the construction defect noted earlier persisted almost intact while in some areas the pavement surface was showing significant aggregate loss, and the last two photos show the effects of oil spots.

Figure C-139 Condition of the section on Hulahe Street, treated with Slurry Seal by Alakona Corp., on 8/29/2015.

Figure C-140 Condition of the section on Hulahe Street, treated with Slurry Seal by Alakona Corp., on 3/3/2016.

Figure C-141 Condition of the section on Hulahe Street, treated with Slurry Seal by Alakona Corp., on 6/27/2016.

Figure C-142 Condition of the section on Hulahe Street, treated with Slurry Seal by Alakona Corp., on 6/27/2016.

Figure C-143 Condition of the section on Hulahe Street, treated with Slurry Seal by Alakona Corp., on 12/14/2016.

Figure C-144 Condition of the section on Hulahe Street, treated with Slurry Seal by Alakona Corp., on 2/7/2018.

Figure C-145 Condition of the section on Hulahe Street, treated with Slurry Seal by Alakona Corp., on 2/7/2018.

C.6 SLURRY SEAL IN CUL-DE-SAC SECTIONS

C.6.1 Hiana Place - Slurry Seal - Alakona Corporation

Figure C-146 shows the condition of the section's surface on 1/26/2015, soon after it was opened to traffic on 1/26/2015. The top photo shows the typical appearance of the slurry seal mix. The photo on the bottom illustrates the significant amount of loose aggregate this treatment may leave behind. This would typically need to be brushed.

Figure C-146 Condition of the section on Hiana Place, treated with Slurry Seal by Alakona Corp., on 1/26/2015.

Figure C-147 shows the conditions on 8/29/2015, seven months after the application of the slurry seal. The section had an overall nice appearance but some closeups show some typical marks and changes in texture with this treatment due to the handwork required by the marks left at the edges of the spreader box of the slurry sealer truck. Some of these photos show some barely noticeable incipient cracking either new or reflecting from sealed cracks.

