Evaluation of Winter Pothole Patching Methods

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16. Abstract

The main objective of this study was to evaluate the performance and cost-effectiveness of the tow-behind combination infrared asphalt heater/reclaimer patching method and compare it to the throw and roll and spray injection methods. To achieve this objective a national survey was first conducted to document the experience of the infrared asphalt heater/reclaimer users in different states. In addition, a comprehensive testing program, that included installing over 60 patches using the three considered methods as well as monitoring the performance and survivability of those patches, was performed. The results of the survey and subsequent phone interviews indicated that the infrared asphalt heater/reclaimer equipment can significantly improve the performance and longevity of pothole patches and can be cost-effective when proper installation procedures are followed. The results of testing program indicated that the infrared method had much lower productivity than the other two methods. In addition, the throw and roll had better productivity than the spray injection method. The properties and storage procedure of the asphalt mixture used in the infrared method were found to affect the performance of the installed patches. Improper storage of the infrared heater/reclaimer equipment also was found to cause problems in igniting the infrared heater, which significantly increased the patching duration. In general, most of the deterioration in the patches installed using the different methods occurred in the first month of installation and continued after that but at much slower rate. The infrared patches had significantly better performance than those installed using the two other patching methods. The main distress in infrared patches was raveling, while it was dishing for the throw and roll and spray injection patches. The results of survivability analyses also indicated that the patches installed using infrared had much longer expected life than those installed using the other two considered methods. The results of the cost analyses showed that the infrared method can be more cost-effective than the spray injection method when used for winter pothole patching. For short term repairs, the throw and roll method was found to cost less than the infrared method if the user cost were not considered. However, for permanent repairs, the infrared method can be more cost effective than throw and roll method. In summary, the tow-behind infrared heater/reclaimer was found to be an efficient and cost effective method for patching certain types of potholes as well as performing other pavement repairs. A strategy for its deployment in Ohio is provided in this report.

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Abstract

The main objective of this study was to evaluate the performance and cost-effectiveness of the tow-behind combination infrared asphalt heater/reclaimer patching method and compare it to the throw and roll and spray injection methods. To achieve this objective a national survey was first conducted to document the experience of the infrared asphalt heater/reclaimer users in different states. In addition, a comprehensive testing program, that included installing over 60 patches using the three considered methods as well as monitoring the performance and survivability of those patches, was performed. The results of the survey and subsequent phone interviews indicated that the infrared asphalt heater/reclaimer equipment can significantly improve the performance and longevity of pothole patches and can be cost-effective when proper installation procedures are followed. The results of testing program indicated that the infrared method had much lower productivity than the other two methods. In addition, the throw and roll had better productivity than the spray injection method. The properties and storage procedure of the asphalt mixture used in the infrared method were found to affect the performance of the installed patches. Improper storage of the infrared heater/reclaimer equipment also was found to cause problems in igniting the infrared heater, which significantly increased the patching duration. In general, most of the deterioration in the patches installed using the different methods occurred in the first month of installation and continued after that but at much slower rate. The infrared patches had significantly better performance than those installed using the two other patching methods. The main distress in infrared patches was raveling, while it was dishing for the throw and roll and spray injection patches. The results of survivability analyses also indicated that the patches installed using infrared had much longer expected life than those installed using the other two considered methods. The results of the cost analyses showed that the infrared method can be

more cost-effective than the spray injection method when used for winter pothole patching. For short term repairs, the throw and roll method was found to cost less than the infrared method if the user cost were not considered. However, for permanent repairs, the infrared method can be more cost effective than throw and roll method. In summary, the tow-behind infrared heater/reclaimer was found to be an efficient and cost effective method for patching certain types of potholes as well as performing other pavement repairs. A strategy for its deployment in Ohio is provided in this report.

Chapter 1: Introduction

1.1 Problem Statement

Potholes are one of the most aggravating forms of pavement deterioration because of the danger they pose to the travelling public and the potential damage they can cause to vehicles. Despite all measures taken by transportation agencies, the occurrence of potholes is inevitable, which presents a challenge to all national, state, and local highway agencies involved in pavement maintenance.

Pothole patching is the most common pavement maintenance operation used by transportation agencies to remedy the presence of potholes. The most widely used pothole patching method in Ohio is the throw and roll method. This conventional patching method is effective if done properly and performed during the time of year when warmer temperatures are predominant. However, potholes generally form during the winter months due to freeze-thaw cycles. Since most asphalt plants are closed in wintertime, cold asphalt mixtures are typically used instead of hot mix asphalt. The use of cold mixtures may result in reduced adhesion to the existing pavement material, leading to premature patch failure.

Patching using the spray injection method can be used to overcome the reduced adhesion between the patching material and the existing pavement. This method consists of blowing the debris and water out of the pothole followed by spaying a layer of tack coat on the bottom and sides of the pothole. Aggregate is then premixed with heated asphalt emulsion using specialized equipment before being applied into the pothole and finally the patched area is covered with a layer of aggregate. While this process generally enhances the survival rate and performance of patches installed during the winter, the heated patching material may not become homogeneously integrated with the cold surface of the existing pavement. This may lead to the formation of a cold joint along the interface between the pavement surface and the patching material, resulting in the separation of the two materials and ultimately leading to the failure of the patch.

In recent years, a tow-behind combination infrared asphalt heater/reclaimer has been used to improve the performance of pothole patches. This system consists of an infrared reclaimer and a pavement heater mounted on a dual axle trailer. The reclaimer consists of a hopper that is designed to reclaim the asphalt material by reheating it to a workable temperature, which allows for creating a hot patching material even during the winter. In addition, this heater/reclaimer combination system has a heater that is capable of heating the existing pavement surface, within and around the area to be patched, to a workable temperature close to 320^{o}F without burning or oxidizing it. This enables the heated patching material obtained from the reclaimer to blend in with the existing asphalt material, which allows for patching without leaving seams that permit water to penetrate the repaired areas, resulting in quick deterioration of the installed patches. By improving the performance and longevity of pothole patches, the infrared asphalt heater/reclaimer can reduce the costs of materials, labor, equipment, traffic control, and user delay associated with re-patching. Furthermore, it may enhance the safety conditions by allowing less crew time in traffic. The use of infrared heater/reclaimer may also help in eliminating or reducing the amount of new asphalt mix needed for patching by reclaiming waste asphalt materials.

In spite of the potential benefits from using the infrared heater/reclaimer, no research has been conducted to investigate its use in pothole patching and evaluate its advantages and disadvantages. Main issues that need to be addressed before implementation include: 1) the properties of the asphalt materials reclaimed using the infrared heater and its quality as a patching material, 2) the optimum temperature range that the infrared heater/reclaimer can be used at, 3) the performance and survival rate of patches installed using this technique, and 4) the efficiency and cost-effectiveness of this technique as compared to other patching methods.

This study was conducted to evaluate the performance and cost-effectiveness of three methods, namely, the throw and roll method, the sprayer injection (trailer mounted), and the tow-behind infrared asphalt heater/reclaimer, for use in winter pothole patching in northeastern Ohio. In addition, this study also determined the benefits and limitations of the tow-behind combination infrared asphalt heater/reclaimer technique and identified the proper procedure and materials that should be used to ensure optimal usage of this technique.

1.2 Study Objectives

The primary objective of this study is to evaluate the performance and longevity of pothole patches installed using three methods, namely, throw and roll, spray injection, and tow-behind combination infrared asphalt heater/reclaimer methods. The specific objectives of this interim report include:

- Identify best practices of the throw and roll, the spray injection, and the tow-behind combination infrared asphalt heater/reclaimer methods available when used for winter pothole patching.
- Determine the advantages and limitations of each of these three methods that are reported in previous studies.
- Summarize the results of the online survey that was conducted to gather information from users of tow-behind combination infrared asphalt heaters/reclaimers.
- Select the most suitable infrared asphalt heater/reclaimer system for use in Ohio.

1.3 Report Organization

This report is organized into seven chapters. Chapter 2 presents a literature review of subjects pertinent to this study. It provides an overview of the results of studies that evaluated the different pothole repair techniques and identifies the best practices for winter pothole patching. Chapter 3 presents the steps pursued to select the most suitable tow-behind combination infrared asphalt heater/reclaimer equipment for use in pothole patching as well as other pavement maintenance practices in in Ohio. Chapter 4 provides a summary of the survey responses and its key findings. Chapter 5 presents a description of the performed testing program and the all the data collected as part of this program. Chapter 6 provides a summary of results of all analyses that were conducted on the installation and performance data that was collected in this study. Finally, Chapter 7 presents the main conclusions and recommendations for future study as well as the deployment stagey for infrared asphalt heater/reclaimer equipment in Ohio.

Chapter 2: Literature Review

2.1 Background

Potholes are one of the most aggravating forms of pavement deterioration because of the danger they pose to the travelling public and the potential damage that can cause to vehicles. Despite all measures taken by transportation agencies, the development of potholes is inevitable, which presents a challenge to all national, state, and local highway agencies involved in pavement maintenance. A pothole is a bowl-shaped depression in the pavement surface to the extent that it causes significant noticeable impact on the vehicle tires and handling. Transportation agencies typically define potholes based on the size of the depression. ODOT defines a pothole as a hole in the paved surface exceeding two inches in depth and 144 square inches in area with both area dimensions greater than four inches (*1*).

Potholes form due to two main factors: traffic loads and water. The mechanism of pothole formation varies depending on the type of pavement. For flexible pavements, potholes generally develop in weak areas of the pavement where heavy traffic loads result in excessive bending (flexing) and cause it to crack. Water can then easily enter the pavement system through these cracks and weaken the various layers of the pavement structure to the point where the pavement can no longer support heavy loads. Freezing and thawing during the winter further lead to the expansion and contraction of the pavement structure, which expedite the formation of potholes under subsequent traffic loads. For rigid concrete pavements, potholes usually form at the contraction joints or in areas where concrete has deteriorated. Cracks can form at the joints due to pavement curing after construction as well as contraction or expansion under adverse weather conditions. As for composite pavements, potholes typically develop in the top layer due to reflective cracking, which occurs at the location of the joints or cracks in the underlying concrete slab. The reflective cracks in the asphalt overlay will gradually widen with time, and if not sealed, water can enter and weaken the asphalt layer due to freezing and thawing, and eventually lead to the formation of potholes.

2.2 Pothole Patching Methods

The remedy for repairing a pothole is generally referred to as "patching". Patching can be described as the filling of a hole or a depression in a road surface by an appropriate asphalt mixture. The goal of patching is to return the pavement to a working condition that will not deteriorate the vehicles that ride on the road. There are different methods to perform pothole patching. This chapter focuses on three patching methods: the throw and roll, the spray injection, and the infrared asphalt heater methods. The following sections present a detailed description for each of the three methods and summarize the results of previous studies that evaluated them.

2.3 Throw and Roll

This method is one of the oldest methods used for pothole patching. It is the most widely used since it is easy, fast, and does not require specialized equipment. This method mainly involves filling a pothole with an asphalt mix and compacting it with truck tires or a vibratory roller/plate. Different procedures were reported in previous studies for executing this method and are summarized in the following subsections.

2.3.1 Throw and Roll Method 1

The simplest procedure for the throw and roll method, also known as the throw and go, consists of the following steps (*2*):

- Throw the hot or cold mix into the pothole regardless of the amount of debris or water that is in the hole.
- Compact the asphalt mix with a shovel or by truck tire.
- Move on to the next pothole.

2.3.2 Throw and Roll Method 2

Different procedures were reported for this method (*2*,*3*), the best practice was found to consist of the following steps:

- Remove water and debris from the pothole.
- Pour the hot or cold asphalt mixture and compact it in lifts with maximum thickness of two inches using the truck tires or vibratory roller/plate (preferred) until a 0.15 to 0.25 inch crown is formed.
- Move on to the next pothole.

For deep potholes, the patching material can be compacted in lifts with a maximum thickness of three inches using a roughened surface to ensure a tight fit between layers.

There are certain advantages and disadvantages of the aforementioned procedures that need to be considered when selecting the right one. The main advantage of the first method (throw and go) is that it can be performed in a relatively short time and using few workers. Although the second throw and roll procedure requires more time to patch a pothole, it is preferred to the throw and go procedure because it significantly extends the life of the patch. This leads to reducing the overall repair costs and improves the safety as the patching crew is less frequently exposed to traffic. Therefore, it is generally recommended to use the second procedure (i.e. Method 2) when installing the pothole patch using the throw and roll method.

There are some practices that were reported in previous studies that help in improving the patch performance and longevity when the throw and roll method is used. To this end, it is recommended that hot mixes to be generally heated to a temperature of at least 275 °F (*4*). This is the most essential in cold weather conditions. Another important practice that should be followed is to leave a crown of asphalt (0.125 to 0.25 inch) above the pothole surface. This allows passing traffic to further compact the patch and create a tighter seal, which corresponds to a higher density. The slipping and compressing of the asphalt will allow for the extra crown to be squeezed into the cracks as much as possible, which will result in a tight patch. Furthermore, patching compaction should start from the center of the patch towards the outer edges. This ensures that the patch is tight against the edge of the existing pavement. Finally, the patching layer(s) should be properly compacted to adequate density. Proper density will result in reducing the air voids as well as permeability, which helps in decreasing the amount of water and debris entering the patch. Proper density will also ensure that the patch will have similar deflection to surrounding pavement materials. Therefore, it is essential to control the density during patching.

Different types of asphalt mixtures can be used for pothole patching with the throw and roll method. Hot mix asphalt from an asphalt plant is typically the best patching material (*2*,*5*,*6*). However, as most asphalt plants are closed in the winter, cold asphalt patching mixes are typically used for pothole patching in this season. Cold mixtures do not have adequate adherence to the exiting pavement materials, which significantly affects the patch performance and longevity. When using cold mixes, it would be beneficial for the patching crew to apply a tack coat to the top and bottom of the patch layers to ensure adequate bonding. For large potholes, it is essential to use hot asphalt mixes, as the permeability rate is much lower than that of the cold mixes.

Regardless of whether hot-mix asphalt or cold-mix asphalt is used, the main drawback with the throw and roll method is the difference in temperature between the patch and the existing pavement, which results in the formation of cold joints. This adversely affects the bonding between the patch and the surrounding pavement material, and leads to multiple entry points around the edges for water and other debris to enter the pothole patch, which may severely shorten the lifespan of the patch.

2.4 The Semi-Permanent Method

This method is a more-involved throw and roll procedure and can be considered as a partial-depth repair. The time and effort needed to perform this procedure are thought to improve the success rates for pothole patches. The steps for the semi-permanent procedure reported in previous studies are as follows (*2*,*7*):

- Remove all water and debris from pothole using compressed air, brooms, shovels, or other available equipment.
- Square up the sides of the pothole so that they are vertical and have sound pavement material. This can be achieved by using either a jackhammer with a spade bit or a pavement saw. It is not necessary to create a square or rectangular area as long as the sides are vertical.

- Place the patching material into the cleaned, squared hole. The material should mound in the center and taper down to the edges so that it meets the surrounding pavement edge.
- Compact the material starting in the center and working out toward the edges, which will cause the material to pinch into the corners. A one-man compaction device, such as a single-drum vibratory roller or vibratory plate compactor should be used.
- Move on to the next pothole.

This method results in the longest life for the pothole patch due to the solid compaction against the sides, but also requires more workers and equipment (*8*). The productivity rate is much lower than the throw and roll method. Previous studies showed that four workers is the optimum number to be used in this method, and also that this method is less effective in winter conditions (*2*). In terms of longevity, the semi-permanent method was found to be superior as compared to the throw and roll and edge seal methods since it enhances the performance of the patches by improving the surrounding support. However, some studies showed that with high quality mixes (e.g. UPM High-Performance Cold Mix) the throw and roll method can be as effective as the semi-permanent method while being comparatively less labor intensive (*2*,*7*).

2.5 The Edge Seal Method

This method is similar to the throw and roll method. However, in this method the patch is left to dry for one day after installation and a ribbon of asphaltic tack material is placed on the patch edge and a layer of sand is placed on it. This procedure is intended to limit the amount of water that penetrates through the edges of the patch. The steps for the edge seal procedure are as follows:

- Place material into pothole (no preparation or removal of water and debris is needed prior to material placement).
- Compact the patching material using truck tires (between four and eight passes) leaving a slight crown.
- Allow pavement and patch surfaces to dry, generally one day after the installation. Place a band of bituminous tack coat material, 4 inch to 6 inch wide, along the perimeter of the patch.
- Place a layer of cover aggregate over the tack material to prevent tracking; coarse sand can be used.
- Move on to next pothole.

The main disadvantage of the edge seal method is that it requires a long recovery time between patching and opening the roadway to traffic.

2.6 Spray Injection Method

The spray injection is another method that has been used for patching potholes. This method is also referred to as blow patching. It requires the least expensive materials and utilizes air pressure as the main source of compaction. The air pressure also works to dry the hole and remove water. The equipment required is the spray injection system, hose, and boom. While three different units can be used for placing spray-injection patches, the same basic procedure can be used in all cases. Based on the results reported in previous studies, the steps for the spray injection method are as follows (*2*):

- Blow water and debris from pothole using.

- Spray bottom and sides of pothole with binder material to act as tack coat.
- Spray aggregate and binder into the pothole simultaneously so that the aggregate is coated as it impacts the repair.
- Continue spraying aggregate and binder into the pothole until it is filled just above the level of the surrounding pavement.
- Cover the top of the patch with a layer of aggregate to prevent tracking by passing vehicles.
- Move on to next pothole location.

The spray injection method utilizes heated emulsion and virgin aggregate to be sprayed into the area of interest. The mix of virgin aggregate and heated emulsion can be varied dependent on the size and location of the pothole. This allows the spray injection method to be very flexible. The sprayed mix needs to achieve a high density, which occurs through proper mix design. However, poor mix design and excess water can greatly affect the longevity of patches. For example, low binder content may lead to premature failures and raveling in the patches. Finally, it is not recommended to utilize volcanic aggregate that has high absorbing characteristics as this may result in reducing the binding strength between the aggregate and pavement.

There are three different units that can be used for the spray injection method:

1. A trailer unit: This unit is towed behind a truck. It has the aggregate stowed in it. This method requires a minimum of two workers. The aggregate is fed through a hose suspended from a boom on the truck. This is the most popular unit. An example of such unit is the DuraPatcher pavement sprayer (Figure 2.1) that is currently being used by ODOT.

2. Modified truck unit: This unit is similar to the trailer unit. The main difference is that the equipment is reconfigured to be mounted on a dump truck bed, which eliminates the need for a trailer. This method requires at least two workers.
3. Self-contained unit: This unit involves patching with a joystick and remote control from the inside of the cab. The aggregate, heated binder tank and delivery system all are mounted on the truck unit. This method only requires one operator.

Figure 2.1 DuraPatcher Equipment

Griffith (*6*) reported that the spray injection using trailer type units is versatile and can be utilized for a variety of highway repairs. In addition, a more exact repair can be made with this type as the operator is on the ground close to the distressed pavement area. Aside from these advantages, this type of spray injection has minor drawbacks: 1) An increased crew size is required compared to the other types (one truck driver and one spray injection operator), 2) The spray injection operator is typically exposed to errant traffic even when proper work zone traffic control is used, and 3) The operator and parked vehicles may become coated with overspray.

Similar to other patching methods, the spray injection method is more effective during summer weather conditions. This method should be used in urban areas due to the easiness of transporting materials to a site and the simplicity of using one unit to do the repair, preventing frequently passing cars to interrupt workers. There are several advantages for the spray injection method over the throw and roll method. In this regards, this method requires the least expensive materials. It is very versatile and can be used for potholes, transverse crack repair, alligator cracks, utility cuts, corrugations, depressions, slipping cracks, ruts, and spalls in Portland cement concrete. Another important advantage of the spray injection method is that it can be used in most weather conditions, including mild rain and slightly cold weather. Furthermore, the advantage of this method is that the spray hose is easy to handle. Ease of use therefore prevents the user from being in the line of traffic for an extended period of time (*9*). The patch does not need to be further compacted after it is sprayed due to the fine sizes of the materials used. The fineness of the materials also allows the patch to reach deeper into the cracks of the pothole. The extension of the spray hose and boom off of the unit makes it easy to reach potholes in various locations.

In terms of disadvantages, one of the downfalls of this method is that the operator is exposed to traffic and the flying debris that ricochets off of the ground. Not only could the hose operator be covered with the overspray, but traffic and nearby objects can also be covered. Another downfall is that there is an inadequate bonding between the patching material and the existing pavement due to the drastic temperature difference between patching and existing asphalt materials during installation, which results in the formation of a cold joint between these materials. The high temperature of the material makes this method more effective than the throw and roll in winter conditions. Immediately after the fixing of the pothole, the new material may be soft and deflect under traffic (*9*). Other complications of this method are that it requires well trained and experienced operators to install the patches (2) and that the system may malfunction and become jammed.

