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Preliminary Evaluation of Pavement Surface Distresses Related to Pavement Markings

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16. Abstract
Since road marking research is traditionally focused on the life-cycle performance of various marking materials in terms of durability and visibility, little is known about the effect of surface markings on pavement performance. Nevertheless, transportation agencies have reported the presence of pavement distresses, such as cracking and raveling, under or along pavement markings. This project aimed at investigating if pavement markings cause pavement surface deterioration in Pennsylvania and, if so, to develop approaches for mitigation of this problem. Pavement sections with distresses potentially caused by pavement markings were identified. Visual surveys were performed to identify if the surface distresses are located directly below or in the vicinity of the markings relating the damaged area to the overall surface condition. Nondestructive testing was performed to evaluate the marking/pavement condition. Finite element modeling was conducted to evaluate the potential effect of temperature differentials on the interaction between markings and pavement surface. Results strongly indicate the issues with longitudinal joint compaction are the main culprit for pavement deterioration around longitudinal pavement markings. Recommendations regarding longitudinal joint construction and evaluation as well as pavement marking installation are proposed to avoid early pavement marking deterioration.

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Disclaimer

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1. Introduction

Pavement marking research has made significant advances, especially in the life-cycle performance analysis of various marking materials in terms of durability and visibility. However, little is known about the interaction between pavement markings and the various pavement surfaces on which markings are placed which includes. The effect of markings on pavement performance is also overlooked by pavement research. Nevertheless, transportation agencies have reported the presence of pavement distresses, such as cracking and raveling, exclusively under or along pavement markings. These visual reports, although subjective, raise concerns that marking materials, placement, or another unknown marking related variable is causing pavement deterioration.

Several issues have been identified as a potential cause for pavement distresses located on or around pavement markings. Both the trapping of excess moisture under the marking and the difference in temperature between the marking and pavement surface may initiate and/or facilitate pavement distresses in the vicinity of the marking. The former is a known issue for structures using sealant paints and the latter has been observed in studies on the albedo in pavements where temperature for some types of markings was significantly different than the pavement surface temperature. The main cause might also be related to the location of the marking since most longitudinal markings are placed at the longitudinal joint which is a location prone to distresses due to the low density of the asphalt mixture.

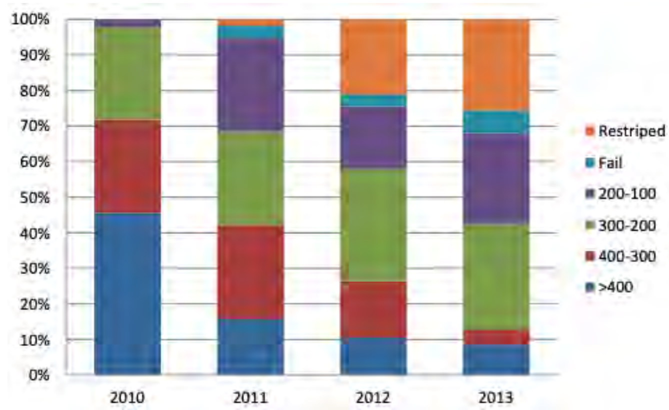
In this project, pavement markings were investigated as a potential cause of pavement surface deterioration in Pennsylvania. For that, several pavement sections with distresses potentially on or around pavement markings were identified and field evaluations were conducted for representative sections. Visual surveys were performed to identify if the surface distresses are located directly below or in the vicinity of the markings relating the damaged area to the overall surface condition. Nondestructive testing was performed to evaluate the marking/pavement condition. Finite element modeling was conducted to evaluate the potential effect of temperature differentials on the interaction between markings and pavement surface.

2. Pavement Markings and Pavement Distresses

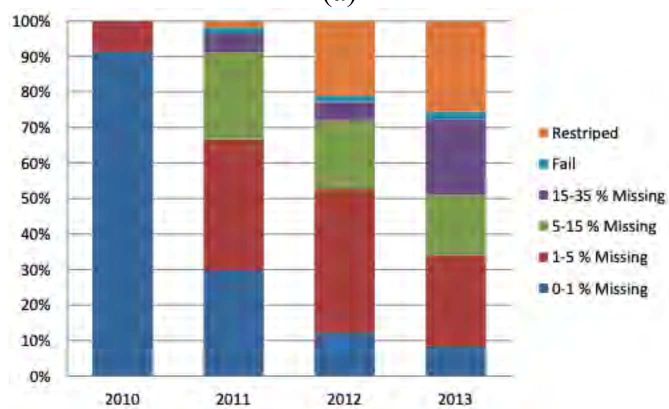
Although, the research areas for pavement surface distresses and pavement markings performance are well established in the transportation community, these areas rarely overlap. Therefore, technical literature on pavement distresses related to pavement markings is very limited. There are some observational reports on potential distresses influenced by pavement markings, but their scope was also limited. Common types of pavement markings were considered for their properties and how they related to different pavement surface types. In addition, three main hypotheses that could help explain pavement distresses happening on or close to pavement markings were explored.

2.1 Pavement Marking Materials

Horizontal pavement markings provide guidance and visibility for drivers, especially during nighttime, which has a direct impact on road safety. Pavement markings are used so that a driver does not need to divert their attention from the road, encouraging traffic safety and flow [1]. Pavement marking performance is usually quantified based on two parameters: durability and retroreflectivity. Durability is usually evaluated by visual surveys where a trained evaluator gives a rating for a marking based on the percentage of marking lost. The evaluation is very subjective and varies from one survey to another. Another way to assess marking durability is to test the bond between marking and pavement surface as well as resistance to different traffic levels. Retroreflectivity is a phenomenon in which a portion of the vehicle's lights are reflected back into the driver's line of sight after hitting the marking. Several studies have shown an increase in driver visibility and interpretation capacity at night when exposed to markings and signs with higher retroreflectivity levels [2]–[5] significantly improving driving skills [6]. As can be seen in Figure *1* from a study conducted in Illinois with the evaluation of several marking materials in different surfaces, both retroreflectivity and durability (evaluated as marking presence) deteriorate in short periods [7].