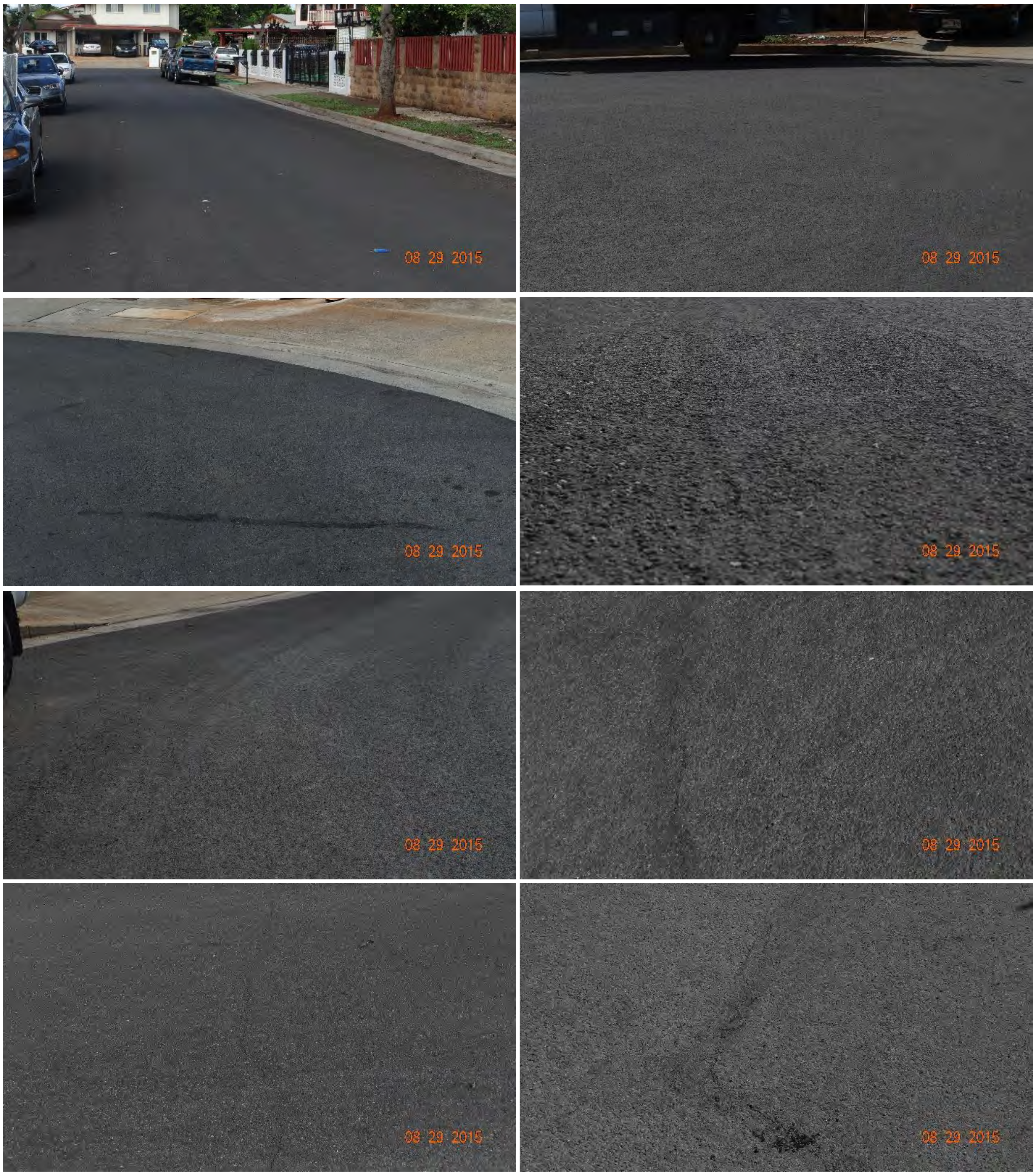

Figure C-147 Condition of the section on Hiana Place, treated with Slurry Seal by Alakona Corp., on 8/29/2015.

Figure C-148 shows the conditions on 3/3/2016, about 13 months after the treatment application. The photos in the first row show the overall nice appearance of section. The second-row photos show that cracks were more noticeable whereas the third-row photos provide closeups to illustrate some of the textures that can be observed with this treatment. The last two photos illustrate again the high amount of loose aggregate, which typically accumulates near the gutter.