2.7 Comparison Between Throw and Roll And Spry Injection Methods

There are a number of factors that need to be evaluated when selecting the optimal patching method to be used. These variables include, but are not limited to: the size of the pothole, time required patching, distancing between potholes, traffic flow, traffic control measures, required materials, equipment required and equipment costs, number of potholes, crew size required, productivity rates, and transportation of materials

Sizes of potholes directly affect which method to be selected for pothole patching. For shallow potholes (less than 2 inch deep) and medium depth pothole (2 inch to 4 inch deep), the throw and roll or spray injection methods can be used, but the spray injection method is preferred for shallow depth potholes that occur entirely in an asphalt layer. For a medium depth pothole, the layers of asphalt or aggregate should be roughened for added adhesion and then bonded using a tack coat. Therefore, for most cases the throw and roll method will be more suitable. For deep potholes (greater than 4 inch deep) resulting from structural failure from underlying layer, the throw and roll will be preferred, as the spray injection results in a patch that significantly deflects due to the fineness of its materials. For such potholes, it essential to remove the water and the water source itself before repair.

Traffic control, traffic flow, and pothole location are also important factors that will dictate the method to be used for patching. For high volume roads where traffic control is difficult and the time for installing the pothole is limited, the optimal method will be the one with best productivity. Previous studies that evaluated the productivity of the throw and roll and spray injection methods (e.g. 2,*7*) indicated that 2.6 minutes were needed on average to repair a 1.1 ft^3 pothole using the throw and roll method. Such that the average productivity of this method was estimated to be about 3.2 tons/person-day (*2*). On the other hand, on average 2.8 minutes spent on a pothole that is 1.3 ft^3 in volume when the spray injection method was used. Thus, the spray injection method had on average a productivity of 3.4 tons/person-day (*2*), which is slightly better than that of the throw and roll method.

Cost also plays a significant role in the selection of the pothole patching method. To this end, the analysis should depend only on the initial cost but rather on the life cycle cost. The life cycle cost accounts for the initial installation cost as well as cost incurred during the service life of the patch. The main disadvantage of spray injection as compared to the throw and roll method is the high initial cost of needed equipment. For example, the trailer unit costs around $40,000 while a single chassis unit costs around $125,000. Despite that, Wilson and Romine (*3*, *4*) reported that based on comparing the performance of various pothole patching methods, the spray injection method was found the least expensive. This was mainly attributed to the significantly better service life of patches installed using the spray injection method as compared to those performed with the throw and roll method. The throw and roll method can produce a pothole that lasts up to one year (*7*). On the other hand, some patches lasted up to 5 years when using spray injection properly. It is worth noting that the service life of the throw and roll greatly depends on the patching materials utilized. The use of high quality materials extends the survival rate of the pothole by 50% for the throw and roll.

2.8 Tow-Behind Combination Infrared Asphalt Heater/Reclaimer

One of the main causes of failure of winter pothole patches when using the throw and roll and the spray injection patching methods is inadequate bonding between the patching material and the existing colder pavement material surrounding the pothole. The temperature difference can result in the separation of the two materials, which in turn creates a point of entry for debris and water to penetrate and may ultimately lead to the failure of the patch. The tow-behind combination infrared asphalt heater/reclaimer (Figure 2.2) can help in addressing the temperature difference problem encountered during winter pothole patching. This system consists of a reclaimer and a pavement heater. The reclaimer, a hopper that is heated by two infrared heaters, is designed to recycle asphalt material by reheating it to a workable temperature without burning it. This system enables hot patching mixtures to be created in cold weather conditions. The reheating process can take between 8 to 16 hours, depending on the ambient temperatures and the amount of asphalt that is being heated. This combination system also has an infrared pavement heater that is placed over the area to be repaired for 5 to 10 minutes to heat both the pothole and the surrounding area. This allows heating the existing pavement material to a temperature adequate for remixing, rejuvenation, and recompaction. A steel rake is typically used to square the area around the pothole and scarify the existing asphalt material. Recycled hot mix asphalt obtained from the reclaimer is then added and compacted with the existing asphalt material, creating a watertight, seamless patch. By creating a seamless patch, the infrared asphalt heater can improve the performance and longevity of the pothole patches. This eliminates the need to re-patch the same pothole and results in significant savings in labor, equipment, and traffic control costs as well as a reduction in user delays. The use of infrared asphalt heaters/reclaimer can also be considered an environmentally friendly patching method as it helps in reusing waste asphalt mixes and eliminates the need for new asphalt mixes.

Figure 2.2 Example of a Tow-Behind Combination Infrared Asphalt Heater/Reclaimer System

Despite the potential benefits from using the infrared heater/reclaimer system, no study has been conducted to evaluate its use in pothole patching and verify its benefits. One study (by the Utah Department of Transportation) was only found in the literature on the use of infrared asphalt heaters for pothole patching. This study demonstrated the use of an infrared heater called Heatwurx for pothole patching at two locations (*10*). The results showed that based on preliminary data and observations, the Heatwurx process appeared to provide a better fusing of the repaired area to the surrounding pavement than conventional patching methods. Other states reported the use of infrared asphalt heaters for other applications related to pavement maintenance and construction practices such as alligator cracking, failed joints, and bridge joints, but not for pothole patching (*11*, *12*). For example, the Tennessee Department of Transportation conducted a study to evaluate the use of different longitudinal joint construction techniques including an infrared heater (*11*). This study demonstrated the infrared heater exhibited the best performance among all other joint construction techniques. The infrared heater was effective in reducing the air void content and water permeability as well as increasing the indirect tensile strength of asphalt cores obtained at the longitudinal joints.

2.9 Summary

In this chapter, the throw and roll, spray injection, and infrared asphalt heater methods were discussed. In addition, best practices for these pothole patching methods were provided. The results of the literature review conducted in this study, indicated that there are several factors that should be considered to select the best method to patch a pothole, including: the size of the pothole, crew size required, productivity rates, and life cycle costs. Despite the advantages that the throw and roll and spray injector methods have, one main limitation for these methods when used in winter pothole patching is the inadequate bonding between the patching material and the existing pavement materials surrounding the pothole, which mainly results from the formation of cold joint between these materials. Based on the previous discussion, the use of the infrared asphalt heater/reclaimer system has the potential to solve this problem and to improve the performance of winter pothole patching and reduce its cost. In addition, it may also provide a more economical solution to other pavement maintenance problems when compared to conventional methods currently being used. However, research is needed to validate the cost-effectiveness and benefits of this method and identify its limitations.

Chapter 3: Selection of Infrared Asphalt Heater/Reclaimer

Several infrared asphalt heaters/reclaimer systems are available in the market. This chapter presents the steps pursued to select the most suitable tow-behind combination infrared asphalt heater/reclaimer unit for use in pothole patching as well as other pavement maintenance practices in in Ohio.

3.1 Available Infrared Asphalt Heaters/Reclaimers

The research team identified the main tow-behind combination infrared asphalt heater/reclaimer systems that are available in the market and have been used for pothole patching as well as other pavement maintenance applications. The three infrared asphalt heater systems manufacturers, namely, Ray-Tech, Heat Design Equipment, and KASI were contacted to obtain price quotations and descriptions of their tow-behind combination infrared asphalt heater/reclaimer units (i.e. Ray-Tech Mini Combo, Heat Design Equipment HDE 750-MT, and KASI Minuteman) as well as the contact information of the users of their systems. The obtained prices for three systems are provided in Table 3.1.

Table 3.1 Prices of main tow-behind combination infrared asphalt heater/reclaimer systems

Equipment	Price of Equipment and Training ($)
Heat Design Equipment (HDE 750-MT)	$95,200.0
Ray-Tech Mini Combo	$49,790.0
KASI Minuteman	$59,960.0

As can be noticed from the information presented in Table 3.1, the HDE 750-MT infrared asphalt heater/reclaimer has much higher price than the other two equipments although it has similar features. This was discussed with ODOT technical panel members. Based on this discussion the technical panel members and research team have decided to focus on the other two equipments; the KASI Minutemen and Ray-tech Mini Combo, which had comparable prices. The proceeding section presents a summary of the comparison between these two systems.

3.2 Comparison Between KASI and Ray-tech Systems

The research team obtained information from KASI and Ray-tech website for the Minutemen and Mini Combo infrared heater/reclaimer systems. This information was used to evaluate and compare the two systems to determine the most suitable one for use in Ohio. Different factors were considered including: compatibility with ODOT equipment, pothole size range that can be repaired, operational costs, safety features, ease of operation, durability, life expectancy, and maintenance, and other possible applications of the equipment.

3.2.1 Compatibility with ODOT existing Equipment

The Ray-Tech equipment has 24-volt blower motor system. On the contrary, KASI equipment has a 12-volt brushless motor system that is compatible with ODOT truck 12-volt systems. Thus, KASI equipment is compatible with ODOT truck, while Ray-Tech is not.

3.2.2 Operational Costs

The Ray-Tech chamber has a propane consumption rate of 9.8 gallons per hour, while the KASI chamber has a consumption rate of 6.8 gallons per hour. Thus, the KASI system has 2/3 the operational cost of the Ray-Tech system.

3.2.3 Safety & Ease Of Operation

While the Ray-Tech chamber is raised and lowered by an electric winch and cable, the KASI chamber is raised and lowered by a dual cylinder hydraulic system eliminating the dangers of cable breakage and/or pulley issues. In addition, the Ray-Tech roller platform is accessed by a vertical winch tower, boom, and cable, which may pose potential injury issues. On the other hand, KASI incorporates the roller ramp system that eliminates the hazards associated with raising the 600 lbs roller on a cable and manually pushing the boom around for loading and unloading. The Ray-Tech reclaimer has manually operated top loading doors that require climbing onto the unit to open and close. The KASI reclaimer has hydraulically operated top loading doors operated from ground eliminating the potential for slipping or falling while opening and closing the top loading doors at the asphalt plant. Finally, the KASI system has all of the necessary lighting for safety including a 6 way LED light bar.

3.2.4 Durability, Life Expectancy, Maintenance of Equipment

Ray-Tech utilizes ceramic tile infrared burners in their reclaimers. These burners must be removed a minimum of once per year to have the fibrofrax replaced. On the other hand, KASI uses Solaronics nickel/chromium screen stainless steel shell infrared burners in its reclaimers eliminating ceramic tiles and fibrofrax, which may need to be replaced every 10 to 15 years depending on the usage. The Ray-Tech chamber support arms are carbon steel tubing. The KASI chamber support arms are stainless steel tubing.

The Ray-Tech converters must operate at 1850°F to be functional. This significantly shortens the life of the Inconel grids that generates the infrared. The KASI converters operate at a temperature of 1650°F, which may result in longer service life of the Inconel grids.

While the Ray-Tech system utilizes dual spring leaf 6,000 lbs axles, the KASI system employs dual 7,000 lbs Dexter Torflex axles which might be superior in handling and durability. Ray-Tech utilizes black iron pipe for all of their LPG lines; on the other hand, KASI uses continuous stainless steel tubing with Swagelok fittings, which eliminates any leak potential, debris potential or safety issue.

Based on this comparison, KASI equipment was found to more suitable to be used in Ohio, although it's a little bit more expensive.

3.2.5 Pavement Maintenance Application

The Ray-tech Mini Combo and KASI Minutemen were found to be used for pothole patching as well as other maintenance applications that include: Utility cuts, expansion joints, catch basins, trenches.

Based on the aforementioned comparison, the research team has consulted with the ODOT technical liaison and has decided to purchase the KASI Minuteman equipment for use in this study.

3.3 Procedure For Pothole Patching using KASI Minutment System

One of the main issues with using infrared asphalt heater/reclaimer method for pothole patching is following the right procedure. KASI has provided a procedure for pothole patching using their infrared asphalt heater/reclaimer. This procedure is demonstrated in Figure 3.1 and was used and evaluated in this study. It is noted that a revised version of is provided in Appendix D.

1. CLEAN & MARK OUT REPAIR

2. LIGHT THE INFRARED HEATER

3. LOWER HEATER OVER REPAIR

4. SCARIFY THE DAMAGED AREA

4. APPLY REJUVINATOR

5. ADD VIRGIN ASPHALT

Figure 3.1 KASI Recommended Infrared Pothole Patching Procedure

7. LUTE THE ASPHALT SMOOTH

8. PATCH IS READY TO ROLL

9. THE EDGES ARE ROLLED FIRST

10. COMPACTION IS COMPLETED

Figure 3.1 KASI Recommended Infrared Pothole Patching Procedure (Continued)

Chapter 4: Results of Infrared Users Survey

This chapter presents the survey approach pursued in this study to collect information from the users of tow-behind combination infrared asphalt heater/reclaimer regarding their experience. In addition, it provides a summary of the survey responses and the key findings.

4.1 Survey Procedure Steps

The following steps were followed for conducting the survey. A 10-question survey containing primarily multiple choice- type questions was first developed. A copy of the prepared survey was sent for review to ODOT technical panel member and is provided in Appendix A. The survey was then implemented in SurveyMonkey for distribution as a web survey. The email addresses of the users of the infrared asphalt heater/reclaimer systems that were obtained from the three asphalt heater manufacturers (Ray-Tech, Heat Design Equipment, and KASI) were inserted in the SurveyMonkey. A unique link was then created and emailed using SurveyMonkey for each of the provided users.

The survey participants were provided ten days to complete the survey. A reminder email was sent to the participants that did not respond after the first week. In addition, those who did not respond after ten days were contacted via phone and asked to complete to the survey. Based on the responses, a few respondents were contacted for additional questions and to review certain responses. These interviews were conducted to clarify any discrepancies found in the questionnaire or to obtain additional information.

A Microsoft Excel file with the collected survey data was downloaded from SurveyMonkey. These results are presented in Appendix B. A summary of the obtained results with explanations are provided in the proceeding section.

4.2 Survey Results

The survey was sent to 28 users, and a total of 12 responses (43%) were received. In the survey analysis presented here, the total number of responses used is 12. Salient details of the surveys are presented in this chapter; the rest of the details are provided in Appendix B.

About 75% of the respondents have owned the infrared heater/ reclaimer for more than one year. As shown in Figure 4.1, all users have noticed an improvement in the performance and the longevity of pothole patches where an infrared heater/reclaimer was used. In addition, more than 90% indicated that this improvement was significant. This improvement was reflected in the cost-effectiveness of infrared heater/reclaimer; such that more than 90% of the users suggested that it was more cost effective than other patching methods, Figure 4.2. In addition, the responses to question 10 (Appendix B) indicated that all users who were surveyed indicated that they were satisfied with this equipment.

With respect to the factors affecting the infrared asphalt heater improvement, 9 of the 12 respondents indicated that weather conditions during patch installation is one of those factors, as shown in Figure 4.3. Few respondents, who were further interviewed over the phone after completing the survey, indicated that rain adversely affects the capabilities of the infrared asphalt heaters if water accumulates in the pothole. The reason is that infrared rays do not penetrate puddled water. It is worth noting that moisture and dampness do not affect infrared. In addition, the users who were subsequently interviewed stated that wind and very cold temperatures prolong the heating time.

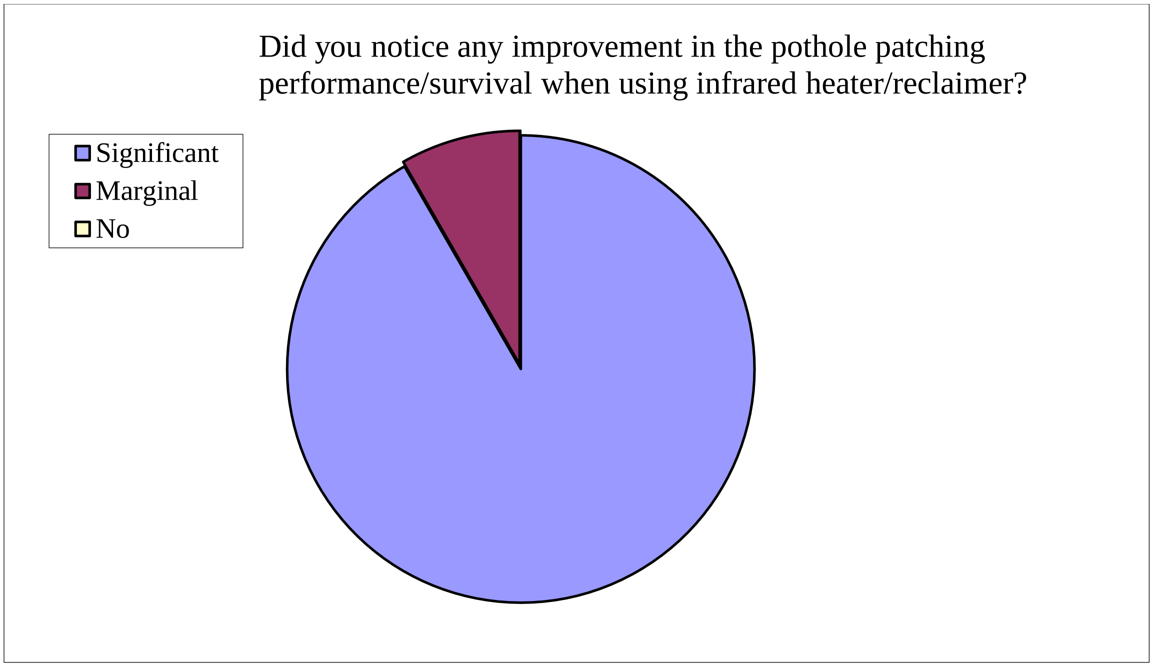


Figure 4.1 Infrared Asphalt Heaters/Reclaimers Improvement

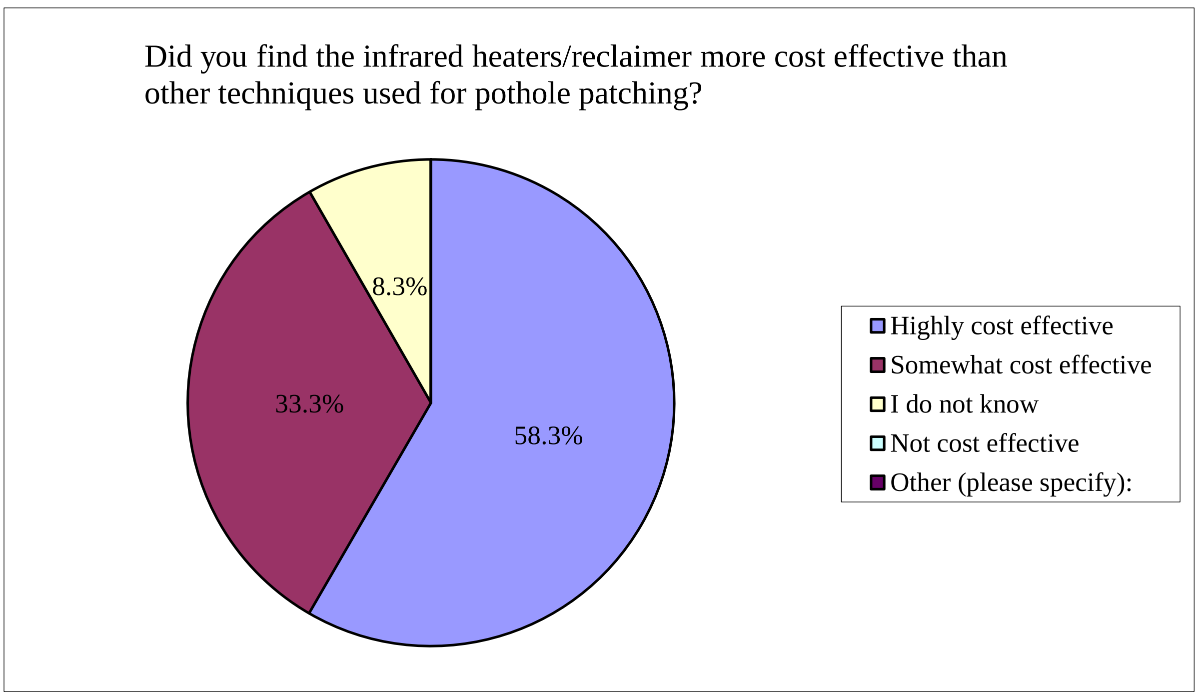


Figure 4.2 Infrared Asphalt Heater/Reclaimer Cost Effectiveness

As shown in Figure 4.3, more than 40% of the respondents indicated that pavement type plays a significant role in the improvement achieved using the infrared heater method. In general, better results are obtained for potholes in flexible pavements compared to composite pavements. However, this also depends on the thickness of asphalt layers and the properties of existing asphalt mixtures such as aggregate size. In addition, the asphalt content of existing pavement also plays a big factor on how the edge lines of a patch ties in.

Another factor that 5 out of 12 respondents have identified to affect the improvement of the infrared heater method is the patching material. As shown in Figure 4.4, more than 80% of the respondents have used virgin asphalt mixture that was reclaimed using the infrared asphalt heater/reclaimer system. In addition, about 60% of respondent have indicated that they used 10 to 30% reclaimed asphalt pavement (RAP) material in patching using the infrared heater. One respondent has used more than 50% RAP but with a rejuvenating agent.

The survey also was used to identify the procedure/measures that were followed to ensure optimal usage of infrared heater equipment in pothole patching. In this regards, six respondents have provided helpful guidelines that should be followed, which include: 1- patching material has to be stored dry, 2- The operator must follow the proper procedure recommended by the manufacturer and make sure the pothole area is heated long enough, 3- Timing is critical: the repair must be "seamed" when temperatures are still high to ensure a solid seam, 4- Quantity of virgin asphalt must be monitored carefully as patching crew may mix more of the existing asphalt, which will cause raveling around the edges.