(a)



(b)

Figure 1: Field marking deterioration as measured by (a) retroreflectivity (mdc/m^2/lux) and (b) presence [7]

In order to provide higher levels of durability and retroreflectivity, pavement marking materials evolved greatly over the last 30 years. In this literature review, a basic analysis of the most common marking materials currently used in Pennsylvania was conducted. Factors considered were material performance, cost-benefit ratio, and their relation to different pavement surfaces.

Pennsylvania's paving industry must chose products and manufacturers approved by the National Transportation Product Evaluation Program (NTPEP) [7]. NTPEP guidelines are based on rigorous marking material testing in Minnesota, Pennsylvania, Wisconsin, and Florida [7]. Pennsylvania also has specifications on several marking materials: Hot Thermoplastic (Section 960), Cold Plastic (Section 961), Waterborne (Section 962), Epoxy (Section 964), Preformed Thermoplastic (Section 965), and Snowplowable Raised (Section 966) [8]. Pennsylvania Publication 408 also has several recommendations regarding pavement markings. It suggests that longitudinal joints be constructed in a way that avoids placing pavement markings directly on top, that tape be primarily used as a temporary marking during construction rather than a long-term marking, and that epoxy should primarily be used on concrete.

Decisions on what marking material is used is mainly chosen based on projected life and cost rather than traffic volume, environment, or pavement surface. If a roadway is brand new, agencies tend toward the more expensive choices with a better life span that best suit the surface material. If it is an overlay or repair, paint is generally the choice since it is inexpensive. Several DOTs have guidelines for marking material selection based on traffic, pavement service life, and others. Table 1 presents the selection matrix for hot mix asphalt pavements as established by the Texas Department of Transportation (TxDOT) [9].

Five common marking materials will be discussed in this literature review based on the use in Pennsylvania: waterborne paint, thermoplastic, tape, epoxy, and polyurea. Table *2* shows a brief summary and the following sections detail each marking material.

Table 1: TxDOT guidelines for marking material selection for asphalt pavements [9]

(The highest-recommended material is emphasized.)			
-	**Pavement Remaining Service Life**		
Traffic Characteristic	**0–2 years**	**2–4 years**	**> 4 years**
AADT[2] < 1,000	**Thermo**, Water-Based Paint	**Thermo**, Water-Based Paint	**Thermo,** Water-Based Paint, Epoxy[3, 4], Modified Urethane[4], Polyurea[4], MMA[4]
1,000 < AADT < 10,000	**Thermo**, Water-Based Paint	**Thermo**, Epoxy[3, 4], Modified Urethane[4], Polyurea[4], MMA[4]	**Thermo**, Preformed Tape, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]
AADT > 10,000	**Thermo**, Epoxy[3, 4], Modified Urethane[4]	**Thermo,** Preformed Tape, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]	**Preformed Tape, Thermo**, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]
Heavy Weaving or Turning	**Thermo**, Epoxy[3, 4], Modified Urethane[4]	**Thermo**, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]	**Thermo**, Epoxy[3, 4], Polyurea[4], Modified Urethane[4], MMA[4]

Footnotes:

1. Materials may be used for shortlines or longlines — with the exception of two-component materials, which should only be used for longlines. Other materials may be used on an experimental basis with approval of TRF or CST-MAT. Contrast markings may be used to improve visibility and safety as needed.
2. AADT = Average Annual Daily Traffic.
3. Epoxies specially formulated as high-quality, high-durability permanent markings.
4. Experimental material.

Table 2: Summary of advantages and disadvantages of common marking materials.

Marking Material	Advantages	Disadvantages
Paint	Inexpensive, widely used	Short service life, limited traffic level
Thermoplastic	Low cost, high durability, widely used	Sensitive to application factors, low performance on PCC
Tape	Versatile, high visibility	Sensitive to application factors, expensive
Epoxy	Good performance on PCC, low application requirements	Poor resistance to UV radiation, deteriorates from absorbed contaminants
Polyurea	Low application requirements, high initial and long-term visibility, resistance to UV radiation	Expensive, specialized equipment

2.1.1 Paint

There are two types of paint for pavement marking: solvent based and waterborne. Solvent based paints have negative environmental effects and most places have restricted the use [1]. Waterborne paints are more environmentally friendly and are widely used in the United States [10]. Paint is the most common marking material because of its low cost. However, paint has a very short service life, the lowest initial retroreflectivity, and requires regular restriping. Paint wears especially quickly when exposed to high levels of traffic or snow removal. It is only recommended for use on low volume roads [1], [10]–[12]. Paint is also sensitive to application factors including wind speed, ambient and surface temperature, and moisture [1].

Paint is compatible with both concrete and asphalt but surface roughness must be considered in application. Smoother pavements will cause paint to have a better retroreflectivity because there are more glass beads correctly reflecting on the pavement surface [12]. Rougher surface textures like a bituminous treatment, also called chip and seal, causes paint to have a lower visibility and durability [12], [13]. It is recommended to slow application rate of the paint and glass beads so that the marking is thicker and there are more glass beads on the marking surface [14], [15]. Paint, and any marking material, performance and life span can be improved by inlaying the marking in a shallow groove [16]. Inlaying markings adds cost to a project because it requires grinding the pavement surface so it is not always done, however, research has been done to form grooves during construction to avoid grinding and reduce cost [16].