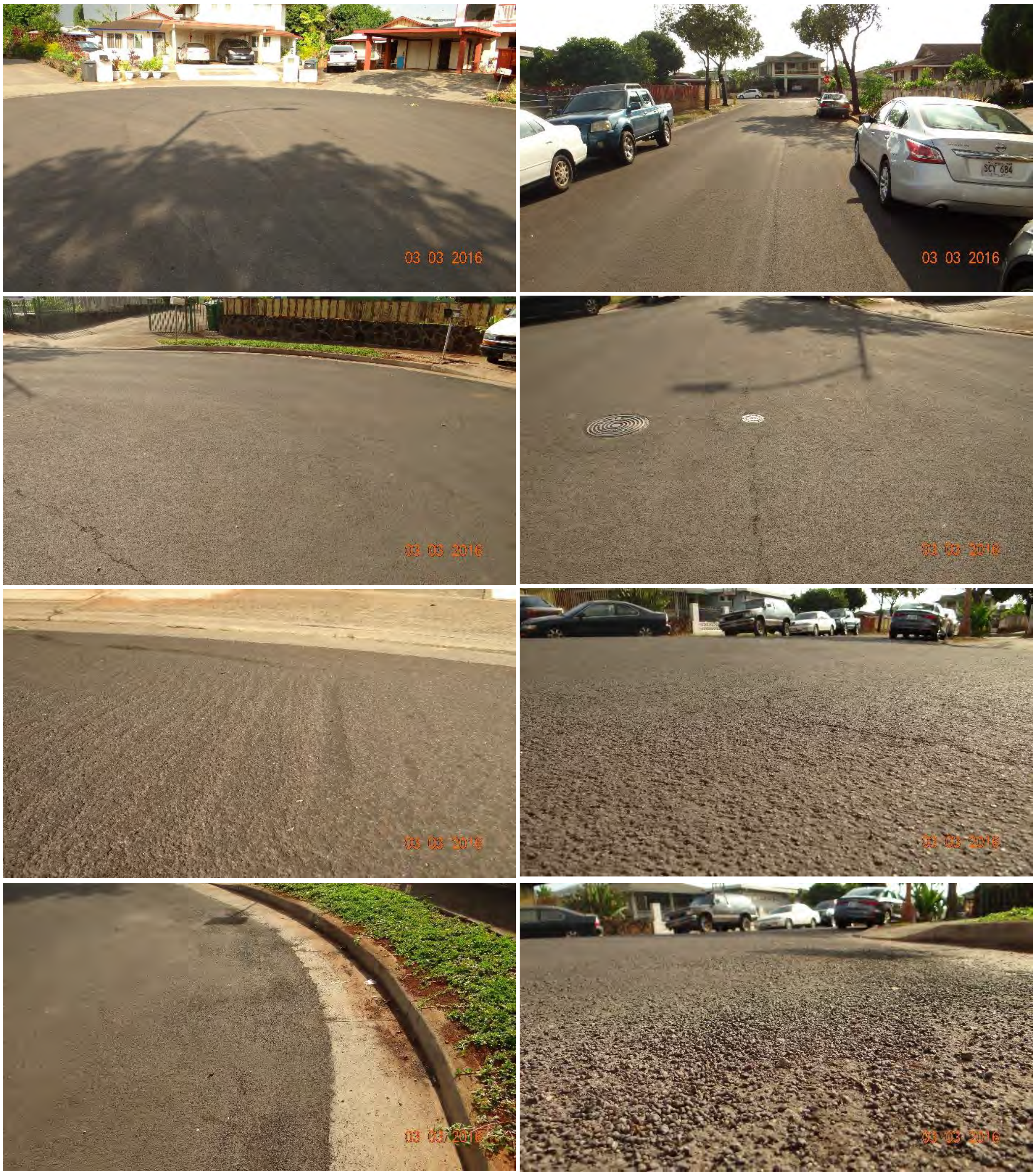

Figure C-148 Condition of the section on Hiana Place, treated with Slurry Seal by Alakona Corp., on 3/3/2016.

Figure C-149 shows the conditions on 6/27/2016, about 17 months after the treatment application. The figure provides several examples of the cracking observed in the section and once again the existence of loose aggregates on the surface.

Figure C-149 Condition of the section on Hiana Place, treated with Slurry Seal by Alakona Corp., on 6/27/2016.

As seen in the top left photograph in Figure C-150, on 12/14/2016, with 23 months in service, the cul-de-sac had a distinctive appearance from the adjacent straight portion. It was not clear at the time what was had been done but on the last survey a neighbor indicated that it had been treated. It appears that a seal coat may have been applied to stop the aggregate loss. The other photos just provide additional examples of the condition observed on that date.