Figure 4.5 presents the survey responses related to the main drawbacks of using infrared asphalt heater/reclaimer equipment. It is noted that about 35% have indicated that there was no drawback for using this equipment. In addition, two out of 12 respondents suggested that the traffic control and the equipment maintenance are the main issues when using this equipment. One respondent using the Ray-Tech Mini Combo has identified the following problem that was not included in the list: loading the reclaimer box requires a machine with a narrow bucket, but with enough height. However, this problem has not been identified by the KASI Minuteman users.

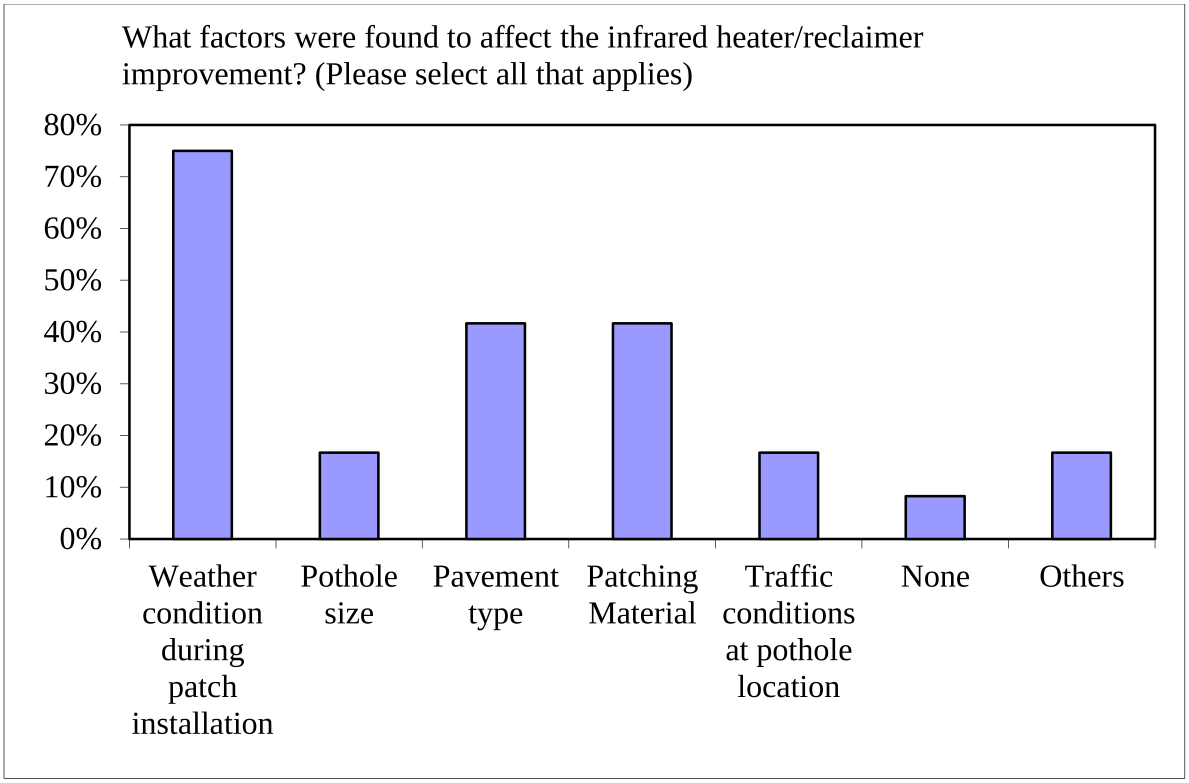


Figure 4.3 Factors Affecting Infrared Asphalt Heaters/Reclaimers Improvement

Finally, in regards to other pavement maintenance applications for the infrared asphalt heater/reclaimer equipment. As can be noticed in Figure 4.6, 90% of the respondents had used the infrared asphalt heater/reclaimer equipment for utility cuts. Furthermore, most respondents have used it in expansion joints and trenches. The least used application by the respondents was catch basins. Other applications that were not listed in the survey and the respondent provided include: spider web and facial cracks, water pockets, and curbing.

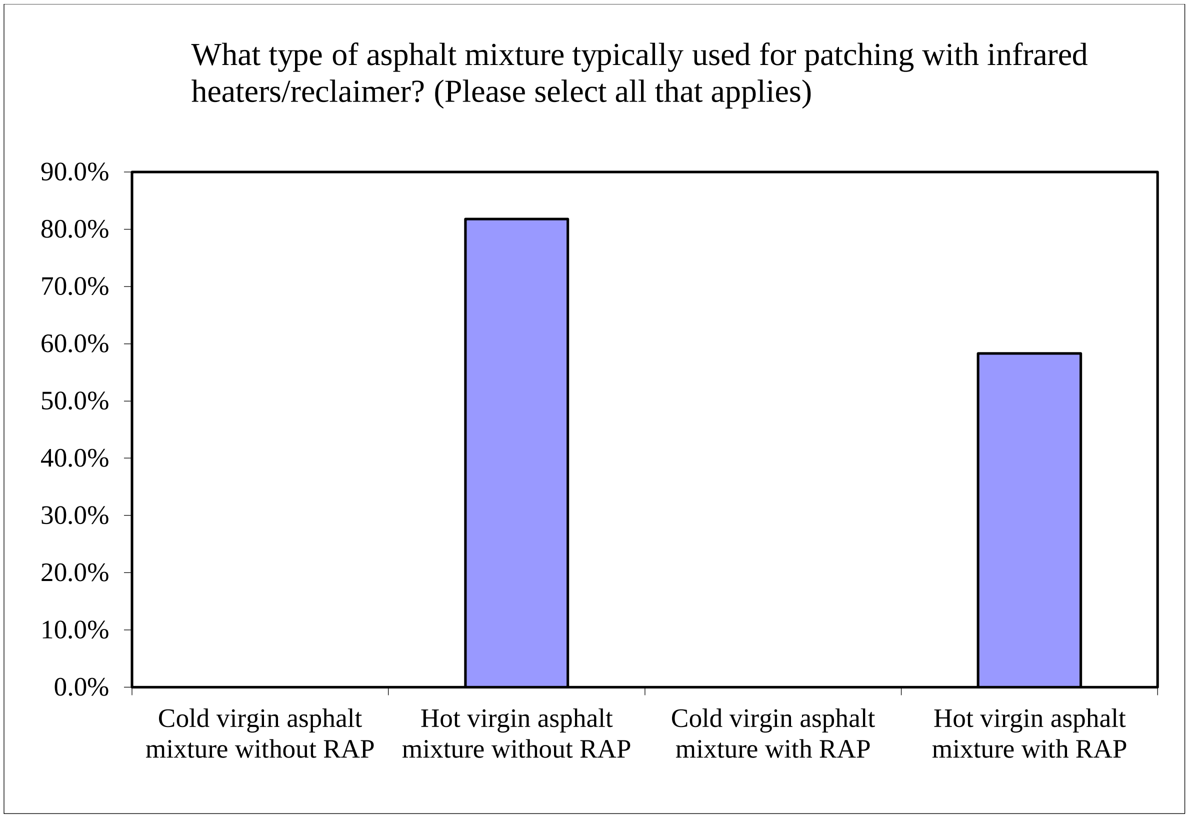


Figure 4.4 Type of Mixture Used for patching with Infrared Asphalt Heaters/Reclaimers

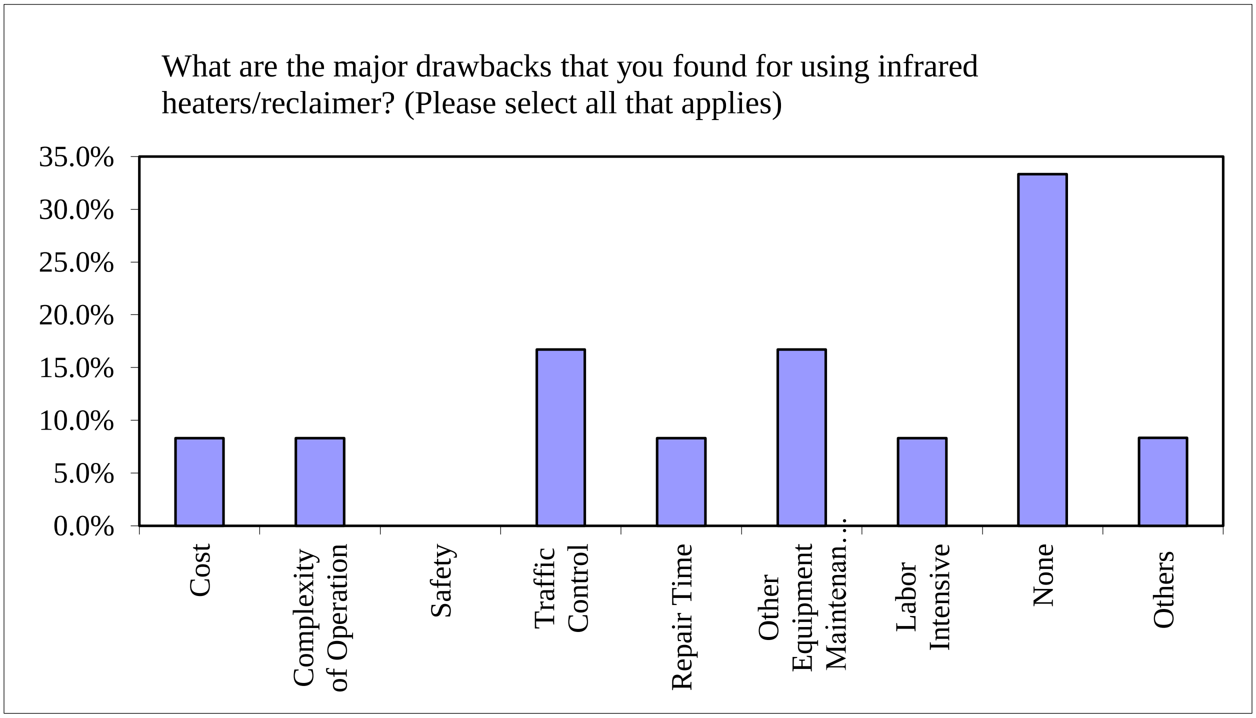


Figure 4.5 Main Drawbacks of Infrared Asphalt Heaters/Reclaimers

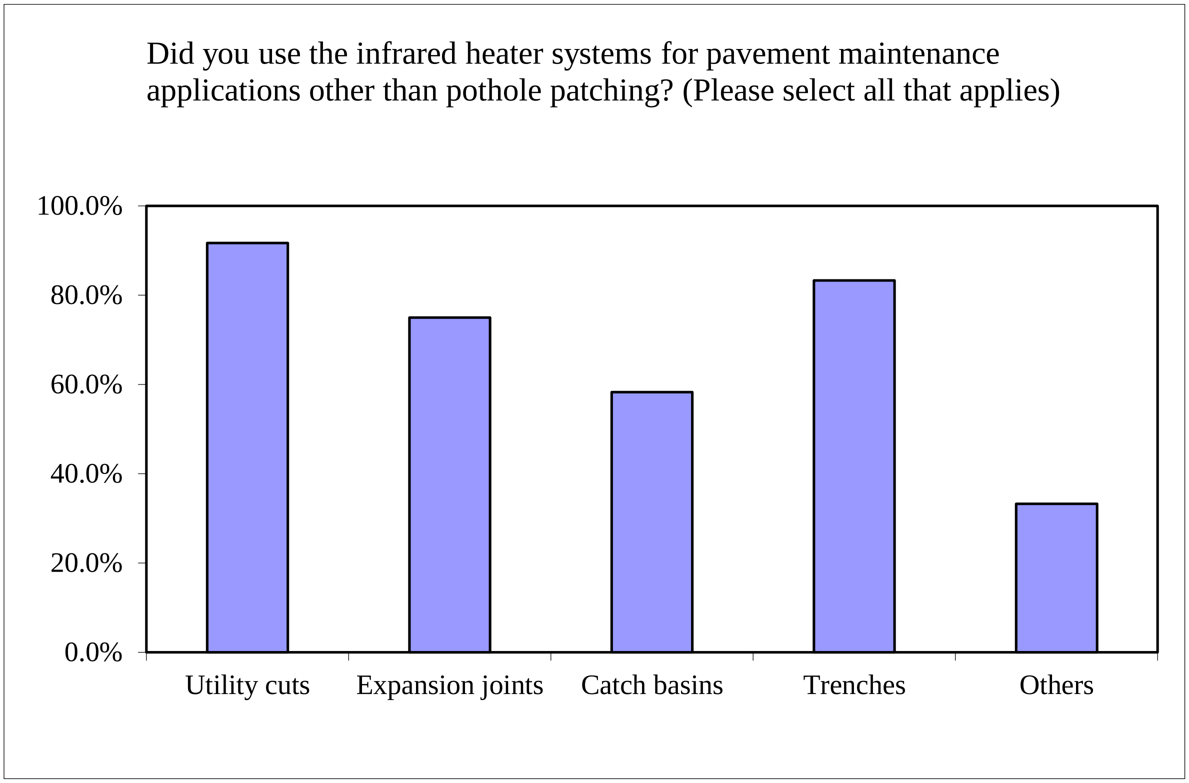


Figure 4.6 Other Pavement Maintenance Applications for Infrared Asphalt Heater/Reclaimer

Chapter 5: Testing Program

5.1 Introduction

A testing plan was developed in this project to evaluate the performance, cost-effectiveness, and limitations of the infrared asphalt heater/reclaimer method and compare it to those of the throw and roll and the spray injection patching methods. In addition, the testing plan examined the potential of using infrared asphalt heater/reclaimer method in different applications within ODOT pavement maintenance operations. The following sections provides a description of the performed testing program and the all the data collected as part of this program.

5.2 Description Of Testing Program

The research team consulted with ODOT highway management administrators in Districts 12 and 2 in selecting sites for the installing patches using the three different methods considered in this study. More than 60 patches were installed at six different sites in ODOT Districts 12 and 2. Figure 5.1 shows the locations of the testing sites. The following sections provide a description of each of those sites and the main observations noted during the installation procedure.

5.2.1 Site 1: Interstate 480

The first testing site was located on the outer lane of the east bound of Interstate 480 (I-480) between mile posts four and five. Figure 5.2 presents a Google map of this site. In this site, 45 man-made potholes were created and patched on January 9, 2013. All potholes were created by ODOT by drilling holes in the pavement that are 3 to 4 ft wide, 3 to 5 ft long, and 3 to 4 inch deep and cleaning them. The pavement structure in this site consisted of the following layer: 1.5” asphalt concrete surface course layer, 3.5” asphalt concrete intermediate course layer, and 9” Portland cement concrete base layer, 6” aggregate subbase layer. Figure 5.4 presents the testing layout for potholes at this site. The spacing between potholes was 40 ft, while avoiding creating a pothole on cracked areas of the pavement. Each of the three methods evaluated (i.e. throw and roll, spray injection, and asphalt heater/reclaimer patching methods) were used to patch 15 potholes. In addition, for each method 10 of the patched potholes were located on wheel path, while the other five were between the wheel path. It is worth noting that man-made potholes were used to ensure that the performance of the various pothole patching methods were evaluated under the same conditions.

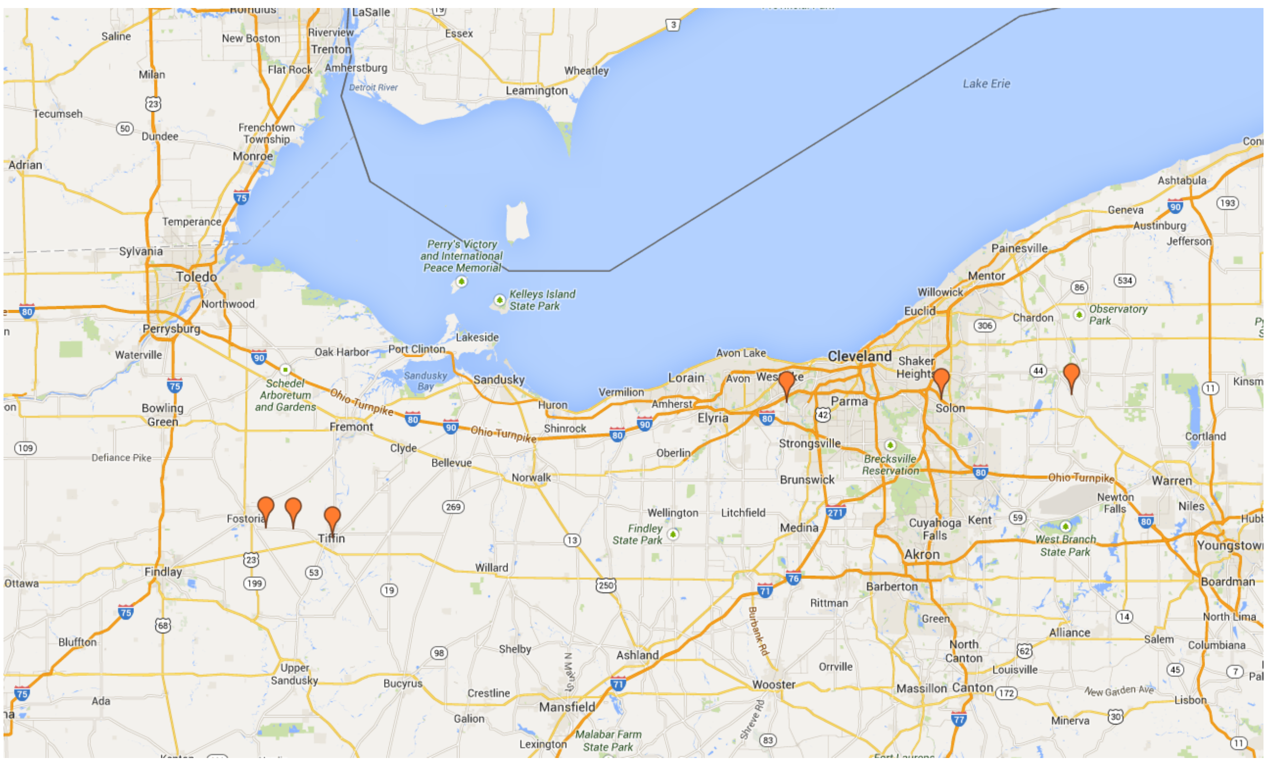


Figure 5.1 Locations of Testing Sites

The throw and roll patching procedure involved first throwing the cold mix into the pothole and then compacting it by driving a truck tire over it. For the spray injection method, the procedure included: 1) spraying the bottom and sides of pothole with binder material to act as tack coat, 2) spraying aggregate and binder into the pothole simultaneously until it is filled just above the level of the surrounding pavement, 3) covering the top of the patch with a layer of aggregate and 4) compacting the patch with a vibratory roller. It is noted that the last step is typically not done in spray injection method. For the infrared method, a similar procedure as that described in Figure 3.1 (Chapter Three) was followed. For each pothole, a patch ID was labeled on the shoulder and guardrail. Pictures were taken for all potholes before and after installation of the patches. Figure 5.3 depicts pictures of the some potholes before and after patching.

Figure 5.2 Google Map Of The Testing Site At I-480

Main Observations

During the installation of pothole patches at I-480 the following observations were noted:

General

1. The potholes seemed too clean when compared with real potholes on highways. In addition, no water was present in any of the pothole.
2. The surface of the potholes made at this site consisted mainly of uncoated aggregates. However, the surfaces of naturally occurring potholes typically consist of

asphalt coated aggregates. Thus, this may cause poorer performance of the control pothole patches than that of patches of natural potholes.

Figure 5.3 Pictures of Potholes Before And After Patch At I-480

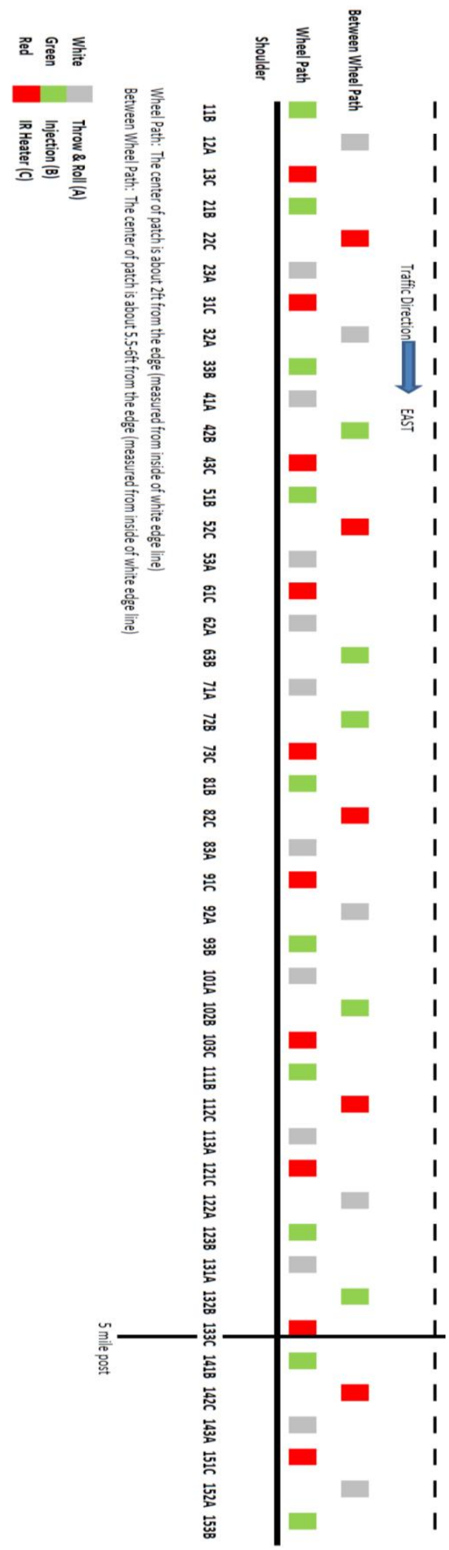


Figure 5.4 Layout of Potholes Installed at I-480

Throw and roll method

3. The patching material used for the throw and roll method was the regular cold mix ODOT typically used. The material for most patches was contaminated with many leaves, incompletely coated aggregates (grayish colored), and uncoated big rocks. While the uncoated big rocks were manually thrown out by the patching crews, leaves and incompletely coated aggregates were routinely included in the patching operation. Figure 5.5 shows a picture of the cold-mix patching materials contaminated with leaves.
4. The throw and roll procedure used in this project was slightly different than that typically used by ODOT, as the patches were compacted driving a truck tire over it.