2.1.2 Thermoplastic

Thermoplastic, first used in 1958, is a widely used pavement marking that has been successful in a variety of situations [1], [10]. It consists of four primary ingredients: binder, pigment, glass beads, and a filler (typically sand or calcium carbonate). Performance is heavily influenced by application environment including pavement surface type, surface cleanliness, ambient and material temperature, and pavement moisture [10]. Thermoplastic is a popular marking material due to the high durability and relatively low cost when compared to other high durability markings [15]. However, when improperly installed, thermoplastic is also known to de-bond quickly [16].

Thermoplastics are highly recommended for asphalt. There is a lower performance on concrete due to premature debonding [10], [11], [16]. This difference in performance is due to the type of bond with the surface. For installation, the surface is heated until the material melts and bonds to the surface [11]. On asphalt surfaces, the asphalt binder also melts to create a tight thermal bond. Although, a laboratory study indicated that the installation of thermoplastics inlay markings can cause additional aging to the asphalt which can be detrimental especially for old surfaces [17]. On a concrete surface, when the thermoplastic is heated the material seeps into the pores of the concrete and hardens creating a mechanical bond which is not as strong as the thermal bond [10], [11]. It is suggested to use an epoxy primer to improve performance on concrete [10], [11]. It is also recommended that a thicker layer of thermoplastic be applied when a surface treatment like chip and seal is used due to the increase in roughness reducing the retroreflectivity [15]. When applied correctly, thermoplastics can have a service life of 6 years on asphalt and 5 years on concrete in cold climates [15].

There are two common types of thermoplastics which are differentiated on the type of resin used. Hydrocarbon thermoplastic is petroleum derived and is therefore susceptible to oil [11]. This type is recommended for arterial and non-urban highway use [14]. The other is alkyd thermoplastics which is a naturally occurring resin. This type is resistant to oil but sensitive to heat so extra care must be taken in the installation process [11]. Alkyd thermoplastics are recommended for use in high traffic areas like urban roadways [14]. Thermoplastics can be mixed and formed onsite or can be pre-formed. Figure *2* presents a layout of thermoplastic processing for pavement markings. Pre-formed thermoplastic keeps retroreflectivity better because glass beads are distributed evenly through the depth of the marking so that as it wears, it still reflects. Preformed has a higher initial cost than standard thermoplastics and requires a sealer when used on concrete and aged asphalt [11]. When installing in a snow region, it is also recommended that the thermoplastic be recessed to reduce damage from snow plows [15], [16]. With snow plow damage and general winter exposure, thermoplastics tends to have a steep drop in retroreflectivity after the first winter [14].

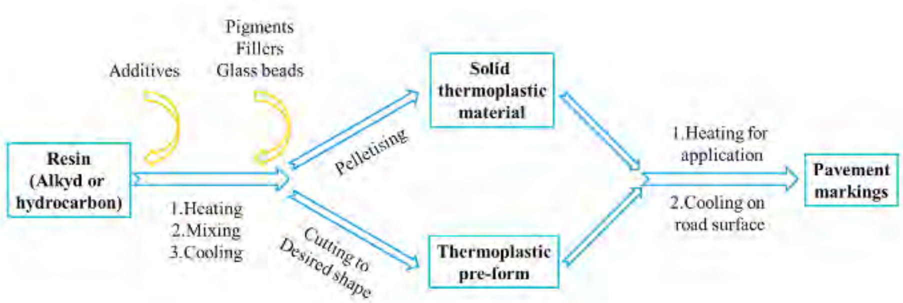


Figure 2: Thermoplastic processing for pavement marking application [1]

2.1.3 Tape

Tape is a versatile pavement marking because it can be used in temporary and permanent settings. Tape is a popular choice for pavement marking because it has very good initial retroreflectivity when dry and wet [1], [10], [11], [16]. The permanent tape is also shown to have high durability and a long service life. The disadvantage is that higher performing tape is expensive. The least expensive tape is typically only for temporary construction markings. Due to these characteristics, tape is not recommended for low traffic levels but is suitable for medium and high traffic [10].

Tape is made by melting and extruding plastic into the desired shape with a pre-applied adhesive on the back [10]. Tape can either be embedded into fresh asphalt or can be placed on an existing surface and pressed using a roller or truck tire [10], [11]. There are strict placement requirements set by the manufacturers (including cleanliness and specific temperatures) that must be met for the tape to have a good bond with either concrete or asphalt. Tape can also be inlaid in a groove to improve performance when compared to surface application [11]. The application and removal process for tape is easy but slow. At the end of its service life, the tape must be removed because it is incompatible with other marking materials [11].

2.1.4 Epoxy

Epoxy is a thermosetting material first developed in the 1970s consisting of two parts [10]. The first is a mix of resin, pigments, extenders, fillers, and glass beads. The second is the catalyst for setting. Epoxy is shown to adhere well to both concrete and asphalt but tends to have a higher retroreflectivity on concrete [11]. Epoxy is a popular choice for markings due to its good abrasion resistance and the lower sensitivity to applications factors [10], [11], [14]. Depending on the manufacturer, epoxy can be installed at surface temperature as low as 35°F and while the surface is wet. Proper cleaning is still required before application. The lower requirements for application makes epoxy attractive to many state departments, especially ones that experience winter, because the installation period can go longer into the colder weather [14]. Epoxy has a service life of about 4 years in cold climate conditions [15]. In a survey of several State DOTs epoxy was found to be the popular choice for concrete pavements, however, permanent tape was considered the best material [10].