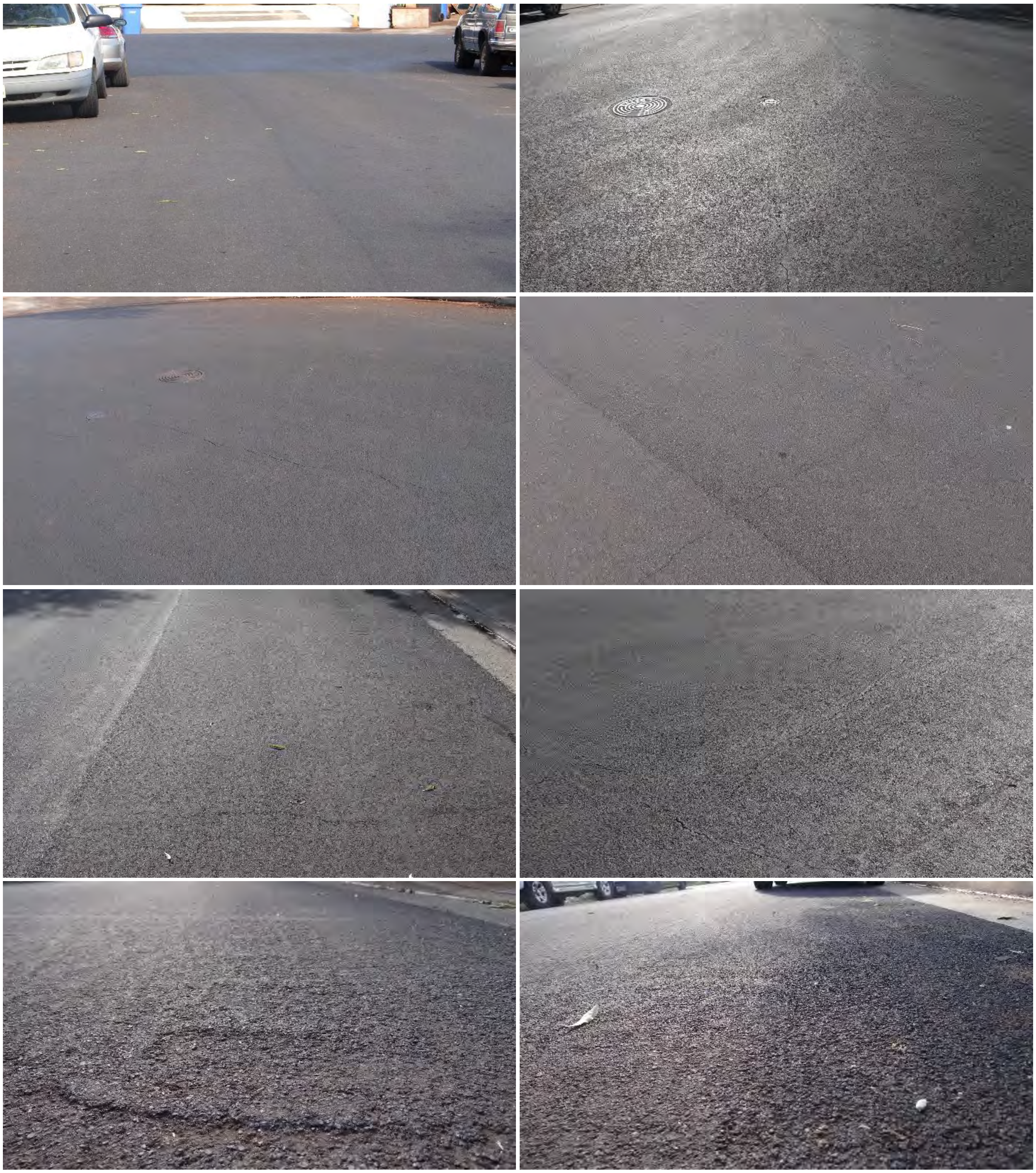

Figure C-150 Condition of the section on Hiana Place, treated with Slurry Seal by Alakona Corp., on 12/14/2016.

Finally, Figure C-151 shows that on 2/7/2018, about three years after the slurry seal application, the section still exhibited a nice appearance with cracking mostly of low severity. As shown in the last two photos, there were still areas with loose aggregates on the surface on the straight portion of the segment.

Figure C-151 Condition of the section on Hiana Place, treated with Slurry Seal by Alakona Corp., on 2/7/2018.

Figure C-152 shows the conditions on 5/24/2019. As expected, the aggregate loss from the slurry was a lot less in the cul-de-sac portion, which as described before was apparently sealed, than on the straight portion where it is still noteworthy.

Figure C-152 Condition of the section on Hiana Place, treated with Slurry Seal by Alakona Corp., on 5/24/2019.

C.6.2 Hapapa Place - Slurry Seal - Alakona Corporation

The top four photos in Figure C-153 show the condition of the section's surface (cracking and texture) before the slurry seal appication on 12/17/2014 and the last four photos show the section appearance immediate after its application. The original section had an advanced block cracking pattern though apparently not yet fully developed. The last two photos illustrate the typical appearance of the slurry mix shortly after its application. The grade of the cul-de-sac is about 4.4%, which is steep and clearly visible in the photos.

As shown in Figure C-154, by 8/29/2015, nine months after the application of the slurry seal, several cracks had formed or reflected on the slurry seal. Other than that, the treatment still exhibited a good appearance.

The same can be said about the conditions on 3/3/2016 shown in Figure C-155, with slightly more than 15 months in service, except that cracking was getting much more noticeable. These photos also illustrate the common occurrence of oil spots and the marks left during the slurry seal application.

Figure C-156 shows the conditions almost four month later, on 6/27/2016. Note the last two photos in this figure showing the common issue of loose aggregates in the surface.

Figure C-157 and Figure C-158 show the conditions on 12/14/2016 and 2/7/2018. These figures illustrate that cracking continued growing in length steadily and eventually surpassed the length of cracking existing before the application of the slurry seal. Many of these cracks were also getting wider.

As shown in Figure C-159, part of the section had been patched before 5/24/2019. The figure also illustrates that in some areas there was significant loss of aggregate on the surface, creating a rough texture.