Spray Injection Method

5. While the operator in the spray injection method coated the surrounding top surface with binder, he did not completely coat the sides of potholes as shown in Figure 5.6.
6. The spray injection hose had to be cleaned due to cooling down when not in use. This can be a serious problem in routine patching operation where the time interval from one pothole to the next can be relatively very long.

Figure 5.5 Throw-And-Roll Cold Mix Patching Material At I-480

Infrared Heater Method

7. Big lumps of patching mix were observed in the reclaimed patching material. This mainly resulted from the method in which the asphalt mixture was stored. The storage method involved obtaining the asphalt mixture from the asphalt plant at the end of construction season and dumping it in one large pile under the shed. Thus, when reclaiming the mixture, large pieces were placed in the reclaimer, which were not totally reheated and resulted in having large lumps in the patching material.
8. The infrared method requires rolling parallel and across the traffic direction. The across rolling could increase the probability of accident with running traffic.
9. There were problems with igniting the infrared heater for the first time in very cold weather. This problem was attributed to equipment storage method. When contacted, the manufacturer suggested that the problem might be solved by proper storage of the equipment.

Figure 5.6 A Picture Taken During Patching A Pothole At I-480 Using Spray Injection Method

5.2.2 Site 2: US Highway 422

In this site, a large area (12 ft by 12 ft) of the pavement on the outer lane of the east bound of US highway 422 near Solon, Ohio had significant amounts of cracking (Figure 5.7), which posed danger to moving traffic. Five patches were installed using the infrared asphalt heater/reclaimer on February 07, 2013 to repair the distressed area of the pavement. Figure 5.8 presents pictures that were taken of the installed patches. The same procedure was followed as those used in the first site at I-480. Although the infrared heater/reclaimer was parked outside the garage only the night before the installation for reclaiming the asphalt patching material, problems in igniting the infrared heater reoccurred in this site. The manufacturer was contacted again and he suggested the following steps to solve this problem:

1- Draining manifolds at the bottom of the infrared chamber by opening the drain plugs (see Figure 5.9) protruding from bottom of each manifold.
2- Lowering the infrared chamber all the way down when the unit is outside. If moisture that enters freezes, the manifolds need to be warmed with the drain plugs out to get the water out. It is noted that it takes very little in the manifolds to disrupt the air/LPG vapor flow because it is such a low pressure system.
3- When the unit is inside the blower motor should be removed and covered.

5.2.3 Site 3: State Route 168

This site is located on Ohio state route 168 in Geauga County in ODOT District 12. In this site, the infrared asphalt heater and throw and roll were used to install spot patches to repair the damage in the pavement surface layer that resulted from grinding and skidding action of the horseshoes worn by horses that pull Amish buggies. The installation took place on June 19, 2013. Figure 5.10 shows pictures of some of the repaired areas before patching. Three methods were used to perform the repairs using the infrared asphalt heater. The first method involved heating the area to be repaired, scarifying it, adding a small amount of the new asphalt mixture (two shovels for an area of 4x6 ft), and compacting the existing and new mixture.

Figure 5.7 Distressed area on US 422

Figure 5.8 Patches Installed At US 422

Figure 5.9 Drain Plug at the Bottom Of Each Manifold In The Infrared Heater

In the second method, the repair was done in the same way as in the first method but without the addition of any new material. Finally, the third method included adding the same amount of asphalt mixture that was used in throw and roll (about 10 shovels for area of 4x6 ft). All asphalt materials used in patching at this site was not reclaimed, but it was obtained from the asphalt plant and placed in conventional harpers typically used by ODOT maintenance crew. Figure 5.11 through 5.13 present pictures of patches installed using the three methods, respectively. It was clear that the patches installed in the second method were not as good as other two methods; yet the patch was holding up without the addition of any new asphalt material.

Figure 5.10 Pictures Taken of Distressed Area at SR 168

5.2.4 Site 4: State Route 67

The main objective in this site was to demonstrate and evaluate the ability the infrared heater to repair pavement surface due to settlement in three trenches located between mile posts 6 and 7 along Ohio state route 67. The trenches at this site were at least 15 ft wide. For the first trench, asphalt mixtures were directly obtained from the asphalt plant by filling the infrared reclaimer. No problems were observed during the loading of the asphalt mixture at the asphalt plant, but it was necessary to guide the truck driver to make sure that he stops at the right spot under the asphalt silo during loading. Figure 5.14 shows pictures taken during loading the infrared asphalt heater/reclaimer at the asphalt plant.

During the patching of the pavement in the first trench it started raining, and the installation had to be stopped and completed in another day. It was decided to keep the asphalt mixture in the reclaimer and reheat it again the night before the next installation. However, it was found that this could not be done and it was very difficult take out the reheated asphalt material. Based on that, it is recommended to empty the infrared reclaimer and discard all of the asphalt mixture remaining in it at the end of the patching day. The maintenance crew obtained new amounts of the same asphalt mixture, but they stored them in small piles about 1.5 ft by 1.5 ft as recommended by the infrared heater/reclaimer manufacture. Figure 5.15 shows picture of the stored asphalt mixtures blocks. For the other trenches, the blocks were placed in the infrared reclaimer and the reclaimed asphalt material was used in patching.

Figure 5.11 Patches Installed Using Infrared Method 1 at SR 168

Figure 5.12 Patches Installed Using Infrared Method 2 at SR 168

Figure 5.13 Patches Installed Using Infrared Method 3 at SR 168

Figure 5.14: Pictures Of Loading The Infrared Reclaimer With Asphalt Materials At The Plant

Figure 5.15 Asphalt Patching Materials Stored In Small Piles

During patching in this site, it was very difficult to maintain the same surface level along the entire patched area as the infrared chamber needed to be moved several times for heating the area. Such that the repaired area was not as smooth as that done using the conventional ‘mill and fill’ method, which is typically used by the maintenance crews for performing such repairs. Based on the work done in this site, it was concluded that it is difficult to use the infrared heater for patching trenches with width greater than twice that of the asphalt heater chamber (8 ft).

5.2.5 Site 5: State Route 18

In this site, the infrared heater was used to repair the pavement surface due to settlement that occurred in three trenches located at Ohio state route 18, Figure 5.16. The installation took place during the month of July. The width of trenches at this site ranged between 3 ft to 6 ft. The same patching material as that used in the previous site was utilized. No problems were observed during patching of the trenches. In addition, as shown in Figure 5.17 smooth patches were achieved using the infrared heater at this site. This demonstrates the ability of the infrared heater to repair surface settlement problems in trenches that are up to 6 ft wide.

Figure 5.16 One of the Trenches at Ohio State Route 18 Before Repairing It

Figure 5.17 Infrared Patches installed at Ohio State Route 18

5.2.6 Site 6: State Route 635

In this site that infrared asphalt heater/recalimer system was used to repair shoving in the pavement surface that occurred near an intersection on Ohio SR 635, Figure 5.18. It was clear that problem in the pavement surface resulted from loss of contact between surface and binder course layers. Some difficulties were encountered during patching at this site as the surface had chip seals, which was burned during heating and was difficult to scarify and compact. However, the patch was successfully installed as shown in Figure 5.19. Based on the problems encountered during patching in this site, it is recommended not to use the asphalt heater/recalimer system to repair pavement surfaces with chip seals.

Figure 5.18 Distressed Pavement Area That Was Patched at Ohio SR 635

Figure 5.19 Patch Installed Using Infrared at Ohio SR 635

5.3 Development of Interactive Database

An interactive database was developed to assist in collecting, storing, processing, and analyzing the field data. This database was developed using Microsoft Visual Basic for Applications and Microsoft Access. The interface has two basic input modules, namely (1) pothole information and installation data, and (2) performance data. The first module consisted of all installation information and included the following inputs: site location, pavement type, list of pavement structure layers, pothole dimensions (width, length, depth), patching method, patching id, name(s) of person(s) recording the data, time and date of installation, air and pavement temperatures, pavement condition, weather condition, patching material type, amount of patching material used, temperature of patching material (at container), crew size, equipment used, duration of infrared pavement heater placement, installation duration, temperature of the bottom of pothole before and after infrared pavement heater placement, temperature of the materials surrounding of pothole before and after infrared pavement heater placement at 6 inch , compaction temperature immediately before compaction. Figure 5.20 presents a screen shot of this module. The second module consisted of a table of the different types of patch distresses along with their rating criterion developed in the Strategic Highway Research Program (SHRP) studies (*2*). Figure 5.21presents a screen shot of this module.

5.4 Performance Data Collection

Field inspections were conducted 29, 66, 99, 161, and 188 days following the patching of potholes in the first site at I-480. In addition, the patches in the second site at US 422 were evaluated only for the first two months as the roadway was rehabilitated in the fourth month. Finally, the repairs in the other sites were inspected after one month except for those on Ohio state route 68 since repairs were redone using the conventional 'fill and mill' method.

Figure 5.22 depicts pictures taken during performing the field evaluation. Two main types of data were collected during the field evaluations of pothole patches to monitor and evaluate their performance longevity. The first includes survival data, which refers to the number of patches that are still in service. The second consists of distress data obtained through visual surveys of the installed patches, including bleeding, cracking, dishing, edge disintegration, missing patch, raveling, shoving, and lack of adhesion to the side or bottom of the repair. Photos were taken to document the distresses observed in the patches.

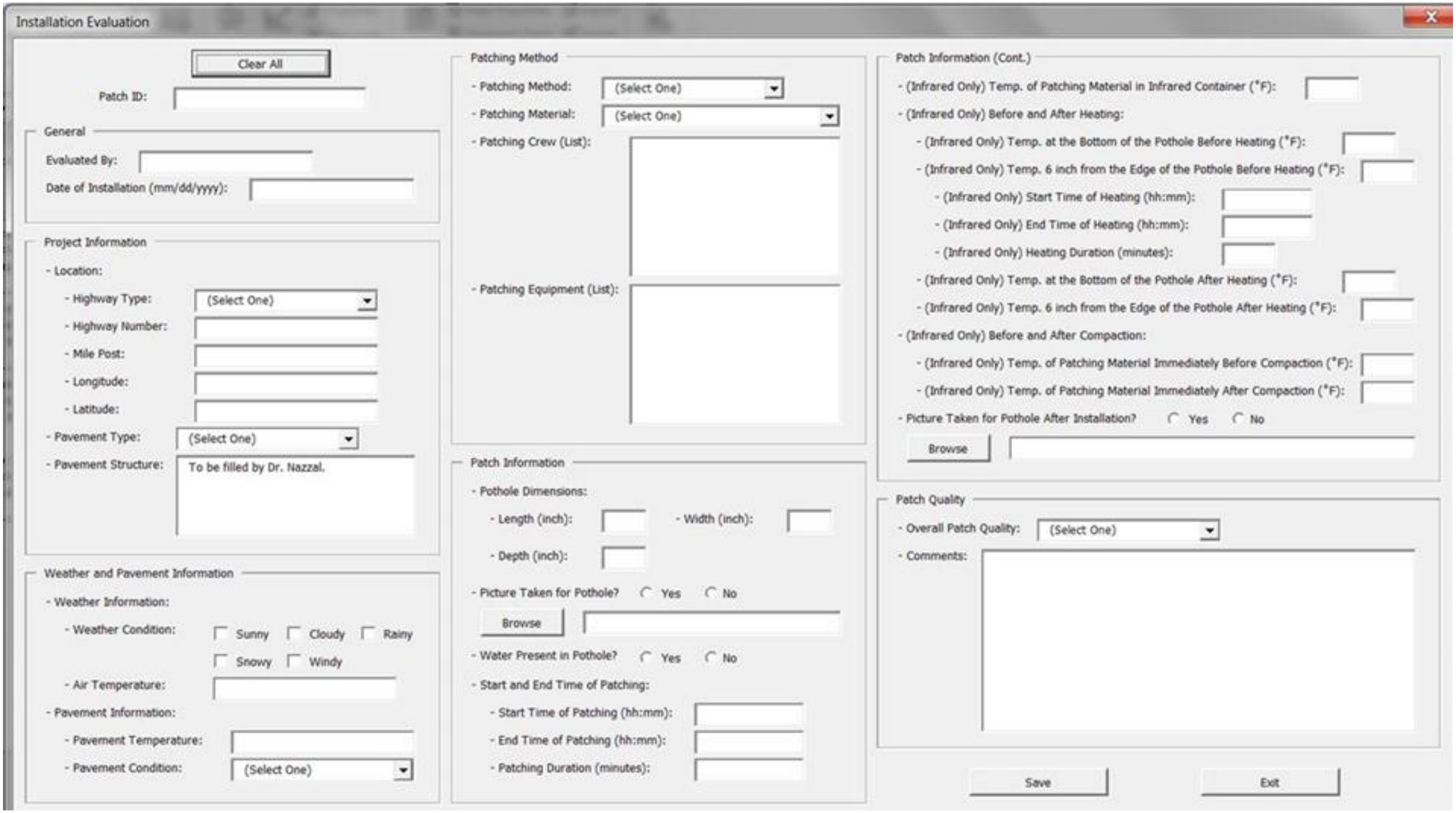
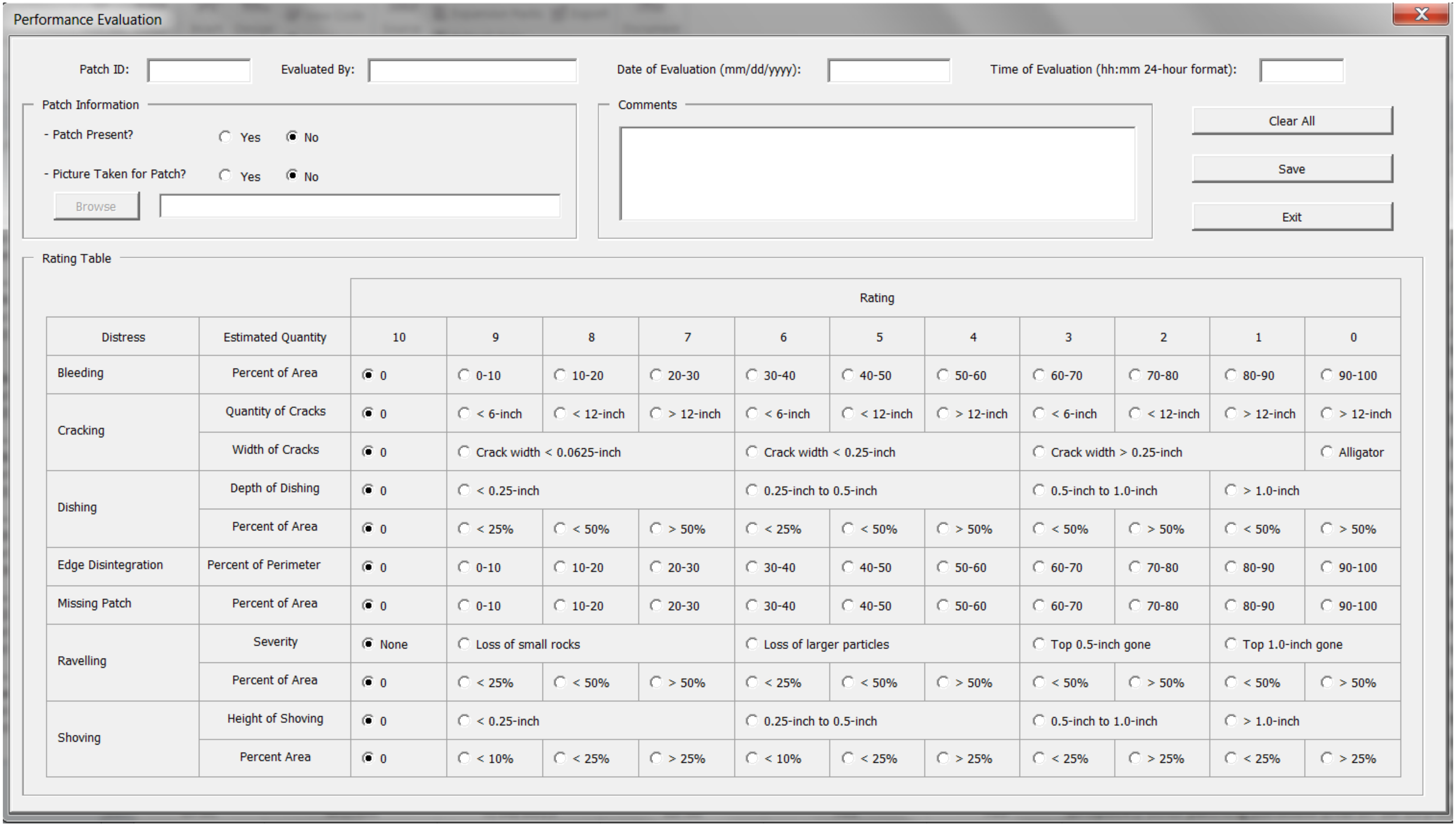


Figure 5.20 Screen Shot Of The First Module To Record Installation Data



Performance Evaluation

Patch ID: Evaluated By: Date of Evaluation (mm/dd/yyyy): Time of Evaluation (hh:mm 24-hour format):

Patch Information

- Patch Present? Yes No
- Picture Taken for Patch? Yes No

Browse

Comments

Clear All

Save

Exit

Rating Table

		Rating										
Distress	Estimated Quantity	10	9	8	7	6	5	4	3	2	1	0
Bleeding	Percent of Area	0	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
Cracking	Quantity of Cracks	0	< 6-inch	< 12-inch	> 12-inch	< 6-inch	< 12-inch	> 12-inch	< 6-inch	< 12-inch	> 12-inch	> 12-inch
	Width of Cracks	0	Crack width < 0.0625-inch			Crack width < 0.25-inch			Crack width > 0.25-inch			Alligator
Dishing	Depth of Dishing	0	< 0.25-inch			0.25-inch to 0.5-inch			0.5-inch to 1.0-inch		> 1.0-inch	
	Percent of Area	0	< 25%	< 50%	> 50%	< 25%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
Edge Disintegration	Percent of Perimeter	0	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
Missing Patch	Percent of Area	0	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
Ravelling	Severity	None	Loss of small rocks			Loss of larger particles			Top 0.5-inch gone		Top 1.0-inch gone	
	Percent of Area	0	< 25%	< 50%	> 50%	< 25%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
Shoving	Height of Shoving	0	< 0.25-inch			0.25-inch to 0.5-inch			0.5-inch to 1.0-inch		> 1.0-inch	
	Percent Area	0	< 10%	< 25%	> 25%	< 10%	< 25%	> 25%	< 25%	> 25%	< 25%	> 25%

Figure 5.21 Screen Shot Of The Second Module To Record Performance Data

Figure 5.22 Pictures Taken During Evaluation of Potholes Patches at I-480

Chapter 6: Results and Analysis

This chapter presents a summary of the installation and performance data that was collected at the different sites in this study. In addition, it also discusses the statistical analyses that were conducted on the collected data to evaluate and compare the performance and longevity of the patches installed using the three different patching methods. Finally, this chapter documents the results of cost-effectiveness analyses that performed in this study.

6.1 Patching Duration

Each patching method consists of different activities. Therefore, the beginning and ending times were recorded during the installation of each pothole patch, and the elapsed time from beginning to end of patching was computed. Thus, the patching duration for each of the three techniques was determined. During patching two potholes with the infrared method there were problems in igniting the infrared heater, which significantly increased the patching duration. In addition, the spray injection equipment had to be cleaned during the patching of one of the potholes due to cooling down when it was not in use, this resulted in a much longer patching time for that pothole as compared to others. Therefore, the average patching time for the infrared and the spray injection methods was computed with and without including the patches in which problems in the equipments encountered. Figure 6.1 presents the average and standard deviation values for patching time for each of the three methods that was recorded at I-480 site. It is clear that the infrared method took significantly longer duration than the other two methods. This is mainly due to the heating of the existing pavement material which taken between 7 to 10 minutes in very cold temperatures. The spray injection method took about one and half the time that the throw-and-roll method takes.