Two component markings, which includes epoxy, tend to have poor resistance to ultraviolet radiation and absorbs contaminants from traffic which leads to discolorations and deterioration [1], [11]. There also has been reports of lower durability in high weaving areas and a decline in retroreflectivity after one winter [11], [14]. To address these issues, polymers can be added to increase durability and resistance to ultraviolet radiation [11].

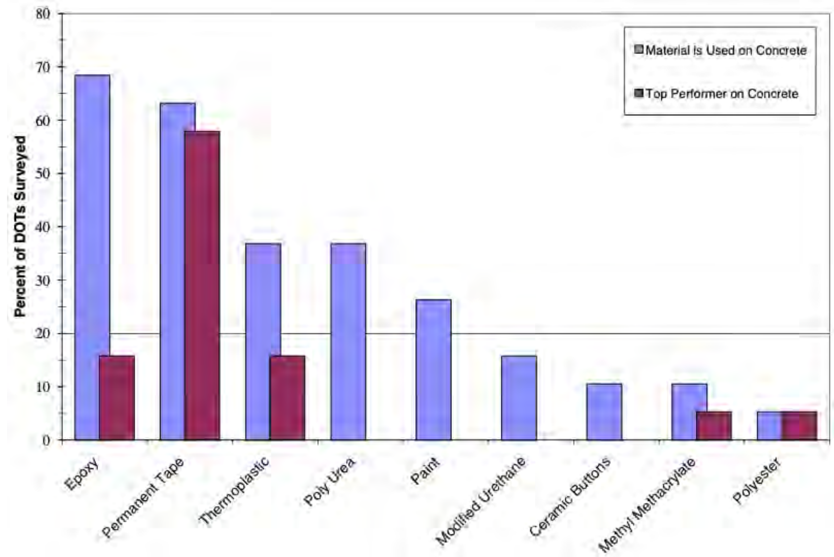


Figure 3: Marking material preference and performance evaluation in PCC pavements by State DOTs [10]

2.1.5 Polyurea

Polyurea is another two component marking that was originally developed in 1989 [10]. This marking material bonds well with concrete and asphalt and can be used for all levels of traffic. Polyurea has an approximate life of five years in cold climate conditions [15]. There are several advantages to this material. There are low application requirements since polyurea is not effected by humidity and can be applied at surface temperatures as low as 40°F [10], [11], [14]. Polyurea also dries fairly quickly when compared to other marking materials. When applied to the surface, polyurea performs similarly to thermoplastics in durability and visibility. Inlaid polyurea tends to retain retroreflectivity better and has an overall better performance especially in bituminous concrete [14]. Polyurea is also shown to have a high initial retroreflectivity and tends to retain it better over time [14]. Two component materials, including epoxy, urea, and urethane, tend to have poor resistance to ultraviolet radiation [1]. The main advantage is that this two component material has improved color stability and lowered sensitivity to ultraviolet light [10], [11]. However, polyurea has a much higher initial cost due to the specialized equipment needed to install [11].

2.1.6 Other

There are several other marking materials that can be used but are not as common as those listed above. Often these methods are more expensive or complex than other more common methods.

Methyl methacrylate (MMA) is a two-component material that does not need external heat to cure. When mixed, it creates an exothermic reaction that causes a strong bond with both concrete and asphalt surfaces [10], [11]. MMA has been shown to perform slightly better on concrete than asphalt, however, proper marking thickness is crucial to the performance [15], [16]. MMA can either be sprayed or extruded for application in temperatures as low as 40°F but has a long curing time when compared to other marking materials [10], [11]. The main advantage of MMA is that it is resistant to oil, antifreeze, and other chemicals commonly found on pavement surface. It also has a high durability when exposed to high traffic levels and snow removal and can typically last about 5.5 years [15]. The reason this material remains uncommon is that it is very expensive to produce and requires specialized equipment.

Another less common material is modified urethane. This material is similar to polyurea and epoxy but has been shown to have increased durability, quicker cure times, and better stability when exposed to ultraviolet radiation [10], [11]. Typical service life in cold climates are about five years [15]. This material is more expensive than epoxy but less so than polyurea because modified urethane is able to be applied using the same machinery as epoxy [11].

There are many other marking materials currently being researched but have extremely limited to no real-world use at this time. Some materials currently being investigated include photoluminescence and nanocomposites [1].

2.2 Pavement Distresses Related to Pavement Markings

A study was done at the Utah Department of Transportation when they observed pavement distress underneath pavement markings [18]. They hypothesized that markings could contribute to the deterioration of the pavement and in some cases are the main source of the distress. This study observed pavement deterioration under both tape and water-based paint as shown in Figure 4 and Figure 5. This study was solely based on observations, but they had two hypotheses on the cause of the distress. First, that water vapor was trapped between the marking and the pavement surface. Asphalt mixtures with low binder content are more susceptible to moisture damage, raveling, and cracking. The state of Utah changed their asphalt gradation to increase the binder content in 2008 to address this issue. The second hypothesis was that there were differential strains in areas with pavement markings due to a difference in reflectivity. It was also noted that some issues began at construction joints where improper density could have been a concern.

Figure 4: Pavement distress focused in pavement markings taken in Spring 2009 near Salt Lake City, Utah when the pavement was 7 years old with tape markings [18].

Figure 5: Pavement distress focused in pavement markings taken in Spring 2009 near Santaquin, Utah when the pavement was 6 years old with water based paint markings [18].