Figure C-153 Condition of the section on Hapapa Place, treated with Slurry Seal by Alakona Corp., on 12/5/2014 to 12/17/2014.

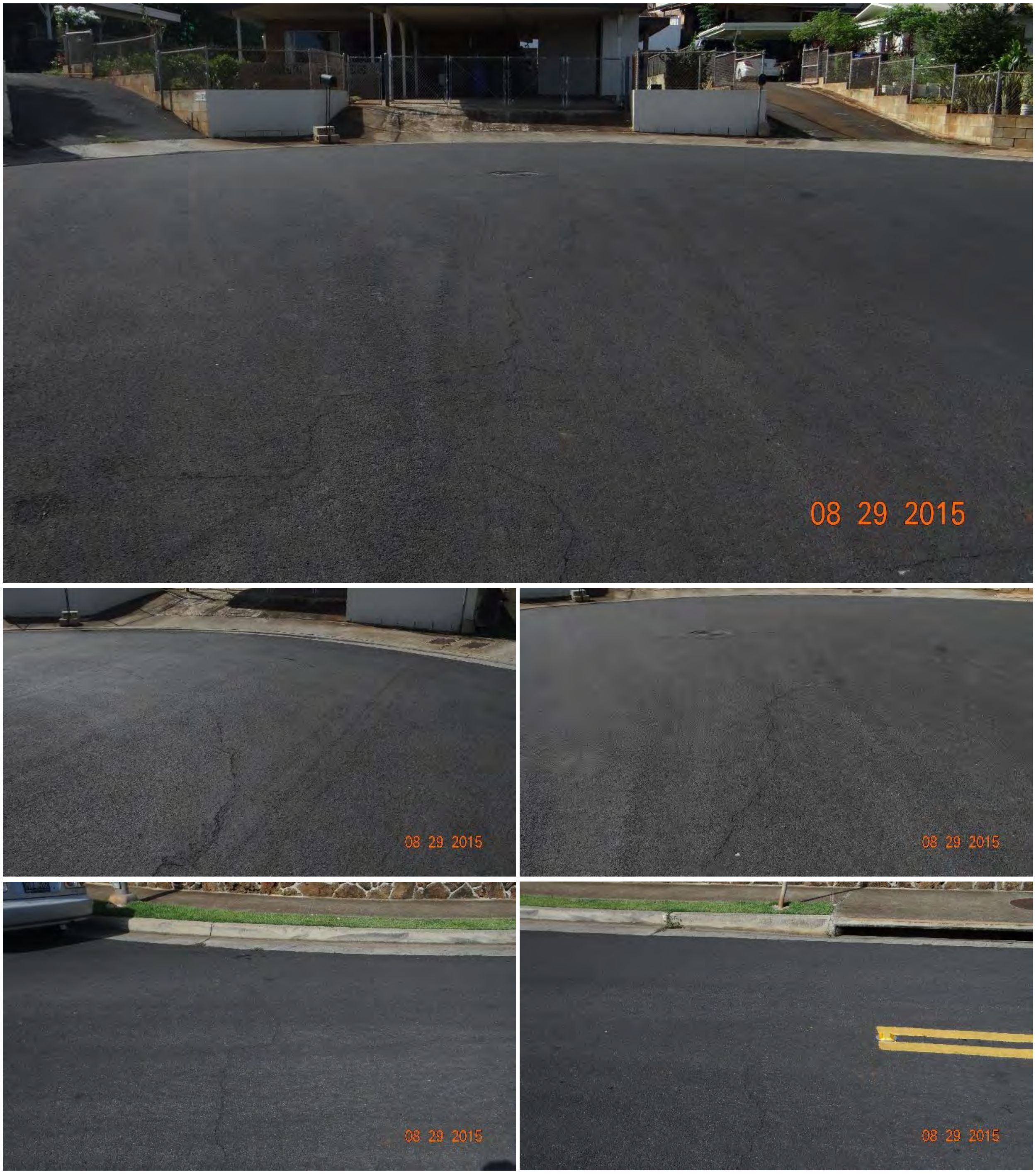

Figure C-154 Condition of the section on Hapapa Place, treated with Slurry Seal by Alakona Corp., on 8/29/2015.