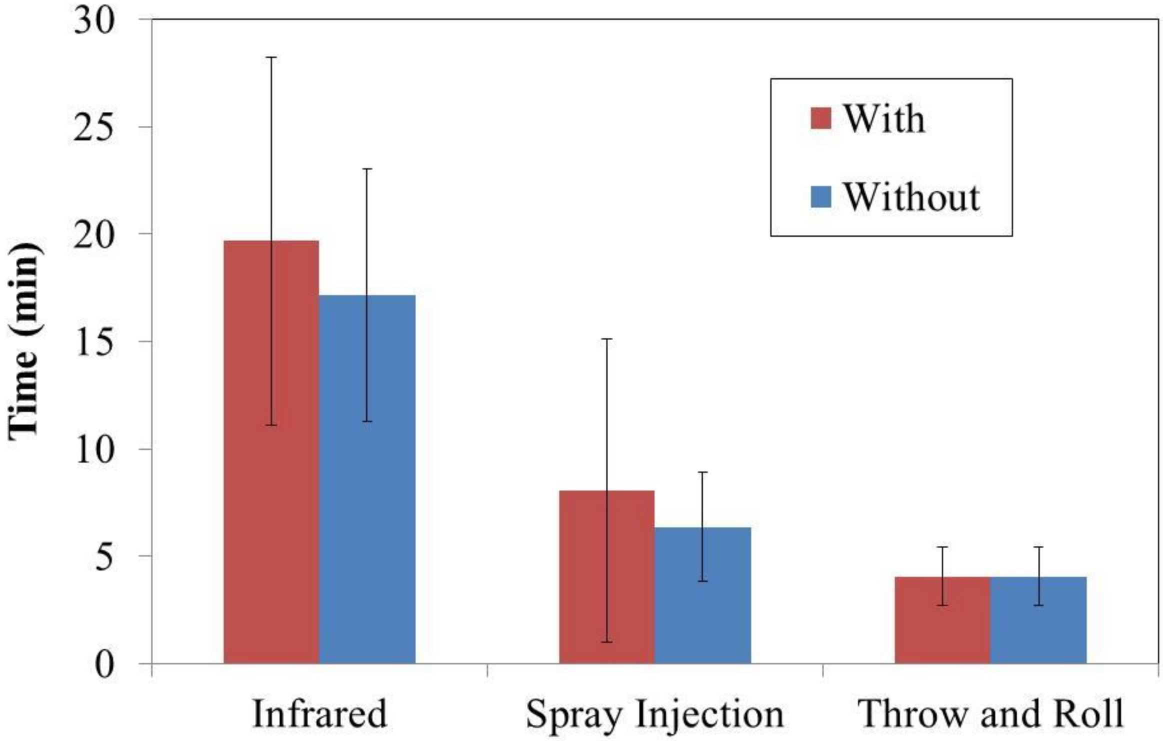


Figure 6.1Average Patching Duration of the Different Patching Methods with or without Patching Operation Encountered Problems

6.2 Productivity

One of the main objectives of this study was to document the productivity of considered pothole-patching methods: infrared heater/reclaimer, spray injection, and throw-and-roll methods. During the first test site installations patching time, and the size of the potholes data were collected on 45 potholes installed using the three different patching methods. By combining this information the productivity of the patching methods was computed using the following equation

$$P = (V_{avg}/T_{avg}) \text{ x } (\gamma) \text{ x } (1/2{,}000 \text{ ton/lb}) \text{ x } (60 \text{ min/hr}) \text{ *}(4 \text{ hr/day}) \quad (1)$$

where

P = Productivity of the patching crew, tons per day

γ = Patch density, lb/ft^3

V_{avg}= Average volume of the potholes being patched using given method, ft^3

T_{avg}= Average time required to patch the potholes using given method, minutes

A density value of 125 lb/ft^3 was used for throw-and-roll and spray injection, which was the value used in a previous study (*2,8*). In addition, a higher density value of 130 lb/ft3 was assumed for the infrared patches. It is worth noting that the value computed using Eq. 1 gives the productivity for the entire crew assuming that patching is performed for half of an 8-hour day. This assumption was made as the actual percent of a day spent patching versus setting up traffic control, taking breaks, or traveling between pothole locations could not be taken into account in this project. Figure 6.2 presents the average productivity of the three considered methods. The throw and roll method had the best productivity, which was 4 times that of the infrared method. In addition, the spray injection had more than double the productivity of the infrared method. It is worth noting, that the potholes created for this project were man-made, so data were lacking as to how far apart naturally occurring potholes would be spaced. The distance between pothole locations affects how much time is spent traveling between patch locations and might results in different average productivity numbers for some method.

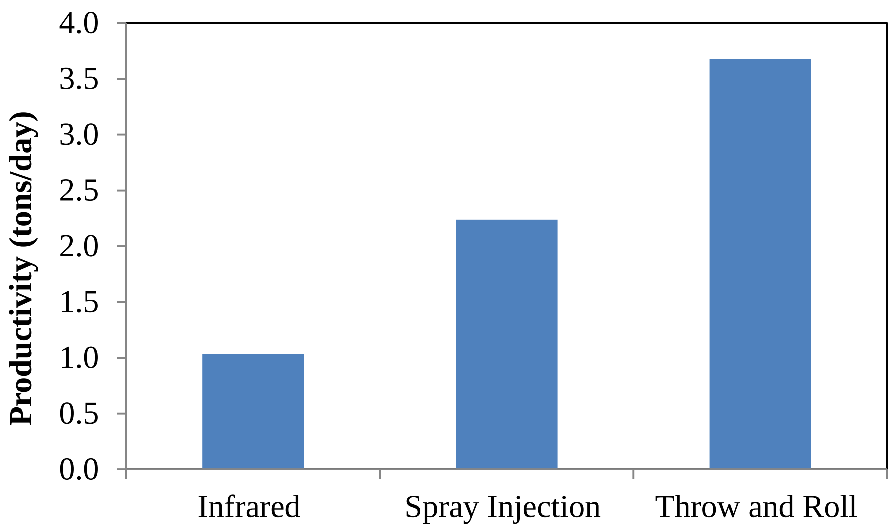


Figure 6.2 Productivity of Patching Methods

6.3 Temperature Data For Infrared Heater

For all patches installed using the infrared heater/reclaimer unit the pavement temperatures were recorded before and after installation. Figure 6.3 shows the pavement temperatures recorded before and after heating for patches versus the infrared heating duration. The pavement temperatures varied between 250 °F to 500 °F, with the majority of recorded points between 275°F and 375°F, which is the temperature range recommended for proper repair. In general, the infrared heating duration needed to achieve the proper pavement temperature ranged between 3 to 10 minutes. It clear that longer time was needed when the initial pavement temperature was below 50 °F. For such low temperatures 7 to 10 minutes was needed to achieve the required pavement temperature. It is worth noting that the temperatures achieved with the infrared heater are a function of the elevation of the infrared heater chamber from the pavement surface. Typically, the infrared burners' grid should be about 10 inches above the highest point in the pavement surface; otherwise the surface will be burned during heating and the material underneath the surface won't be heated. This problem was noted in some patches done on US 422 and SR 167, which might explain the data points with very high final temperatures (<450 °F) in Figure 6.3.

6.4 Performance Data

6.4.1 Performance Data For Patches At I-480

Performance data was collected 29, 66, 99, 161, and 188 days following the patching of potholes in the site. Figure 6.4 through 6.6 depict picture taken immediately, 29 and 188 days after installation for patches performed using the throw-and-roll, spray injection, and infrared heater/reclaimer methods, respectively. It is noted the significant deterioration in the patches condition occurred after 29 days of installation; however, slight change occurred after that.

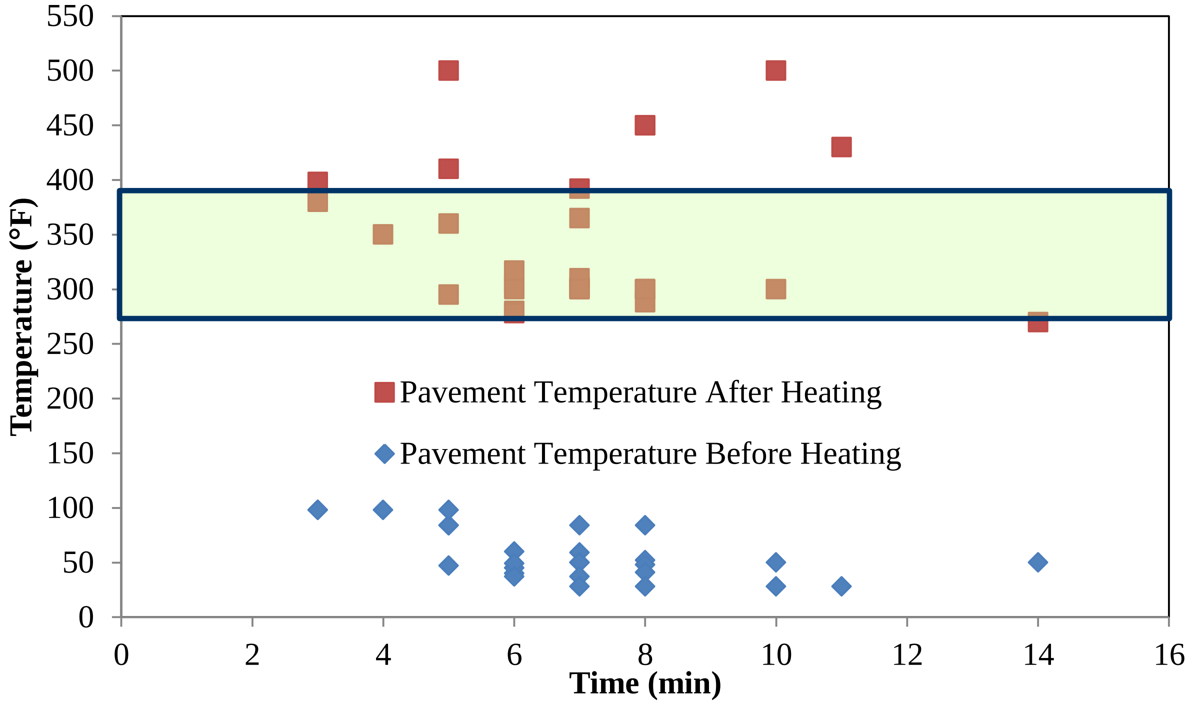


Figure 6.3 Pavement Temperatures Before And After Infrared Heating

During the evaluation, each patch was rated for each of the different types of distresses based on the guidelines that were developed as part of the Strategic Highway Research Program (SHRP) for pothole patches, which were implemented in the interactive database. The considered distresses included: Dishing, cracking, edge disintegration, missing patch, bleeding, raveling, and shoveling. Table C1 in Appendix C provides distresses rating obtained for each pothole 29, 66, 99, 161, and 188 days after installation. Six patches that were installed using the spray injection method were repatched after one month and hence their rating after that was not included in the analysis. The main distress in throw-and-roll and spray injection patches was dishing. By reviewing the installation pictures of the throw-and-roll patches that performed well and did not exhibit significant dishing, it was found that those patches were installed by leaving a crown of about 0.25 to 0.5 inch above the pothole surface, Figure 6.7. Most of the infrared patches showed some raveling issues. The raveling resulted from mainly a problem combination of the mix being somewhat dry, which lends it to segregate more easily, and moving the mix around too much with rake and lute causing more of the fines to drop down.

Figure 6.4 Pictures for Infrared Patch after 0, 29, 161, And 188 Days Of Installation

The overall rating of each patch was computed as the minimum rating obtained for the different distresses. Figure 6.8 shows the variation of the average final rating with time that was obtained for each of the three patching method. Potholes patched using the infrared method had clearly much better rating and thus performance than the other two methods. Furthermore, the throw and roll patches had slightly better performance than those installed using the spray injection.

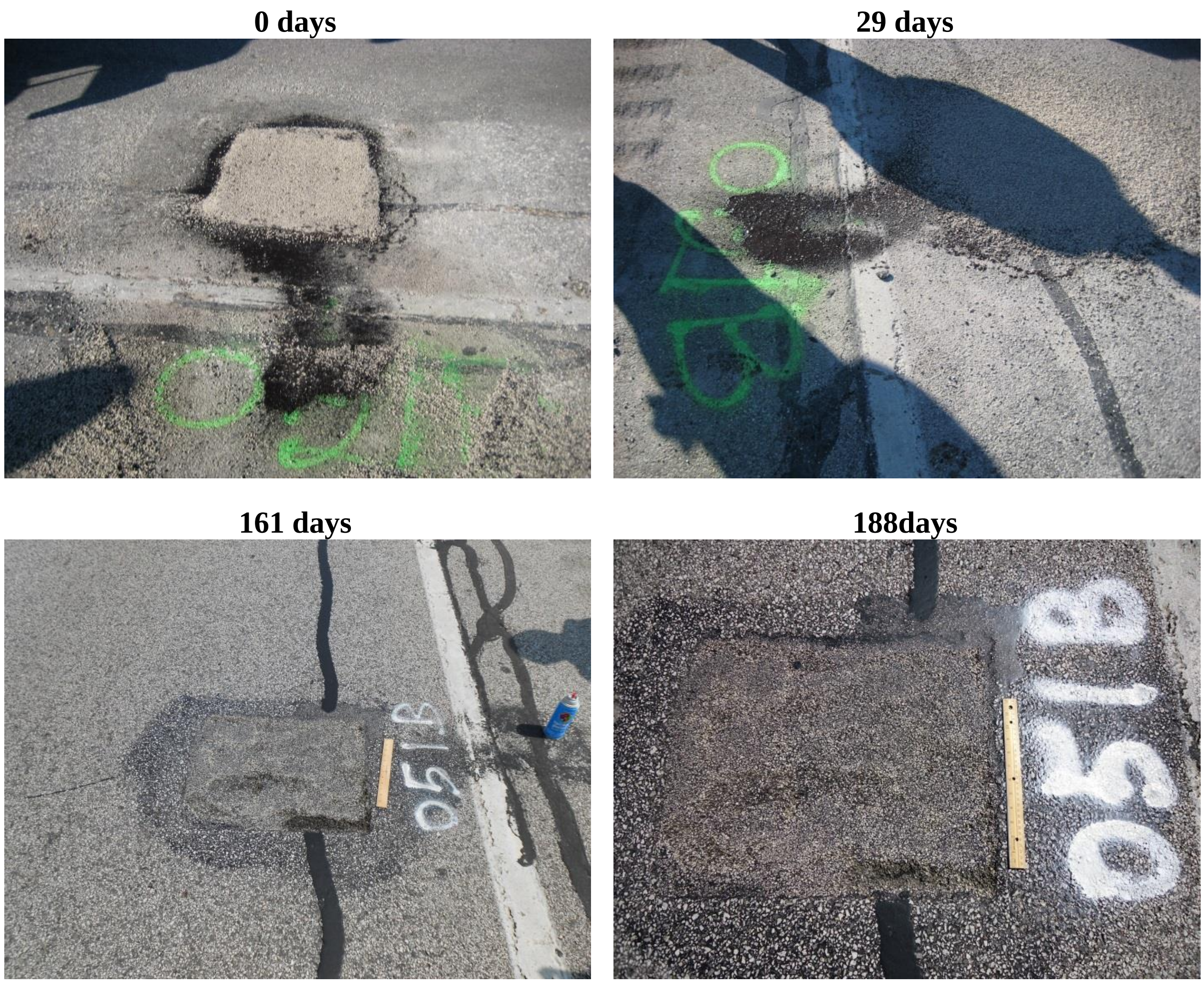


Figure 6.5 Pictures for a Spray Injection Patch after 0, 29, 161, And 188 Days Of Installation

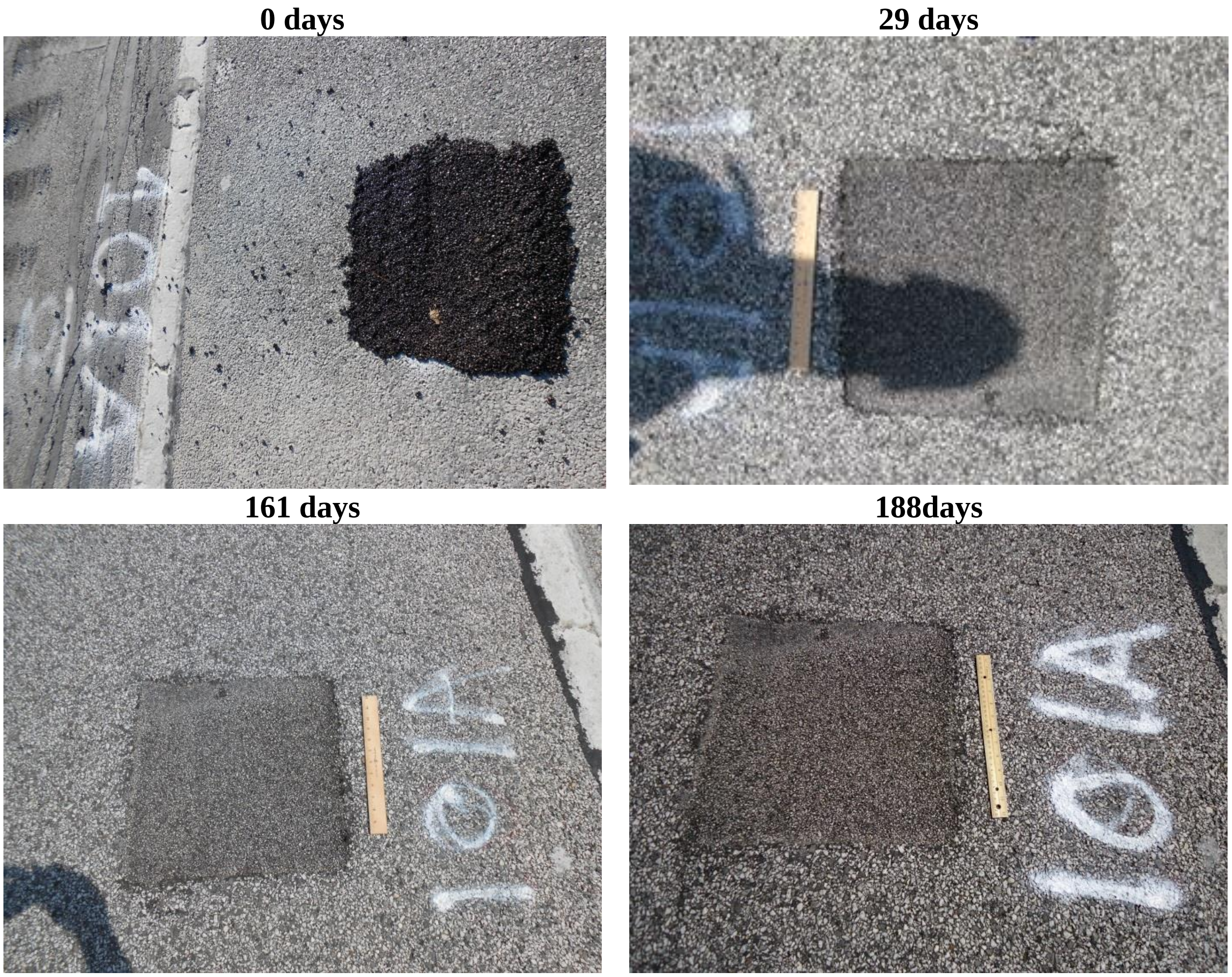


Figure 6.6 Pictures for a Throw-and Roll Patch after 0, 29, 161, And 188 Days Of Installation

Figure 6.7 Right-After-Construction View Of A Throw And Roll Patch That Performed Well

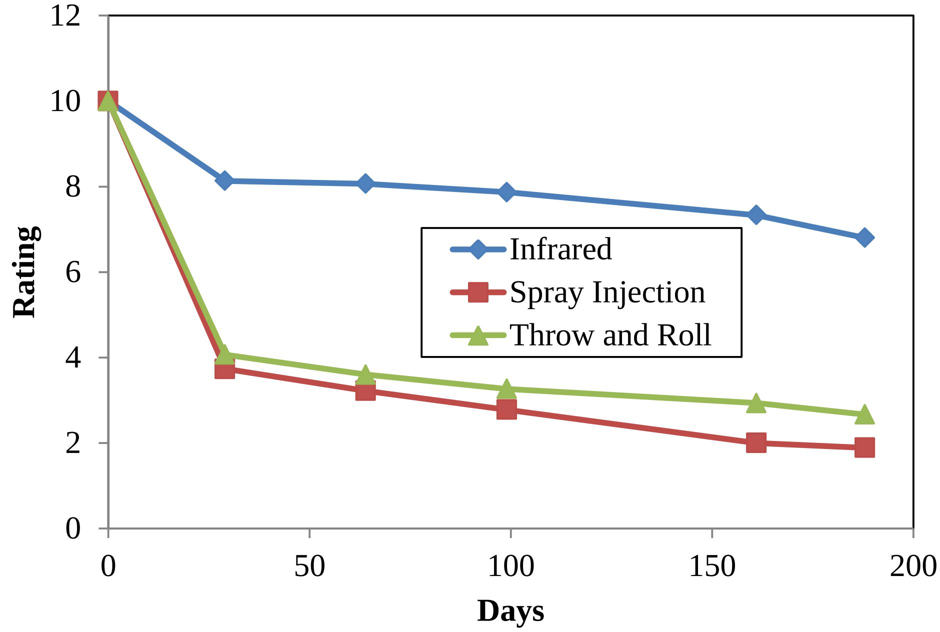


Figure 6.8 Overall Rating With Time For Each Patching Method

Multi-factor Analysis of Variance (ANOVA) and post ANOVA Least Square Mean (LSM) analyses were conducted using Statistical Analysis Software (SAS) (SAS Institute Inc., 2004) to evaluate the effect of the patching method, patch size, patch location, and their interaction on performance. A linear Completely Random Design (CRD) model was used in this analysis. The dependent variable used in the analysis was the patch overall rating. Table 6.1 presents the results of the ANOVA analysis. At 95% confidence level (p-value<0.05), the effects of patching method, evaluation date, and location (wheelpath vs. between-the-wheelpath) were significant on the performance of the installed patches. The patching method was the most significant factor affecting the performance, as indicated by the F-value. The interaction between the location and patching method effect was significant at 95% confidence level. This suggests that the influence of pothole location (or amount of traffic) varied between the three types of patching methods.