The Wisconsin Department of Transportation conducted a project that was originally proposed to investigate an alternative marking method involving milling or ground grooves on concrete pavements [19]. However, a second investigation began when early marking failure was observed on a specific section. Several markings were missing or de-bonded. An example of their observations is shown in Figure *6* [19]. The failed markings are what began the investigation; however, it was concluded that the primary cause of failure was expansive coarse aggregates. A high absorption value and soundness value that was just within the upper limit caused pop outs in several areas on the roadway including below missing markings. There were still observations of missing or de-bonded markings without the pavement distress underneath. They concluded that an adequate bond was not initially achieved, adding to the chance of marking failure. This was the only report with observations found on concrete pavements.

Figure 6: Missing or de-bonded pavement markings due to aggregate pop outs and poor bonding [19].

The Illinois Center for Transportation evaluated the performance of various pavement markings on both concrete and asphalt surfaces over four years with a focus on durability and visibility [13]. The data gathered in this study was ultimately used by the Applied Research Associates to create a pavement marking selection guide for Illinois. They focused on three factors that affect pavement marking performance: environmental condition (specifically snow and the subsequent removal), pavement surface type (determining the bond between marking and surface), and traffic volume. Based on their findings, they created a chart of material recommendations based on region, traffic, pavement type, and surface installation verses recessed. During this study, they observed some pavement distress beneath the pavement marking. As shown in Figure *7*, one of their test sections had deterioration within the four years of the study. This pavement marking material was polyurea. However, distresses were not limited to the areas under the pavement marking and were observed in other locations on the pavement surface.

Figure 7: Pavement distress beneath polyurea pavement markings [13].

Research conducted on pavement distress related to pavement markings is limited and observational. In Pennsylvania, members of the Impactful Resilient Infrastructure Science and Engineering (IRISE) consortium recently reported observations of pavement surface distress located directly over or close by pavement markings, especially center skip lines. As the main objective of this project is to evaluate these distress, three main hypothesis that may be affecting pavement marking interaction with the pavement surface were studied: trapped moisture, temperature differences, and improper longitudinal joint construction.

2.2.1 Trapped Moisture

A potential cause of distress is excess moisture trapped beneath the pavement marking. Trapped moisture under painting is a known problem for building construction. Moisture in a pavement system can cause many distresses which can limit the life and durability of a pavement. In concrete pavements, moisture in the concrete can lead to durability cracking, alkali-silica cracking, and aggregate popouts. Moisture damage within concrete needs another component in order to cause the distress. Durability cracking is caused by freezing and thawing of water within the system, alkali-silica cracking requires reactive aggregates, and popouts require expansive aggregates [20]–[23]. While moisture in a concrete pavement is of concern, asphalt is more susceptible to pavement failure due to moisture because moisture alone can cause many problems in asphalt.

The mechanisms of moisture damage in an asphalt pavement is the loss of cohesion and stiffness, stripping, and the degradation of aggregates [24]. These can lead to strength reduction, fatigue cracking, rutting, raveling, stripping, and pothole formation. These mechanisms are based on the transportation of moisture through the pavement and the systems' response [25]. Under vehicle loads, the water within the pavement is pumped through the voids and will remove the binder which is called stripping [26]. This is common on the bottom of the system where moisture tends to gather but if there is a reason for the water to gather at the surface the same loss of binder will occur, it is then called raveling. Stripping specifically causes pothole formation while raveling causes poor ride quality, increased noise, and loose aggregates on the pavement surface (Figure 8) [27], [28].

Figure 8: Raveling on asphalt pavement surface [27] and stripping between asphalt layers [28].

An open-graded pavement naturally allows water to drain through the system limiting moisture related distresses. Moisture moves through a pavement through (1) vapor diffusion, (2) vapor convection (air movement), (3) capillary action, or (4) gravity flow [29]. Vapor diffusion and convection are especially active at a pavement surface. Vapor diffusion acts to move vapor through air in porous materials from high concentration to low [29]. Blocking this movement may trap moisture in the system and accelerate moisture damage in that area [28]. For example, a study was done on moisture trapped between an open-graded pavement and an asphalt overlay or a chip and seal layer [28]. Moisture is trapped in the underlaying layer and can lead to moisture related distresses including stripping in the porous underlayer and delamination of the overlay. This is often seen in pavements with low density and high air voids, which are already more susceptible to moisture damage [28].

Trapping moisture beneath a lower permeable material like an asphalt overlay will lead to serious distresses in the pavement system. A similar problem has been seen in buildings. Corrosion in the metal components, carbonation, alkali-silica reaction, durability cracking, and volume changes are also seen in buildings [29]. When considering a coating for a building exterior, vapor permeability is an important factor to limit moisture in the underlying layer because it controls the moisture exchange between the building and environment [30]. Paint is a popular coating in building exteriors but even permeable paints can have an effect on the drying rate of the underlaying layer [30]. This limitation of vapor diffusion is also evident in other nonporous materials including some plastics [29].

Pavement markings' vapor permeability would control the moisture diffusion in that area. Since it has been established that paints, plastics, and other nonporous materials can restrict moisture movement, the pavement marking may hold moisture in the pavement longer than if the surface was exposed to air directly. The trapped moisture could lead to accelerated moisture related distresses in concrete pavements. With repeated loads from traffic, especially at high volumes, the movement of moisture beneath the marking could also lead to stripping of an asphalt pavement and the delamination of the marking.

Ground penetrating radar (GPR) has been used with varying degrees of success to analyze moisture content [31], [32] and moisture related damage in asphalt layers [33]. No record of GPR use to study moisture entrapment under pavement markings was found.

2.2.2 Temperature Differences

A potential cause of distress surrounding pavement markings is a temperature difference between the area under and around the pavement marking when compared to the rest of the pavement surface. Temperature can influence the rideability, serviceability, and safety of the pavement as well as the temperature of the surrounding environment [34]. High temperatures paired with high traffic loads can lead to plastic deformation in asphalt pavements like rutting and can lead to warping and curling in concrete pavements [34], [35].