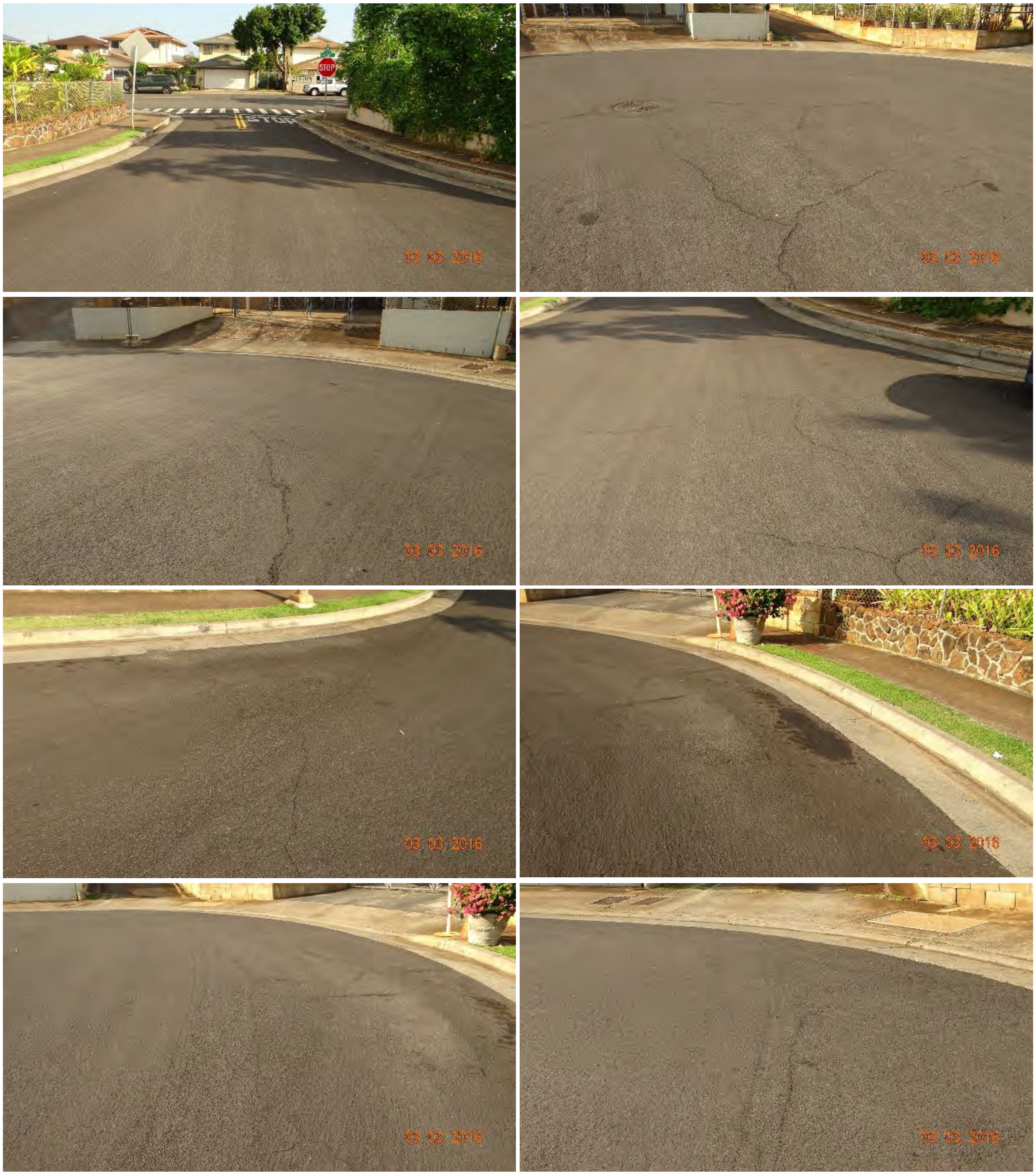

Figure C-155 Condition of the section on Hapapa Place, treated with Slurry Seal by Alakona Corp., on 3/3/2016.

Figure C-156 Condition of the section on Hapapa Place, treated with Slurry Seal by Alakona Corp., on 6/27/2016.

Figure C-157 Condition of the section on Hapapa Place, treated with Slurry Seal by Alakona Corp., on 12/14/2016.

Figure C-158 Condition of the section on Hapapa Place, treated with Slurry Seal by Alakona Corp., on 2/7/2018.

Figure C-159 Condition of the section on Hapapa Place, treated with Slurry Seal by Alakona Corp., on 5/24/2019.