Table 6.2 presents the results of the grouping of the different patching method that was determined using the post ANOVA LSM analysis. In this table, the groups are listed in descending order with the letter “A” assigned to the highest mean followed by the other letters in appropriate order. In addition, groups with same letter next to them are not significantly different. The infrared had the significantly better rating than the two other patching methods. In addition, the throw and roll had on significantly better average rating than the spray injection method. Table 6.3 summarizes the results of the grouping of patch evaluation date. The results are showing that the rating of patches did not significantly different after 29 days and 66 and 99 days. This indicates that most deterioration in the patch occurs in the first month of installation and continues but at much slower rate.

Table 6.4 presents the results of post-ANOVA LSM analysis to group patches based on their location. The patches installed on the wheel path had significantly lower overall rating and performance than those installed between wheel path. The results Table 6.5 suggest this was mainly the case for the spray injection and throw roll meth but not for the infrared method. This is expected as the main distress in the patches installed using the throw-and-roll and the spray injection methods was dishing, which depends on the amount of traffic passing on the patch.

Table 6.1 Results of ANOVA Analyses conducted on Performance Data

Effect	F Value	P-value
Patching Method	146.57	<.0001
Evaluation date	4.13	0.0034
Location	6.68	0.0107
Size	2.16	0.1437
Patching Method*Evaluation date	0.11	0.9987
Location*Evaluation date	0.02	0.999
Location*Patching Method	36.8	<.0001
Size*Evaluation date	0.04	0.9967

Table 6.2 Results of Post-ANOVA LSM Analyses-Patching Method

Patching Method	Rating Estimate	Standard Error	Letter Group
Infrared	7.7700	0.2150	A
Throw and Roll	3.5500	0.2069	B
Spray Injection	2.3325	0.2996	C

Table 6.3 Results of Post-ANOVA LSM Analyses-Evaluation Date

Evaluation days	Rating Estimate	Standard Error	Letter Group
29	5.3081	0.2804	A
64	4.9415	0.3233	AB
99	4.6071	0.3233	AB
161	4.0939	0.3233	B
188	3.8034	0.3233	B

Table 6.4 Results of Post-ANOVA LSM Analyses-Patch Location

Location	Rating Estimate	Standard Error	Letter Group
Between wheel path	4.8422	0.2365	A
On wheel path	4.2594	0.1534	B

Table 6.5 Results of Post-ANOVA LSM Analyses-Patching Method/Patch Location

Location	Patching Method	Rating Estimate	Standard Error	Letter Group
Between wheel path	Infrared	8.1600	0.3511	A
On wheel path	Infrared	7.3800	0.2483	A
Between wheel path	TH	4.7667	0.3205	B
On wheel path	SP	3.0649	0.2857	C
On wheel path	TH	2.3333	0.2617	C
Between wheel path	SP	1.6000	0.5267	C

6.4.2 Performance Data For Patches At US Highway 422

Figure 6.9 and 6.10 show pictures of patches installed at US highway 422 after 37 and 70 days of installation, respectively. The patches exhibited good performance after 70 days of installation. However, there were some cracks that apparently resulted from structural deficiencies in the underlying pavement layers. This patches installed at US highway 422 demonstrate the ability to repair large areas of pavement surface using the infrared method, which typically could not be patched using the conventional throw-and-roll method.

Figure 6.9 Infrared Patches on US 422 after 37 Days of Installation

Figure 6.10 Infrared Patches on US 422 after 70 Days of Installation

6.4.3 Performance Data For Patches At Ohio State Route 67

Figure 6.11 a-c depict pictures taken after 30 days of installation for patches installed on Ohio SR 67. As shown in Figure 6.11 b, the patches installed by heating existing pavement and without using any new HMA material is still holding up, but there are signs of deterioration and ravelling in those patches. It is clear that patches installed using infrared method that included adding new HMA material, shown in Figure 6.11 a and c, perfomed well and in similar way. Therefore, it is recomended to utilize the infrared to repair the damages in pavement surface that resulted from grinding and skidding actions of the horseshoes worn by horses. Small amounts of new HMA material should be used as was done in some patches at Ohio SR 167.

6.4.4 Performance Data for Patches at Ohio State Route 18

Figure 6.12 shows pictures for patches at Ohio SR 18 taken after 30 days of installation. The patches showed excellent performance with no signs of raveling or any type of distresses after one month of installation. This clearly demonstrates the effect of the proper storage of patching material as well as its properties on the patch performance. Based on the results obtained in this site, it is recommended using the infrared method to repair settled areas of pavement surface for trenches that are up to 8 ft wide.

6.5 Survival Analysis

The performance data provided one way of evaluating the quality of patches installed using the three different considered methods. Survival analysis was also conducted to quantify the longevity and determine the expected life of patches installed using each of three methods. To perform this analysis the patch was considered to fail when the performance rating became less than 3 or if it was re-patched.

Figure 6.11 Infrared Patches installed on SR 167 after 30 Days of Installation

Figure 6.12 Infrared Patches installed on SR 18 after 30 Days of Installation

Survival analysis was conducted using LIFETEST procedure in SAS Software on data collected for pothole patches installed on I-480. As some of the patches, particularly those installed using the infrared method, did not fail during the 6 month monitoring period, those patches' survival times were considered censored in the analysis. However, both censored and uncensored observations were used in the analysis. Table 6.6 provides a summary of censored and uncensored observations used in this analysis.

Table 6.6 Summary of Censored and Uncensored (Not Failed) Observations Used In Survivability Analysis

Patching method	Total	Failed	Censored	Percent Censored (Not Failed)
Infrared	15	1	14	93.33
Spray Injection	15	13	2	13.33
Throw and Roll	15	11	4	26.67
Total	45	25	20	44.44

The LIFETEST procedure computes the non-parametric estimates of the survivor function by the Kaplan-Meier method (also called the product-limit method). The survivor function is used to estimate the survival times of the patches installed. Tables 6.7 and 6.8 present a summary of estimated survival times for patches installed using the spray injection and throw and roll methods, respectively. Tables 6.7 and 6.8 contain estimates of the 25th, 50th and 75th percentiles and the corresponding 95% confidence limits as well as the mean survival time and standard error. The mean survival time for the throw and roll and spray injection patches were 65 and 102 days. Survival time for infrared patches would be much larger than those of other two methods; yet cannot be obtained accurately in this study as only one infrared patch failed during the six month period while all other patches performed exceptionally well.

Table 6.7 Expected Life Estimation for Patches Installed Using Spray Injection Method

Percent	Estimate (days)	95% Confidence Interval		
		Transform	[Lower	Upper)
75	99.0	LOGLOG	29.0	.
50	29.0	LOGLOG	29.0	64.0
25	29.0	LOGLOG	.	.
Mean time to fail (days)	Standard Error			
65	13.96			

Table 6.8 Expected Life Estimation for Patches Installed Using Throw-and-Roll Method

Percent	Estimate (days)	95% Confidence Interval		
		Transform	[Lower	Upper)
75	1075.	LOGLOG	161.0	.
50	161.0	LOGLOG	29.0	161.0
25	29.0	LOGLOG	29.0	64.0
Mean time to fail (days)	Standard Error			
102	17.31			

Figure 6.13 shows the graph of the Kaplan-Meier (product-limit) survivor function estimates versus survival time. It is noted that the number of patches at risk at different times are also presented in this figure. It is clear that the infrared have much higher survival probability than the other two methods. Furthermore, the spray injection patches showed worse survivability rates than the throw and roll method.

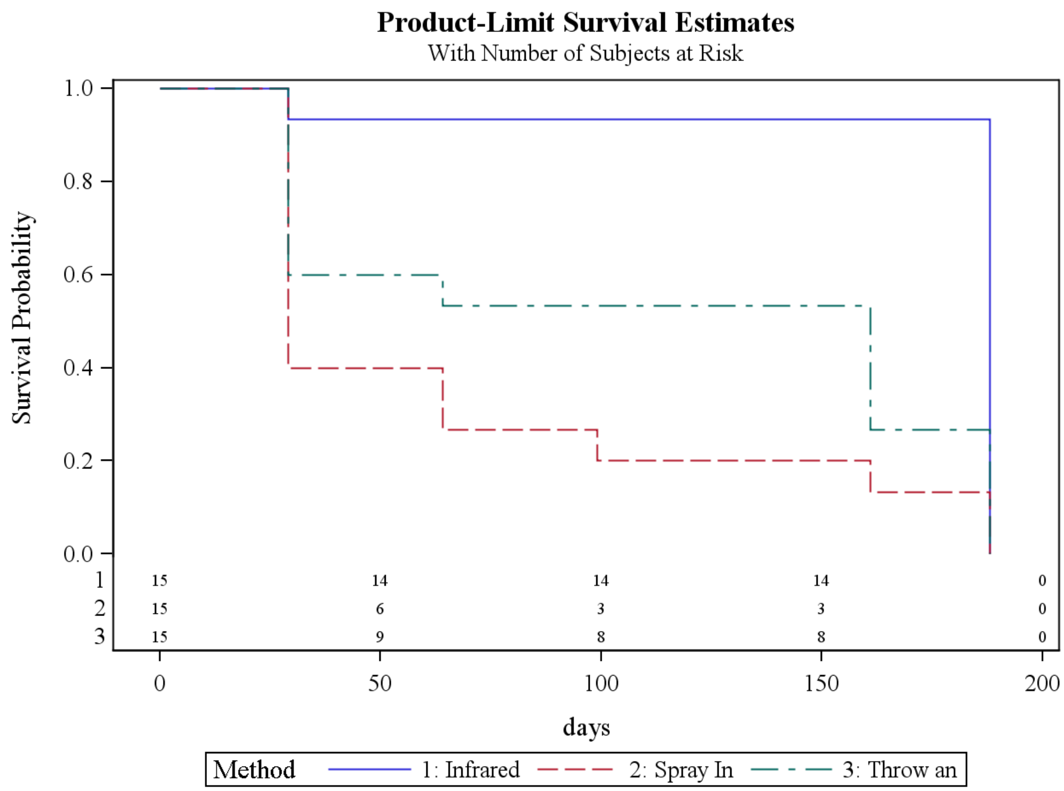


Figure 6.13 Survival Curves For The Different Patching Methods

An important task in the analysis of survival data is the comparison of survival curves. Table 6.9 provides a summary of results of nonparametric log-rank and Wilcoxon tests that were utilized to evaluate the statistical significance between the survival curves of the different patching methods. Both test are indicating that a significant difference between the patching methods (*p*-value <0.0001 for the log-rank and the Wilcoxon tests). Table 6.10 presents results of the multiple comparisons for the Logrank Test. While the infrared had statistical different survival curves and longer survival time than the two other methods, the throw and roll and spray injection had statistically similar survival curves.

As some of data were censored in the analysis, PHREG procedure in SAS software was performed to determine the hazard rates for the different patching methods based on the Cox proportional hazards model.

Table 6.11 provides the ratios between the hazard rate of the throw-and-roll and spray injection methods to that of the infrared method. It is clear that throw and roll and spray injection methods have much higher hazard rates than infrared. Therefore, the patches installed the throw and roll and spray injection methods are expected to fail much sooner than those installed using the infrared.

Table 6.9 Results of log-rank and Wilcoxon tests

Test	Chi-Square	DF	p-value
Log-Rank	21.5988	2	<.0001
Wilcoxon	18.6609	2	<.0001
-2Log(LR)	28.6702	2	<.0001

Table 6.10 Multiple Comparisons For The Log-Rank Test

Comparison		Chi-Square	p-Values	
			Raw	Tukey-Kramer
Infrared	Spray Injection	21.0013	<.0001	<.0001
Infrared	Throw and Roll	10.6721	0.0011	0.0031
Spray Injection	Throw and Roll	1.1379	0.2861	0.5348

Table 6.11 Hazard Ratios (Hazard of failing compared with Infrared method)

Method	Parameter Estimate	Pr > ChiSq	Hazard Ratio
Spray Injection	3.09921	0.0031	22.180
Throw and Roll	2.66599	0.0108	14.382

6.6 Cost Effectiveness

A comprehensive analysis was conducted to evaluate the cost-effectiveness of each of three methods for patching of potholes. Different costs and factors were considered this analysis: Labor costs, material costs, storage costs associated with stock piling reclaimed asphalt needed in the infrared asphalt heater/reclaimer method, traffic control costs, user delay, productivity, equipment costs, and longevity of the repairs and survival rate. The following sections provide a description of the main costs and factors and how it was computed for each method.

6.6.1 Labor Rates

The labor rates for the repair and traffic control crews were determined based on the cost information collected by ODOT Districts 12 and 2 during patching of potholes at the different sites. The number of workers in the repair crew differed from one patching method to another, but each crew had one supervisor/manager. Therefore, a labor cost that represents the average wage of the repair crew workers was first determined ($189.1/*day/person)*. This was then multiplied by the number of workers and added to the labor cost for one manger (323.3/*day*). Table 6.12 shows the labor cost that was computed for each patching method. On the other hand, an average labor cost $662/day was used for the entire traffic control crew.

Table 6.12 Labor Cost For Different Methods

Patching Method	Number Worker in Maintenance Crew	Labor for Labor Crew ($/day)
Infrared	4 worker+1 supervisor	$1,079.64
Spray Injection	3 worker+1 supervisor	$890.55
Throw and Roll	2 worker+1 supervisor	$701.46

6.6.2 Material Costs

The cost of materials used in repairing potholes using the different patching methods at I-480 site was obtained from ODOT Districts 12. Table 6.13 provide summary of materials costs needed for each patching method. It is worth noting that the cost shown for the infrared method include also the stock piling cost of reclaimed asphalt.

Table 6.13 Material Cost For Different Patching Methods

Patching Method	Material	Total cost ($/ton)
Infrared	HMA	$68
Spray Injection	Emulsion and Aggregate	$203.30
Throw and Roll	Cold mix	$101.8

6.6.3 Productivity

The productivity was computed using Eq. 1. The values used in the cost effectiveness are those presented in figure above.

6.6.4 Equipment costs

The costs for devices needed to complete the repair using each of the three considered methods were determined. Table 6.14 provides a summary of the devices used for each method and their corresponding costs. In the table, the cost of the dual patch and Minuteman included their equivalent daily expense (EDE) as well as their operational and maintenance cost. The equivalent daily cost is the cost per day of owning an equipment over its entire lifespan. It was computed using the expression shown in equation based on the initial equipment cost and assuming an expected life of 35 years and inflation rate of 5%.

$$EDE = \frac{Equipment\ \mathrm{cost}}{A} \qquad (2)$$

where,

A: is the present value annuity factor, and computed using as

$$A = \frac{1-(1+i)^{-n}}{i} \quad (3)$$

where,

n: is the expected life of equipment

i: is the inflation

Table 6.14 Costs of Equipment used in Each Patching Method

Patching Method	Equipment	Cost ($/day)
Infrared	Small vibratory Roller	147.30
	One Ton Dump Truck	24.63
	Minuteman Daily Equivalent cost	9.97
	Minuteman Maintenance Cost	1.37
	Minuteman Operating Cost	152.00
	Total	335.27
Throw and Roll	One Ton Dump Truck	24.63
	DODGE 4W Truck	14.38
	Total	39.01
Spray Injection	Small vibratory Roller	147.30
	One Ton Dump Truck	24.63
	Durapatch Daily Equivalent cost	6.69
	Durapatch Maintenance cost	1.37
	Durapatch Operating Cost	319.00
	Total	498.99

6.6.5 Longevity And Survival Rate

The longevity and survival rate are important factors in evaluating the cost-effectiveness as it determine the number of repatch that will occur in analysis period. In this study, the mean expected life value computed in the SAS LIFETEST analyses was used as the average life for repairs performed utilizing the throw and roll and spray injection method. No value was computed for the infrared method in LIFETEST analyses; however, the PHReg procedure indicated that hazard rates is at least 14 times higher for the throw and roll and spray injection method than that of infrared method, which suggests that the infrared patches should at least have 14 times the expected life of the patches installed using the other two methods. Therefore, the patches using the infrared were assumed to last all through the cost analysis duration.

6.6.6 Cost Analyses

A similar approach as that developed and used as part of the SHRP program was utilized in this study for estimating the cost of repairs performed using the three methods considered in this study (11). In this approach, the total cost for repairing potholes for a given time frame in a district is computed using the following expression:

$$C_T = [(T_{TOT}/L_{EXP})\ ] \text{ x } [(N/P_o) \text{ x } (C_L - C_E - C_{TC}\ ) + (N \times C_M)\ ] \tag{4}$$

Where

C_T = Total cost of patching operation for the given time frame, dollars

T_{TOT} = Time for analysis, years

L_{EXP}= Life expectancy for material-procedure combination, years

N = Material needed for patching initial potholes, tons

P_o = Productivity of the operation, tons per day

C_L = Cost of labor needed for patching operation, dollars per day

C_E = Cost of equipment needed for patching operation, dollars per day

C_{TC} = Cost of traffic control for patching operation, dollars per day

C_M= Cost of material delivered to yard, dollars per ton

Table 6.15 presents a summary of inputs that were used for the infrared heater/reclaimer, spray injection, and throw-and-roll methods in the cost analyses performed in this study. Figure 6.14 shows the cost for patching a pothole using different methods without considering the survival rate in the analyses (i.e. assuming that no repatch will do done during the analysis period). It is clear that the infrared method cost more than the spray and injection and the throw and roll methods. Furthermore, the least expensive method for performing the repair is the throw-and roll. Figure 6.14 compares the cost of patching for different analyses periods. The spray injection method will be more expensive if the pothole is expected to last more than four months, as the pothole will be repatched if the spray injection was used initially. Thus, for patching potholes in the winter the infrared will more cost-effective than the spray injection method. The results in Figure 6.14 indicates that the throw-and roll method cost less for analysis period less than 12 months; however, for longer analysis durations, which might be the case for permanent repairs, the infrared method will be more cost effective. As there was no data for the costs of damages to the users' vehicles that result from pothole failing during the analyses period, these costs were not considered in the analyses. In addition, the costs that ODOT might pay through claims or law suits due to a failure in pothole patches were not taken in account. If those costs were considered the infrared might be cost effective for potholes patched in the winter. These costs typically should be considered for medium (2 ft to 3 ft in dimensions) in area and large potholes (more than 3 ft in dimensions) where the pothole might pose more danger to the travelling public.