There are several methods of heat transfer within a pavement system [36]. Solar radiation brings heat into the pavement with the thermophysical properties of the pavement reflecting some radiation back. Another is convection at the pavement surface due to circulation from the surrounding environment and finally the conduction of heat into the lower layers of the pavement structure. These methods of heat transfer all greatly affect the temperature profile of a pavement. External factors that contribute to the amount of heat transfer from these methods include time of day, air temperature, wind velocity, and other environmental factors [37]. Thermal properties of the pavement also affect the temperature profile like thermal conductivity, specific heat capacity, density, albedo, and thermal emissivity [37].

Studies has found that increasing the albedo is the most effective method to decrease the pavement surface temperature [35], [37]–[39]. Other directly related properties include thermal emissivity, which when increased, and diffusivity, which when decreased, will decreased the maximum surface temperature. Albedo, also called solar reflectivity, is the ratio between the reflected solar radiation and the incident or total solar radiation that falls on the surface. A albedo of 0 means that the material is a perfect absorber while a 1 would be the perfect reflector [40]. A new asphalt pavement will have a albedo of 0.05 to 0.10, a grey concrete will fall between 0.35 and 0.40, and a white concrete is 0.20 and 0.30 [40]. Asphalt pavements especially are dark and dense, absorbing and releasing more heat [36]. An asphalt with the albedo value of 0.05 means that 5% of solar radiation is reflected and 95% is absorbed [38]. Materials with lighter colors will have a higher albedo, reflecting more solar radiation and therefore stay cooler. The albedo value will also change over time, asphalt will get lighter due to oxidation and wearing of the binder and concrete will darken with dirt and tire marks (Table *3*) [38], [40].

Table 3: Typical albedo values for pavement surface materials [40].

Pavement Material	New	Weathered
Asphalt	0.05-0.10	0.10-0.15
Grey Concrete	0.35-0.40	0.20-0.30
White Concrete	0.70-0.80	0.40-0.60

Another property that has a direct effect on the pavement surface temperature is emissivity. This reflective property is proven to reduce solar radiation absorption when lowered [37]–[39], [41]. Emissivity is the ratio of energy radiated from a material surface compared to the energy radiated from a blackbody under the same conditions [41]. A 0 represents a perfect reflector and a 1 is a perfect emitter. Asphalt pavements typically have an emissivity of 0.93 and concrete ranges from 0.85-0.95 [42]. In a study done on reducing heat for solar radiation in buildings using external coatings, they used thermal paint which was defined as ceramic or glass beads dispersed in a polymer, similar to paint that would be used in pavement markings [41]. They measured the emissivity of the thermal paint to be 0.86. For pavement markings, this value is most likely even lower since pavement marking is designed with a high reflectivity in mind.

Research has been done to increase albedo and decrease emissivity of pavements using paint coatings to lighten the color or altering thermal and reflective properties with additives including glass beads that are typically used in pavement markings [34], [41], [43]–[45]. A pavement marking that is a lighter color, typically white or yellow, and is required to have reflective qualities would have higher albedo and emissivity values than a pavement surface especially when compared to asphalt pavements. This difference in reflective and absorption qualities between the pavement marking and pavement surface may be significant enough to cause substantial temperature differences in the area surrounding the marking that can lead to pavement distress or contribute to existing distress.

2.2.3 Longitudinal Joint Issues

Joints on any pavement are launching points for a variety of pavement distresses due to the high potential of water infiltration (Figure 9); however, longitudinal joints are necessary in all pavements. Concrete pavements longitudinal joints can experience water-based distresses, such as longitudinal and durability cracking, and be the initial point of pavement failure. For asphalt pavements, poorly compacted joints allow water to penetrate easier causing debonding surface layers, stripping, and oxidizing [46]. When the first asphalt lane is paved, it will have an unconfined edge that will have a lower density compared to asphalt towards the center of the lane. The second lane will be confined by the first and will therefore have a relatively higher density [47]. The asphalt on either side on the joint will still have a higher air void percentage and lower density than the mainline pavement 12 inches away. This density gradient across the joint is a major source of pavement distresses including longitudinal and fatigue cracking, raveling, and crack widening [47]–[49].

Figure 9: Deteriorated longitudinal joints with water infiltration [50]

Due to the observed longitudinal joint problems in Pennsylvania, new procedures have been implemented in 2020 to improve pavement performance and lower maintenance costs. These improvements can be found outlined in the Pub 408 and the 2020 Asphalt Technician Field Program [8], [49]. Previous standard practices that were commonplace in most if not all asphalt roadways included significant handwork and luting at the edges of the pavement. This involved smoothing the edges and pushing fallen material back into the paved surface. This created inconsistent depths and densities along the joint. Updates have been implemented in Pennsylvania in recent years to improve density at longitudinal joints when using vertical joints, cut vertical joints, and notched wedge joints so that handwork in unnecessary when joint construction is performed correctly.

While these new joint procedures are an improvement from the previous standards, the density of longitudinal joints is still 1-2% lower than the mainline [48], [51]. The theoretical maximum density of an asphalt pavement is 2,480 kg/m^3. Most agencies require no less than 92% of the maximum density or 8% air voids in the mainline of the pavement with a maximum of 10% air voids around the joints [47]. In recent years, Pennsylvania increased the required density in longitudinal joints from 90% to 91% of the maximum density, 9% air voids, to increase the quality of asphalt joints [8].