Table 6.15 Summary of Inputs Used In the Cost Analysis

Input	Infrared Method	Spray Injection Method	Throw and Roll Method
Material Cost ($/ton):	99.52	203.30	101.78
Initial Need (tons):	321.04	321.04	321.04
Repair Crew Wages ($/day):	1079.64	890.55	701.46
Traffic Control Wages ($/day):	319.92	319.92	319.92
Repair Equipment cost ($/day)	335.27	498.99	147.30
Traffic Control Equipment Cost ($/day)	26.00	26.00	26.00
Productivity (tons/day):	0.89	2.24	3.68
User Delay Costs ($/day):	0.00	0.00	0.00
Estimated Average Repair Life (months):	Analysis period	2.14	3.52

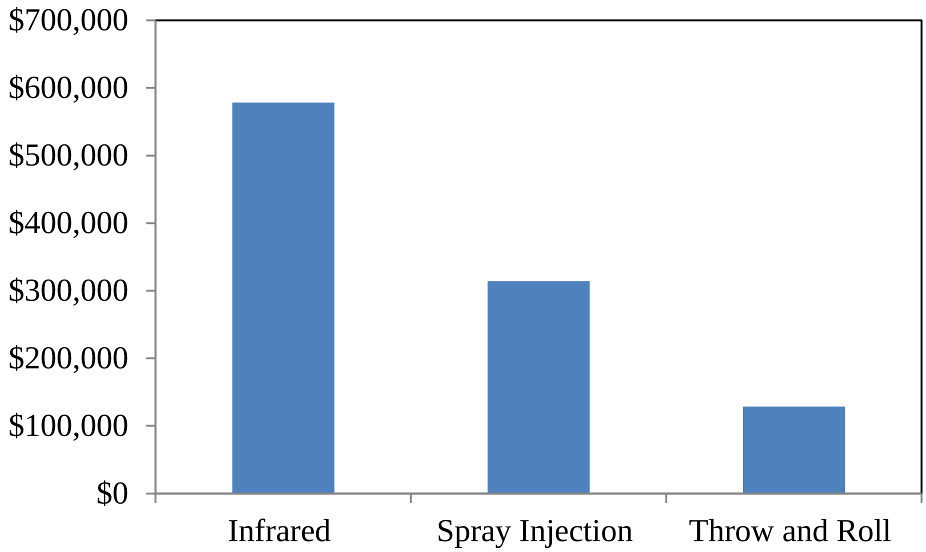


Figure 6.14 Cost of Potholes in District 12 for One time

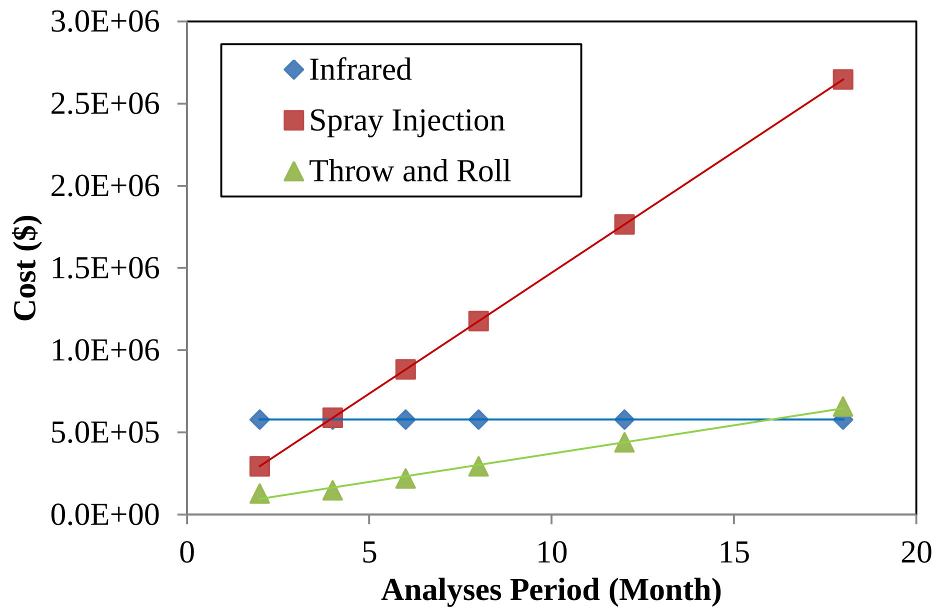


Figure 6.15 Cost of Potholes in District 12 Using Different Analysis Period

Chapter 7: Conclusions

7.1 Summary and Conclusions

This project was conducted to evaluate the performance and cost-effectiveness of three pothole patching methods, namely, the throw and roll, the spray injection, and the tow-behind combination infrared asphalt heater/reclaimer method. To achieve this objective, a comprehensive literature review was first conducted to identify the best practices for winter pothole patching. A national survey was then conducted to document the experience of the infrared asphalt heater/reclaimer users in different states. In addition, a comprehensive testing program, that included installing over 60 patches using the three considered methods as well as monitoring the performance and survivability of those patches, was performed. The following sections provide the main conclusions that were made based on the results of the tests and the findings of subsequent statistical analyses.

7.1.1 Selection of Infrared Asphalt Heaters/Reclaimer Systems

There are several infrared asphalt heaters/reclaimer systems available in the market. The three main infrared asphalt heater systems are: the Ray-Tech Mini Combo, Heat Design Equipment HDE 750-MT, and KASI Minuteman. The HDE 750-MT infrared asphalt heater/reclaimer has much higher price than the other two equipments although it has similar features. The main factors that were considered in the selection of most suitable equipment in this study included: price, compatibility with ODOT trucks and equipment, maintenance and operational costs, safety features and ease of use. Based on those factors the KASI Minuteman was found to be the most suitable equipment to be used and evaluated in this study.

7.1.2 National Survey Results

Based on the results of the national survey and subsequent phone interviews, the following conclusions were made:

- The majority of infrared asphalt heater/reclaimer equipment users indicated that it significantly improves the performance and longevity of pothole patches and is cost-effective when proper installation procedures are followed.
- The survey identified weather conditions, pavement type, and properties of patching material as the main factors that should be taken into consideration during installation in order to ensure optimal performance of the infrared method.
- The main applications of the infrared asphalt heater/reclaimer equipment other than pothole patching include: utility cuts, expansion joints, trenches, catch basins, spider web and facial cracks, water pockets, and curbing.

7.1.3 Time of patching and Productivity Results

- The patching duration using the infrared method was on average 16 minutes, which was more than four times the average time of the throw and roll method.
- The spray injection method took more than one and a half the time to patch potholes as that of the throw and roll method.
- The infrared method had much lower productivity than the other two methods. In addition, the throw and roll had the better productivity than the spray injection method.

7.1.4 Patching Procedures and Materials

- Infrared heater should heat existing asphalt pavement to a temperature 275-350 °F. In general, the infrared heating duration needed to achieve this temperature ranged between 5 to

10 minutes depending on the initial pavement temperature. In cold weather (pavement temperature < 45 °F), a heating duration up to 10 minutes was needed to achieve the required pavement temperature.

- The pavement temperatures heated using the infrared equipment is a function of the elevation of the infrared heater chamber from the pavement surface. The grid of the infrared burners in the heater chamber should be about 10 inches above the highest point in the pavement surface; otherwise the surface will be burned during heating and the material underneath it won't be sufficiently heated.
- The temperature of repaired area of the pavement should be 250 °F prior to compacting it. This may require applying additional re-heating of 1 to 2 minutes prior to compaction in cold weather (temperature < 40 °F).
- The asphalt mixture containing an asphalt content of 6.2% and neat asphalt binder PG 64-22 performed better than that with lower asphalt content of 5.4% and polymer modified binder PG 70-22. This indicates that the properties of the asphalt mixture used in the infrared method affects the performance of installed patches.
- Patches installed using asphalt mixture in small piles (about 1.5 ft by 1.5 ft) performed much better and did not show any signs of raveling as compared to those installed using asphalt mixtures stored in one large pile. Thus, the storage procedure of the asphalt mixture used in the infrared method has considerable effect on the performance of installed patches.
- Improper storage of the infrared heater/reclaimer equipment will lead to problems in igniting the infrared heater especially in the winter. The proper storage procedure includes draining manifolds at the bottom of the infrared chamber as well as lowering the infrared chamber all the way down when the unit is outside.

- The cold mix material used in the throw and roll method was contaminated with many leaves, incompletely coated aggregates (grayish colored), and uncoated big rocks. This might affect the performance of patches performed using this method.

7.1.5 Performance and Longevity

- Most of the deterioration in the patches installed using the different methods occurred in the first month of installation and continued after that but at a much slower rate.
- The infrared patches had significantly better rating than those installed using the two other patching methods. The main distress in infrared patches was raveling, which was attributed to the mix properties as well as moving the mix around too much during patching.
- The main distress in the throw and roll and spray injection patches was dishing. It was found that patches installed by leaving a crown of about 0.25 to 0.5 inch above the pothole surface performed well and did not exhibit significant dishing.
- The throw and roll had significantly better average rating than the spray injection method after six months.
- Potholes patched using the infrared method had much better performance than the other two methods.
- The patches installed using infrared had better survivability and longevity than those installed using the other two methods. Furthermore, the results of the statistical survivability analysis showed that the infrared patches are expected to survive at least 14 times the expected life of throw and roll and spray injection patches
- The throw and roll patches had a slightly better average service life than the spray injection patches. However, both methods had statistically similar survival curves.

7.1.6 Cost Effectiveness

- The infrared is more cost-effective than the spray injection method when used for winter potholes patching.
- For short-term repairs, the throw-and roll method will cost less than the infrared method if the users' costs were not considered.
- For permanent repairs, the infrared method will be more cost effective than throw and roll method.
- If the cost of damage to vehicles of traveling public was considered, the infrared might be more cost effective than throw and roll method especially for medium size (2 ft to 3 ft in dimensions) and large size potholes (more than 3 ft in dimensions).

7.1.7 Other Application of Infrared in ODOT Maintenance Procedure

- The infrared equipment has the ability to repair large areas of pavement surface, which typically could not be patched using the conventional throw-and-roll method.
- The infrared method can be used to repair the damages in pavement surface that results from grinding and skidding actions of the horseshoes worn by horses.
- The infrared method were sucessfully used to repair the damage in pavement surface due to settling in trenches that are up to 8 ft wide.

7.2 Recommendations for Further Study

In this study, asphalt mixtures that have up to 30% RAP were used as a patching material in the infrared method. It is recommended that future work expands the current study to evaluate the performance pothole patches containing higher RAP content(s).

7.3 Recommendations for Implementation

The tow-behind infrared heater/reclaimer was found to be an efficient and cost-effective method for patching certain types of potholes as well as in performing other pavement repairs. The following steps and guidelines are recommended for successful deployment of this equipment in Ohio:

- ***Assessing the Need for Acquisition of Tow-Behind Infrared Heater/Reclaimer***: The results of this study indicated that the infrared method can be more cost-effective and efficient than the throw and roll when used during the winter for patching large size potholes (more than 3 ft in dimensions) and medium size potholes (2 ft to 3 ft in dimensions) that are closely located. This is especially important in highways within urban areas, where the potholes poses more danger to larger volumes of the traffic moving at high speeds and thus the expected user cost can be considerable. The study also demonstrated that the tow-behind infrared heater/reclaimer can be a viable device when used to repair: settled pavement areas in trenches that are up to 8 ft wide, damage in pavement surface that results from grinding and skidding actions of the horseshoes worn by horses, cracked pavement areas that that has maximum dimensions of 12 ft by 12 ft. Users of this device has also indicated that it was successfully used for expansion joints, water pockets, and catch basins. Thus, an ODOT district that repeatedly encounters such types of potholes and pavement distresses will probably benefit from purchasing this device. It is recommended that each ODOT district assess their need for purchasing the tow-behind infrared heater/reclaime based on the results of this report. Based on this assessment, each district can decide whether to purchase its own device or not.

- ***Selection of the Most Suitable Infrared Asphalt Heaters/Reclaimer System****:* There are several infrared asphalt heaters/reclaimer systems available in the market. Based on the comparison that was conducted in this study between the three main infrared asphalt heaters/reclaimer systems, the KASI Minuteman was found to most suitable to be used in Ohio. However, as new systems may become available in the future, a comparison between all available systems similar to that conducted in this study will be needed. The main factors that should be considered in that comparison and the selection process: price, compatibility with ODOT trucks and equipment, safety features and ease of use, maintenance and operational costs, and life expectancy.

- ***Training Needs***: Training on using and maintaining this device is crucial for its optimal performance. Therefore, a one-day training session should be conducted for every district that purchases the tow-behind infrared heater/reclaimer equipment to train the maintenance crew on the proper operation procedure as well as storage and maintenance needs for this equipment. Each district should have at least three maintenance personnel from each county to be trained on operating this device and attend the training session. It is also recommended to hold an annual user-group workshop during the first three years to ensure optimal use of this device and resolve any issues encountered by ODOT workers during it usage. This can be done during the Ohio Transportation Engineering conference (OTEC) and/or the Flexible Pavements of Ohio conference. The research team can assist in organizing such workshop, if needed.

- ***Equipment Storage Procedure***: Proper storage of the infrared heater/reclaimer equipment is essential for its effective usage and to eliminate any problems that can occur during the patching process especially during the winter. The equipment should be parked in a garage, except during the reclaiming process, in which it should be parked under a shed. When the equipment is inside the blower motor should be removed and covered. If it is not possible to park the equipment inside a garage or under a shed, then the infrared chamber should be lowered all the way down when the equipment is outside. At any time the equipment is exposed to rain, the manifolds at the bottom of the infrared chamber (see Figure 5.9) should be drained by opening the drain plugs protruding from bottom of each manifold. If water is not drained and the equipment is left outside at temperatures below 32°F, it will freeze and the manifolds will need to be warmed with the drain plugs out to get the water out. In such case, it is recommended to ignite the infrared heater at the garage for at least 15 minutes before going to the site.

- ***Patching Material Requirements***: The results of this study indicated that the properties of the asphalt mixture used in the infrared method significantly affect the performance of installed patches. The asphalt mixture that will be reclaimed and used in the infrared patching method is recommended to have the following properties:
    - Asphalt content: between 6.2% and 6.7%
    - Asphalt binder type : neat asphalt binder PG 64-22
    - Aggregate type: it is recommended to use less absorptive aggregate with a nominal maximum aggregate size ½ inch (12.5 mm)
    - Reclaimed Asphalt Pavement (RAP) content: may use up to 30% RAP.

- ***Patching Material Storage Requirements:*** The asphalt materials should be stored in small blocks or piles under a shed as shown in Figure 5.15 or as demonstrated in Figure 7.1.

- ***Patch Installation Procedure:*** Proper procedure should be used to ensure best performance of the tow-behind infrared heater/reclaimer equipment. Appendix D provides a detailed step-by-step procedure for installing patches using this equipment. The key step in the installation procedure is achieving the proper pavement temperatures for scarifying and compaction. The pavement temperature should be 275-375 °F for scarifying. As a general rule, it will take 5-7 minutes in temperatures above 60°F to heat the asphalt pavement to this temperature. Furthermore, for temperatures below 45°F, it can take up to 10 minutes for the infrared heater to heat the asphalt to this temperature range. The materials temperature should be 250 °F just before compaction. It is important to note that the infrared chamber should be placed so that the burners grid are 8-10 inches above the highest point in the pavement surface; otherwise the surface will be burned during heating and the material underneath the surface won't be heated.

Figure 7.1 Example of Proper Storage Procedure for Asphalt Mixtures Used In Infrared Method

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Appendix A Survey

Contact Information

1. Please provide your contact information

Name:

Company:

Address:

Address 2:

City/Town:

State:

ZIP:

Email Address:

Phone Number:

***2. What type of infrared asphalt heater unit(s) you have (please provide also number and manufacturer)**

3. How long have you used your infrared heater/reclaimer unit?

- One year or less
- One to five years
- More than five years

***4. Did you notice any improvement in the pothole patching performance/survival when using infrared heater/reclaimer?**

- Significant
- Marginal
- No

***5. What factors were found to affect the infrared heater/reclaimer improvement? (Please select all that applies)**

- Weather condition during patch installation (i.e. cold, warm, raining, etc.)
- Pothole size
- Pavement type
- Patching Material
- Traffic conditions at pothole location
- None
- Others (please specify):

***6. Are there any measures/procedures that you found necessary for optimal usage of infrared heater/relcaimer?**

- Yes
- No

If yes, please specify

***7. Did you find the infrared heaters/reclaimer more cost effective than other techniques used for pothole patching?**

- ◯ Highly cost effective
- ◯ Somewhat cost effective
- ◯ I do not know
- ◯ Not cost effective
- ◯ Other (please specify):

8. What type of asphalt mixture typically used for patching with infrared heaters/reclaimer? (Please select all that applies)

- ☐ Cold virgin asphalt mixture without RAP
- ☐ Hot virgin asphalt mixture without RAP
- ☐ Cold virgin asphalt mixture with RAP
- ☐ Hot virgin asphalt mixture with RAP

If RAP was used, please provide percentage

***9. What are the major drawbacks that you found for using infrared heaters/reclaimer? (Please select all that applies)**

- ☐ Cost
- ☐ Complexity of Operation
- ☐ Safety
- ☐ Traffic Control
- ☐ Repair Time
- ☐ Other Equipment Maintenance Issues
- ☐ Labor Intensive
- ☐ Others (please specify):

***10. Did you use the infrared heater systems for pavement maintenance applications other than pothole patching? (Please select all that applies)**

- [ ] Utility cuts
- [ ] Expansion joints
- [ ] Catch basins
- [ ] Trenches
- [ ] Others (please specify):

***11. How satisfied are you with the infrared heater unit(s) you have?**

- ○ Very satisfied
- ○ Somewhat Satisfied
- ○ Somewhat unsatisfied
- ○ Very unsatisfied

Do you have additional comments:

Appendix B Survey Results

Ohio DOT Survey to Evaluate the Use of Infrared Asphalt Heater/Reclaimer

SurveyMonkey

1. What type of infrared asphalt heater unit(s) you have (please provide also number and manufacturer)

		Response Count
		12
	answered question	12
	skipped question	3

2. How long have you used your infrared heater/reclaimer unit?

	Response Percent	Response Count
One year or less	25.0%	3
One to five years	**50.0%**	**6**
More than five years	25.0%	3

3. Did you notice any improvement in the pothole patching performance/survival when using infrared heater/reclaimer?

	Response Percent	Response Count
Significant	**91.7%**	**11**
Marginal	8.3%	1
No	0.0%	0

4. What factors were found to affect the infrared heater/reclaimer improvement? (Please select all that applies)

	Response Percent	Response Count
Weather condition during patch installation (i.e. cold, warm, raining, etc.)	**75.0%**	**9**
Pothole size	16.7%	2
Pavement type	41.7%	5
Patching Material	41.7%	5
Traffic conditions at pothole location	16.7%	2
None	8.3%	1
Others (please specify):	16.7%	2

5. Are there any measures/procedures that you found necessary for optimal usage of infrared heater/relcaimer?

	Response Percent	Response Count
Yes	**50.0%**	**6**
No	**50.0%**	**6**
	If yes, please specify	6
	answered question	**12**

6. Did you find the infrared heaters/reclaimer more cost effective than other techniques used for pothole patching?

	Response Percent	Response Count
Highly cost effective	**58.3%**	**7**
Somewhat cost effective	33.3%	4
I do not know	8.3%	1
Not cost effective	0.0%	0
Other (please specify):	0.0%	0
	answered question	**12**

7. What type of asphalt mixture typically used for patching with infrared heaters/reclaimer? (Please select all that applies)

	Response Percent	Response Count
Cold virgin asphalt mixture without RAP	0.0%	0
Hot virgin asphalt mixture without RAP	**81.8%**	**9**
Cold virgin asphalt mixture with RAP	0.0%	0
Hot virgin asphalt mixture with RAP	54.5%	6
	If RAP was used, please provide percentage	7
	answered question	**11**

8. What are the major drawbacks that you found for using infrared heaters/reclaimer? (Please select all that applies)

	Response Percent	Response Count
Cost	8.3%	1
Complexity of Operation	8.3%	1
Safety	0.0%	0
Traffic Control	16.7%	2
Repair Time	8.3%	1
Other Equipment Maintenance Issues	16.7%	2
Labor Intensive	8.3%	1
Others (please specify):	**50.0%**	**6**
	answered question	**12**

9. Did you use the infrared heater systems for pavement maintenance applications other than pothole patching? (Please select all that applies)

	Response Percent	Response Count
Utility cuts	**91.7%**	**11**
Expansion joints	75.0%	9
Catch basins	58.3%	7
Trenches	83.3%	10
Others (please specify):	33.3%	4
	answered question	**12**

10. How satisfied are you with the infrared heater unit(s) you have?

	Response Percent	Response Count
Very satisfied	**91.7%**	**11**
Somewhat Satisfied	8.3%	1
Somewhat unsatisfied	0.0%	0
Very unsatisfied	0.0%	0
Do you have additional comments:		4
answered question		**12**

Appendix C Performance Data For Patch At I-480

Table C1: Summary of Performance Data

Patch ID	Location	Patching Method	day after installation	Performance Rating							Overall Patch Rating
				Bleeding	Cracking	Dishing	Edge Disintegration	Missing Area	Raveling	Shoving	
013C	w	Infrared	29	10	10	10	9	10	9	10	9
022C	b	Infrared	29	10	10	10	10	10	9	10	9
031C	w	Infrared	29	10	10	10	10	10	9	10	9
043C	w	Infrared	29	10	10	10	10	10	8	10	8
052C	b	Infrared	29	10	10	10	10	10	9	10	9
061C	w	Infrared	29	10	10	10	10	10	7	10	7
073C	w	Infrared	29	10	10	10	10	10	9	10	9
082C	b	Infrared	29	10	10	10	10	10	9	10	9
091C	w	Infrared	29	10	10	10	10	10	9	10	9
103C	w	Infrared	29	10	10	10	10	10	9	10	9
112C	b	Infrared	29	10	10	9	10	10	7	10	7
121C	w	Infrared	29	10	10	7	10	10	7	10	7
133C	w	Infrared	29	10	10	10	10	10	9	10	9
142C	b	Infrared	29	10	10	10	10	10	9	10	9
151C	w	Infrared	29	10	10	3	10	10	7	10	3
013C	w	Infrared	64	10	10	10	9	10	9	10	9
022C	b	Infrared	64	10	10	10	8	10	8	10	9
031C	w	Infrared	64	10	10	10	9	10	9	10	9
043C	w	Infrared	64	10	10	8	9	10	8	10	9
052C	b	Infrared	64	10	10	9	9	10	9	10	9
061C	w	Infrared	64	10	10	9	7	10	8	10	7
073C	w	Infrared	64	10	10	10	7	10	9	10	9
082C	b	Infrared	64	10	10	10	9	10	9	10	9
091C	w	Infrared	64	10	10	9	9	10	8	10	9
103C	w	Infrared	64	10	10	10	9	10	9	10	9
112C	b	Infrared	64	10	10	10	10	9	7	10	7
121C	w	Infrared	64	10	10	7	9	10	8	10	7
133C	w	Infrared	64	10	10	9	9	10	8	10	8
142C	b	Infrared	64	10	10	10	9	10	8	10	8
151C	w	Infrared	64	10	10	3	7	10	7	10	3
013C	w	Infrared	99	10	10	10	10	10	9	10	9
022C	b	Infrared	99	10	10	10	10	10	9	10	9
031C	w	Infrared	99	10	10	10	10	10	9	10	9
043C	w	Infrared	99	10	10	9	10	10	9	10	9
052C	b	Infrared	99	10	10	10	10	10	9	10	9
061C	w	Infrared	99	10	10	9	5	10	9	10	5
073C	w	Infrared	99	10	10	10	10	10	9	10	9
082C	b	Infrared	99	10	10	10	10	10	9	10	9
091C	w	Infrared	99	10	10	10	10	10	9	10	9
103C	w	Infrared	99	10	10	10	10	10	9	10	9
112C	b	Infrared	99	10	10	10	10	9	7	10	7
121C	w	Infrared	99	10	10	7	10	10	8	10	7
133C	w	Infrared	99	10	10	10	10	10	8	10	8
142C	b	Infrared	99	10	10	10	10	10	8	10	8
151C	w	Infrared	99	10	10	2	5	10	9	10	2
013C	w	Infrared	161	10	10	10	10	10	8	10	8
022C	b	Infrared	161	10	10	6	9	10	8	10	7
031C	w	Infrared	161	10	10	9	9	10	8	10	8
043C	w	Infrared	161	10	10	6	10	10	8	10	6
052C	b	Infrared	161	10	10	10	10	10	9	10	9
061C	w	Infrared	161	10	10	6	5	10	8	10	5
073C	w	Infrared	161	10	10	10	10	10	9	10	9

082C	b	Infrared	161	10	10	10	10	10	9	10	9
091C	w	Infrared	161	10	10	10	10	10	9	10	9
103C	w	Infrared	161	10	10	10	10	10	9	10	9
112C	b	Infrared	161	10	10	9	9	10	7	10	7
121C	w	Infrared	161	10	10	6	10	10	8	10	6
133C	w	Infrared	161	10	10	10	10	10	9	10	8
142C	b	Infrared	161	10	10	10	9	10	10	10	8
151C	w	Infrared	161	10	10	2	9	10	9	10	2
013C	w	Infrared	188	10	10	10	10	10	7	10	7
022C	b	Infrared	188	10	10	9	10	10	7	10	7
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073C	w	Infrared	188	9	10	10	10	10	8	10	8
082C	b	Infrared	188	10	10	10	10	10	8	10	8
091C	w	Infrared	188	10	10	10	10	10	7	10	7
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112C	b	Infrared	188	10	10	10	8	10	7	10	7
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133C	w	Infrared	188	10	10	10	8	10	8	10	8
142C	b	Infrared	188	10	10	10	10	10	7	10	7
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011B	w	SI	29	10	10	3	10	10	10	10	3
021B	w	SI	29	10	10	0	1	8	0	10	0
033B	w	SI	29	10	10	9	9	10	7	10	7
042B	b	SI	29	10	10	0	10	10	7	10	0
051B	w	SI	29	10	10	3	10	10	8	10	3
063B	w	SI	29	10	10	10	5	7	7	10	5
072B	b	SI	29	10	10	6	8	9	7	10	6
081B	w	SI	29	10	10	1	9	10	8	10	1
093B	w	SI	29	10	10	3	10	10	3	10	3
102B	b	SI	29	10	10	1	8	10	3	10	1
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132B	b	SI	29	10	10	3	10	7	3	10	3
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153B	w	SI	29	10	10	10	7	10	9	10	7
011B	w	SI	64	10	10	5	9	10	9	10	5
021B	w	SI	64	10	10	5	5	10	9	10	5
033B	w	SI	64	10	10	9	8	8	7	10	7
042B	b	SI	64	10	10	10	3	10	9	10	3
051B	w	SI	64	10	10	3	9	9	9	10	3
063B	w	SI	64	10	10	6	6	10	9	10	6
072B	b	SI	64	10	10	4	4	8	7	10	4
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093B	w	SI	64	10	10	2	8	10	7	10	2
102B	b	SI	64	10	10	0	5	10	8	10	0
111B	w	SI	64	10	10	2	4	9	9	10	2
123B	w	SI	64	10	10	5	9	10	9	10	5
141B	w	SI	64	10	10	5	7	8	7	10	5
033B	w	SI	99	10	10	5	10	10	6	10	5
051B	w	SI	99	10	10	3	9	9	9	10	3
072B	b	SI	99	10	10	3	10	8	7	10	3
081B	w	SI	99	10	10	1	10	9	9	10	1
093B	w	SI	99	10	10	3	10	10	6	10	3
102B	b	SI	99	10	10	0	10	8	9	10	0
111B	w	SI	99	10	10	2	6	10	9	10	2
123B	w	SI	99	10	10	4	10	10	9	10	4

141B	w	SI	99	10	10	5	7	8	7	10	5
011B	w	SI	161	9	10	2	10	10	9	10	2
021B	w	SI	161	10	10	3	8	10	9	10	3
033B	w	SI	161	9	10	3	9	10	6	10	3
042B	b	SI	161	10	10	9	3	9	8	10	3
051B	w	SI	161	10	10	2	9	9	9	10	2
063B	w	SI	161	10	10	9	8	9	9	10	8
072B	b	SI	161	10	10	2	9	9	7	10	2
081B	w	SI	161	10	10	0	9	9	9	10	0
093B	w	SI	161	10	10	2	10	9	6	10	2
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111B	w	SI	161	10	10	1	6	10	9	10	1
123B	w	SI	161	10	10	4	10	10	9	10	4
132B	b	SI	161	10	10	0	7	10	7	10	0
141B	w	SI	161	10	10	4	7	8	6	10	4
153B	w	SI	161	10	10	9	10	10	10	10	9
011B	w	SI	188	10	10	2	10	10	9	10	2
021B	w	SI	188	10	10	3	8	10	9	10	3
033B	w	SI	188	9	10	2	10	10	7	10	2
042B	b	SI	188	10	10	4	3	10	8	10	3
051B	w	SI	188	10	10	2	10	10	9	10	2
063B	w	SI	188	10	10	8	8	10	8	10	8
072B	b	SI	188	10	10	2	9	9	9	10	2
081B	w	SI	188	10	10	0	10	10	9	10	0
093B	w	SI	188	10	10	2	9	9	6	10	2
102B	b	SI	188	10	10	0	6	9	9	10	0
111B	w	SI	188	10	10	2	6	10	9	10	2
123B	w	SI	188	10	10	5	10	10	10	10	5
132B	b	SI	188	10	10	0	7	8	8	10	0
141B	w	SI	188	10	10	3	10	8	9	10	3
153B	w	SI	188	10	10	5	10	10	10	10	5
012A	b	T&R	29	10	10	7	8	10	10	10	7
023A	w	T&R	29	10	10	2	10	10	10	10	2
032A	b	T&R	29	10	10	5	10	9	9	10	5
041A	w	T&R	29	10	10	2	9	10	10	10	2
053A	w	T&R	29	10	10	2	10	10	10	10	2
062A	b	T&R	29	10	10	4	10	10	10	10	4
071A	w	T&R	29	10	10	5	10	10	10	10	5
083A	w	T&R	29	10	10	5	9	10	9	10	5
092A	b	T&R	29	10	10	10	8	10	10	10	8
101A	w	T&R	29	10	10	5	9	10	10	10	5
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131A	w	T&R	29	10	10	2	10	10	10	10	2
143A	w	T&R	29	10	10	2	8	10	10	10	2
152A	b	T&R	29	10	10	5	10	10	10	10	5
012A	b	T&R	64	10	10	7	9	10	10	10	7
023A	w	T&R	64	10	10	0	5	10	9	10	0
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041A	w	T&R	64	10	10	2	5	10	9	10	2
053A	w	T&R	64	10	10	2	3	10	9	10	2
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113A	w	T&R	64	10	10	2	8	10	9	10	2
122A	b	T&R	64	10	10	5	9	10	9	10	5
131A	w	T&R	64	10	10	2	7	10	9	10	2

143A	w	T&R	64	10	10	2	6	10	9	10	2
152A	b	T&R	64	10	10	5	9	10	9	10	5
012A	b	T&R	99	10	10	4	9	10	9	10	4
023A	w	T&R	99	10	10	0	10	10	10	10	0
032A	b	T&R	99	10	10	5	9	10	9	10	5
041A	w	T&R	99	10	10	2	10	10	9	10	2
053A	w	T&R	99	10	10	2	10	10	10	10	2
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122A	b	T&R	99	10	10	4	10	10	9	10	4
131A	w	T&R	99	10	10	0	10	10	10	10	0
143A	w	T&R	99	10	10	2	10	10	10	10	2
152A	b	T&R	99	10	10	2	7	10	9	10	2
012A	b	T&R	161	10	10	3	10	10	8	10	3
023A	w	T&R	161	10	10	0	9	10	9	10	0
032A	b	T&R	161	10	10	2	9	10	9	10	2
041A	w	T&R	161	10	10	2	9	10	9	10	2
053A	w	T&R	161	10	10	2	9	10	9	10	2
062A	b	T&R	161	10	10	2	9	10	8	10	2
071A	w	T&R	161	10	10	3	10	10	9	10	3
083A	w	T&R	161	10	10	3	10	10	9	10	3
092A	b	T&R	161	10	10	8	9	10	9	10	8
101A	w	T&R	161	10	10	3	10	10	9	10	3
113A	w	T&R	161	10	10	1	9	10	9	10	1
122A	b	T&R	161	10	10	4	9	10	9	10	4
131A	w	T&R	161	10	10	3	10	10	9	10	3
143A	w	T&R	161	10	10	2	10	10	9	10	2
152A	b	T&R	161	10	10	6	10	10	9	10	6
012A	b	T&R	188	10	10	3	10	10	8	10	3
023A	w	T&R	188	10	10	0	8	10	9	10	0
032A	b	T&R	188	10	10	3	10	10	9	10	3
041A	w	T&R	188	10	10	2	9	10	9	10	2
053A	w	T&R	188	10	10	2	9	10	9	10	2
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071A	w	T&R	188	10	10	2	10	10	9	10	2
083A	w	T&R	188	10	10	2	9	9	9	10	2
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113A	w	T&R	188	10	10	2	9	9	10	10	2
122A	b	T&R	188	10	10	4	10	10	9	10	4
131A	w	T&R	188	10	10	2	10	10	10	10	2
143A	w	T&R	188	10	10	2	9	10	9	10	2
152A	b	T&R	188	10	10	5	10	10	9	10	5

Appendix D Recommended Step-By Step Procedure for Performing Pavement Repairs using Infrared Heater/Reclaimer Equipment

Step 1- Setup

Upon arriving at the job site the first step should be to insure having a safe work area. The arrow-board should be activated to properly direct traffic from behind. Signs and cones should be put out in conformance with ODOT recommended safety procedures. It is important to insure that adequate room is allowed on the sides of the equipment to provide the workers safe access to the reclaimer for asphalt and to allow the raker to work on the sides of the patch. It is recommended to have a minimum of 5 ft space on the sides of the equipment.

Step 2- Preparation

The area must be swept to remove any standing water, loose asphalt, and dirt.

Step 3- Heater Placement

It is very important that the infrared chamber is properly positioned over the repair. The area to be restored must be squared off insuring that all the edges are at least 6” away from the damage. It is important that an additional 6” perimeter of the heated surface is left undisturbed. This will insure that when the repair is rolled, the hot asphalt in the restored area is fused to the hot existing road, thereby eliminating any seam.

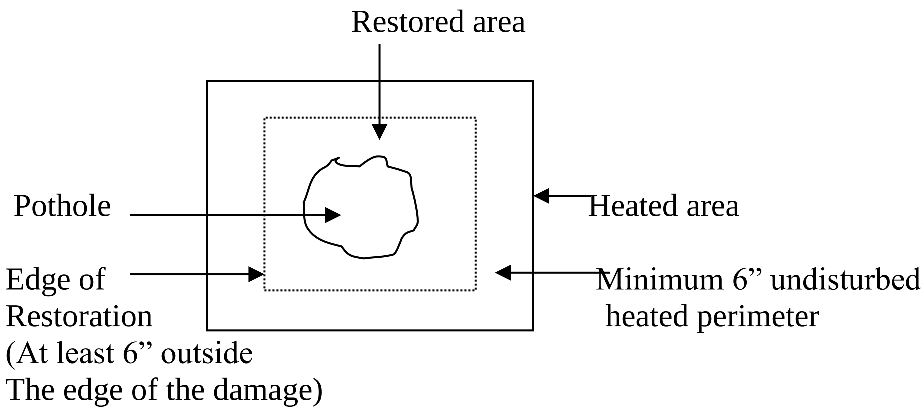

Figure D.1: Proper Heater Placement

If the damaged area is so large that it cannot be contained in the 8' x 6' heated area, consecutive heats can be used to restore the area.

Another important issue that should be considered during heating of the pavement is placing the infrared chamber so that the burners grid are at 8-10 inches above the highest point in the pavement surface; otherwise the surface will be burned during heating and the material underneath the surface won't be heated.

Step 4- Heating Time

It is extremely important that pavement is heated for the proper length of time. If the heater is not on long enough, the asphalt will not be softened deep enough to insure a proper repair. If the heater is down too long then the asphalt could burn which will ruin it. Please note that simply removing the ruined asphalt will not correct the problem. Remember that in order to insure a seamless restoration it is necessary to leave at least 6 inches of heated asphalt undisturbed. If that asphalt is burned then the seam will fail.

As a general rule, it will take 5-7 minutes in temperatures above 60°F to heat the asphalt pavement to 275-350 °F, and can take up to 10 minutes for the infrared heater to heat the asphalt to this temperature range in temperatures below 45°F.

There are three major variables that impact the time it takes for infrared radiation to properly heat asphalt: <u>Material, Moisture, & Mother Nature.</u>

1- Material. Not all asphalt is the same. Many factors affect the quality of the asphalt being worked:

a-The age of the asphalt mixture in the existing pavement: The age of the asphalt affects the percentage of the “maltenes” (light oils) that has been oxidized. The dryer the material, the longer it takes to heat.

b- The properties of the asphalt mixture in the existing pavement: The larger the aggregate in the mix, the longer it takes to heat. ¾ inch mix can take as much as 2-3 minutes longer to soften than ¼ inch top. The the color of the asphalt mixture also affect the required heating duration, since infrared rays must be absorbed into the asphalt. The lighter the color the longer it takes to heat.

2- Moisture. Infrared should not be used to rid an area of standing water. It will, however remove moisture from wet pavement. Depending on how porous the asphalt is will determine how much moisture is in the pavement. The amount of moisture in the pavement will determine how much additional time it takes to properly heat.

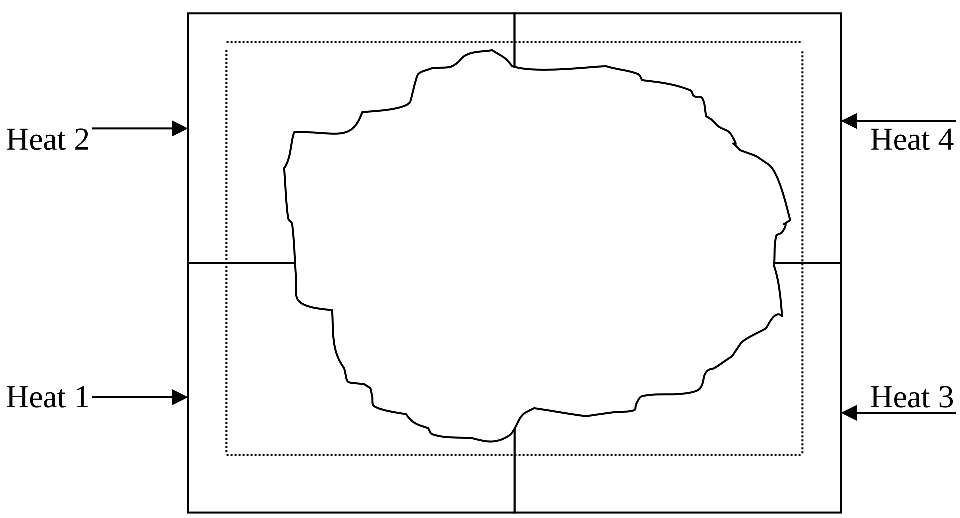

Figure D.2: Multiple Hit Heating Pattern For A Large Repair

3- Mother Nature. The combination of temperature and wind effect both the heating time and the amount of time you will have to work with the asphalt once heated. Obviously, it will take longer to heat the asphalt if the pavement temperature is 30 degrees versus 60 degrees. Also, once the infrared heater is removed from the patch the wind and the temperature will influence how much time the crew has to complete the repair. They will need to have sufficient time to rake, rejuvenate, add material, lute & roll the patch before it cools off.

Step 5- Scarifying

Once the heater is removed the damaged area must be squared off and scarified. To square it off take the back edge of a steel asphalt rake and cut into the asphalt. Push that material into the center of the repair. Once the outside edge is set turn the rake over and deeply scarify the entire area. At least 2 inches of asphalt should be disturbed. Leave the area roughly level with a slight trough at the edges.

Step 6- Rejuvinating

Age and sunlight cause a percentage of the light oils present in new asphalt to oxidize out over time. A small amount of "maltenes" rejuvenator should be applied to the existing asphalt at this time. This is not acting as a tack coat. It is simply replacing exactly what was originally there. Using a good quality commercial hand sprayer, apply a light coat of the rejuvenator over the entire area, including the edges.

Step 7- Adding New Asphalt & Finish Raking

In order to insure proper grade and a level patch, new material might need to be added to the repair. There are a number of things that affects the quality of installed patch that should be considered when adding the new material. First, the type of material in the original surface should match the new material being added. For example, you would not want to add 3/8" top mix to a surface made up of overlay sand mix. Second, the “lute man’s” raking skills. All hand work requires special effort to insure that the material is not segregated with all the stone on top. The raker determines how much asphalt is needed and the material is then wheel barrowed from the reclaimer to the patch. The virgin asphalt is raked evenly throughout the patch and into the trough created around the edges. The entire patch is then luted smooth and level slightly above grade to allow for compaction.

Step 8- Compaction

As soon as the raking is finished, compaction should start immediately. The rolling pattern should always begin with the edges. This is to seal the seam between the repair and the existing pavement. Use approximately 2 inches of the drum to pinch the new asphalt to the existing road. After the edges are sealed, the remainder of the patch is rolled. It is recommended that to use a vibratory roller either single drum or dual drum with a minimum of pressure of 3200 psi. It is important to have sufficient total applied pressure to ensure proper compaction.

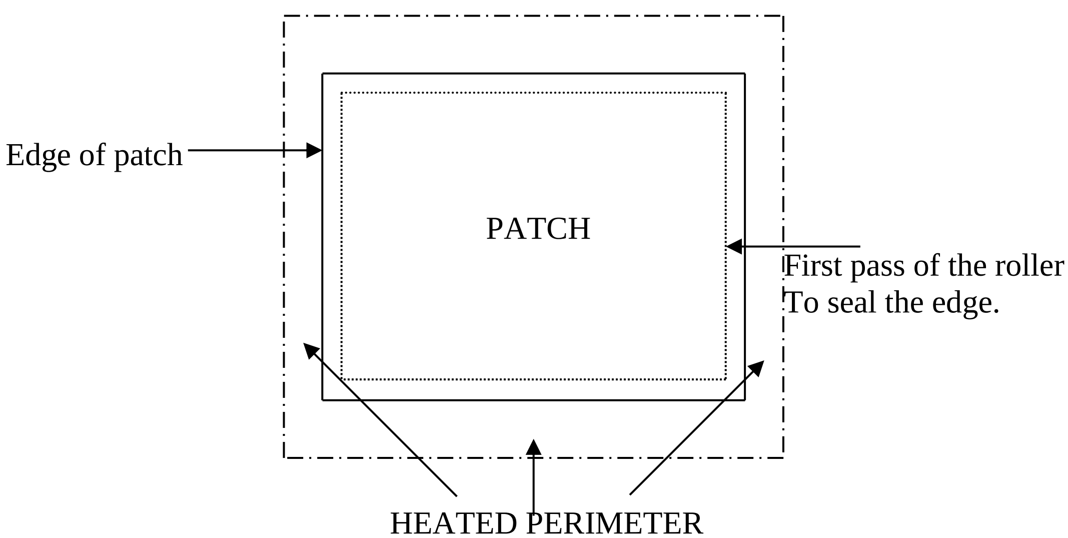

Figure D.3 Demonstration for Proper Compaction Procedure

Step 9- Finish

After the compaction is completed sweep up any mess, pack up the tools, and remove the traffic protection. KASI also suggests dusting the repair with stone dust or some other fine material. This removes any residual tackiness and allows the repair to immediately accept traffic.

Cold Weather Application

For patching in cold weather below 45°F, the chamber must be applied for 1-2 minutes after initial heating, edging, scarifying, and re-juvenating to re-heat the cooled surface. Fresh mix is then added and luted to compaction grade. If the surface has again cooled an additional re-heat of 1 minute should be applied prior to compaction. Make certain antifreeze has been added to roller water in sub-freezing temperatures and the re-juvenator has been kept warm.