While Pennsylvania is taking greater care towards to density of asphalt pavement joints, previously constructed roadways will still be prone to longitudinal joint distresses. When constructing pavements, it is recommended to plan accordingly so that pavement markings will not be directly over the joint [8], [49]. However, the markings are still relatively close to the joint where the density will be lower than the mainline and there may be instances where there is an overlap. The pavement markings may be influencing the distresses caused by the already permeable joint. During installation, some pavement markings are heated or require heating or grinding the pavement which could farther alter the density and surface irregularity of asphalt in that area. The aforementioned moisture issue combined with a higher permeability around the joints could also be increasing the chances of pavement distress under or around a marking. Pavement markings could be contributing to distresses in an already vulnerable area of asphalt pavements, leading to the eventual pavement failure that is already so common around longitudinal joints.

As with trapped moisture, GPR can also be used to quickly and non-destructively determine asphalt density over and around the pavement marking. Several studies have used GPR and its variations to successfully assess asphalt density in different settings[31], [32], [52], [53].

3. Identification and visual survey of sections

A visual survey was conducted by the research team using information provided by several transportation agencies. The IRISE community provided information on highway and arterial segments in the metropolitan area of Pittsburgh, Pennsylvania. The Pennsylvania Department of Transportation (PennDOT) provided photograph and video recordings of sections in two Districts while Allegheny County provided photographs of several sections in and around Pittsburgh. The Turnpike Commission did not report any sections with potential distresses related to markings. However, the Turnpike provided records showing changes in procedures for the location of markings in relation to the longitudinal joint.

The research team conducted visual surveys of the sections located in Allegheny County documenting pavement conditions around the marking and outside the marking. Three Allegheny County sections were selected for nondestructive testing using an ultrasonic device to estimate density differences between marked and unmarked pavement segments.

3.1 PennDOT Sections

PennDOT conducted a wide survey of its districts in search for pavement distresses that could be linked to pavement markings. Representative results came from District 10 and District 12. Unfortunately, by the time that the present research project started, the sections in District 10 were rehabilitated making up-to-date surveys and testing impossible.

3.1.1 US 422 in Butler and Armstrong Counties (District 10)

Based on a 2018 internal memorandum, District 10 has been observing distresses like surface delamination (Figure 1) and potholes (Figure 11) occurring mostly on the white skip markings on multi-lane highways. According to Michael J. Shanshala, former Maintenance Services Engineer for District 10, markings perform well in the initial three to five years after marking placement. After this period, the markings start to delaminate, exposing a dark and raveling asphalt and within two years after the initial distress, delamination becomes more severe with aggregate popouts (Figure 12) around the line migrating to potholes.

The memorandum hypothesizes on potential causes of the distresses mentioning joint density issues, moisture retained in the asphalt mat under the marking, temperature differences between asphalt surface and marking, and chemical incompatibility between marking material and asphalt.

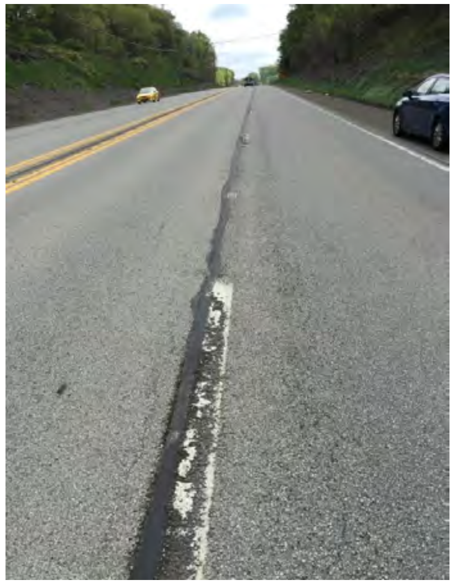


Figure 10: Surface delamination on US 422 skip line

Figure 11: Potholes on US 422 skip line

Figure 12: Aggregate pop out and pothole on US 422 skip lines

As mentioned before, these sections were rehabilitated before the project started in 2020. Nevertheless, one can observe from the pictures that there are issues with the longitudinal joint around the distressed area. However, the memorandum informs that the distresses were only observed in white skip lines. Yellow and continuous lines were sound. The memorandum also presents information on temperature variation between the marking and asphalt surface. The temperature of the white marking was 8°F lower than the surrounding asphalt whereas the temperature of yellow lines only varied by 3°F. Measurements were conducted on a cloudy morning (no month mentioned) under a temperature of 67°F. It is expected that in bright sunshine during the summer, these differences would significantly increase.

3.1.2 I-79 in Butler County (District 10)

I-79 presented similar distresses as the ones observed in US 422 as previously described. Figure 13 shows initial stages of potholes in the white skip line makings in two locations.

Figure 13: Pothole forming on I-79 skip lines

3.1.3 PA-51 in Westmoreland and Fayette Counties (District 12)

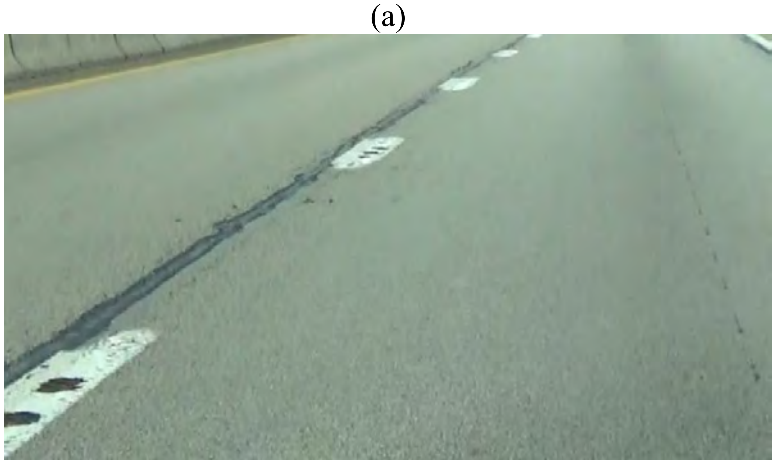
District 12 provided a video survey of PA-51 in between Westmoreland and Fayette Counties. The video (Figure 14) shows evidence of what appears to be asphalt raveling located at the skip marking lines. Evidence of longitudinal joint issues are also present.

Figure 14: Asphalt raveling on PA-51 skip lines

3.1.4 I-70 in Westmoreland County (District 12)

District 12 provided a video survey of I-70 in Westmoreland County. Throughout video survey it is possible to observe asphalt distresses and potential pothole formation in I-70 skip lines in both west and eastbound lanes (Figure 15).

(a)



(b)

Figure 15: Pothole formation in I-70 (a) westbound and (b) eastbound directions

3.2 Allegheny County Sections

Allegheny County pavement management personnel reported several sections with potential pavement distresses on or around pavement markings. A visual survey was conducted in each reported section.

3.2.1 977 to 1065 Forest Avenue

The pavement in this section presents several cracking distresses that connect to the cracking at the longitudinal joint – centerline marking (Figure 16). There is no indication that the markings are the cause of such distresses. Interestingly, the double continuous line in the lane center contains a longitudinal crack in only the line closest to the longitudinal joint. The other line is intact as seen in Figure 17.

Figure 16: Cracking in pavement lane connecting to cracking in longitudinal joint

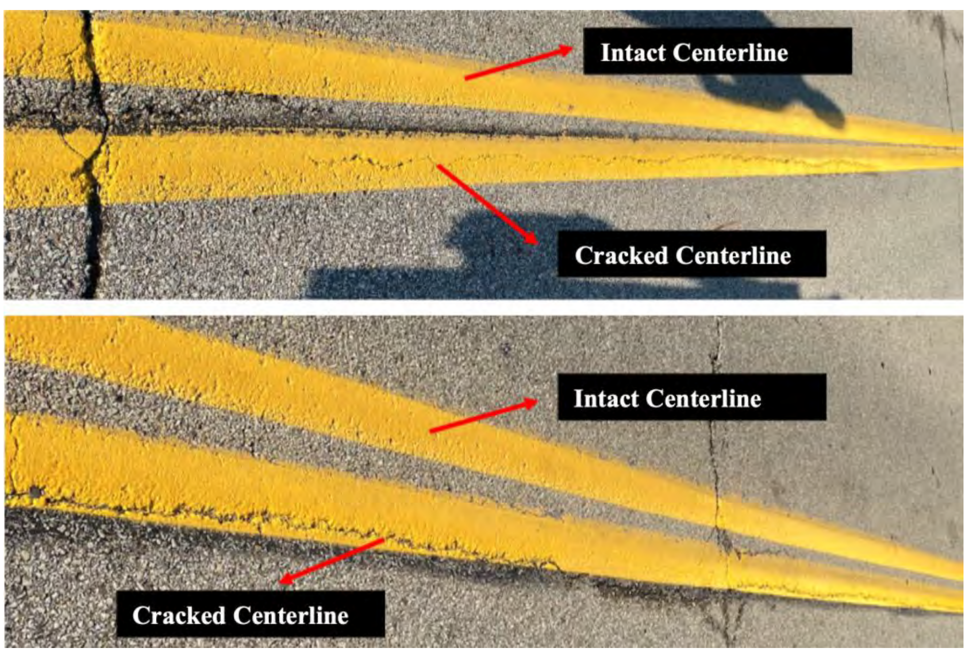


Figure 17: Examples of longitudinal crack in only one of the centerlines

3.2.2 3504 Greenburg Pike

The pavement in this section presents severe cracking in several segments (Figure 18a). Some segments were rehabilitated due to the severity of distress. Again, there is no indication that the markings are the cause of such distresses. As with the previous section, several segments present a longitudinal crack on only one of the centerline markings (Figure 18b).

(a) (b)

Figure 18: (a) Block cracking in two lanes with the centerline intact in the other lane and (b) longitudinal crack in only one of the centerline's lines

3.2.3 5309 Verona Road

The pavement in this section presents several cracked segments with wide-open longitudinal cracks (Figure 19). Several cracks are also present in the centerline marking with some loss in material.

Figure 19: Centerline presenting cracking and losing marking material

3.2.4 Crane Avenue

This section is located at the intersection with Banksville Road. The pavement presents severe cracking with fully formed potholes on both sides of the intersection (Figure 20). The distresses extend to the centerline and edge markings. Several cracks are also present in the centerline marking with some lose of material.

(a) (b)

Figure 20: (a) Deteriorated pavement and centerline on right side of the intersection and (b) deteriorated pavement, edge, and centerline (potholes) on left side of the intersection

3.2.5 McConkey Road with Corrigan Drive

The pedestrian crossing markings present several hairline cracks and loss of marking material (Figure 21) due to the marking material deterioration from heavy exposure to traffic. In Figure 21, the marking in the wheel path has been completely removed by traffic. These cracks are limited to the markings and do not seem to affect the pavement surface. The pavement presents larger transverse and longitudinal fatigue cracking that is unrelated to the markings.

Figure 21: Pedestrian crossing markings with different levels of deterioration.

3.2.6 3050 Bronsville Road

The pavement presents severe distresses at the pavement – shoulder joint and therefore distresses are located at the edge marking (Figure 22a). Distresses are also present at the centerline marking (Figure 22b).

(a)

(b)

Figure 22: (a) cracking and potholes in the pavement shoulder joint and (b) cracking at the longitudinal joint

3.2.7 Round Hill Road

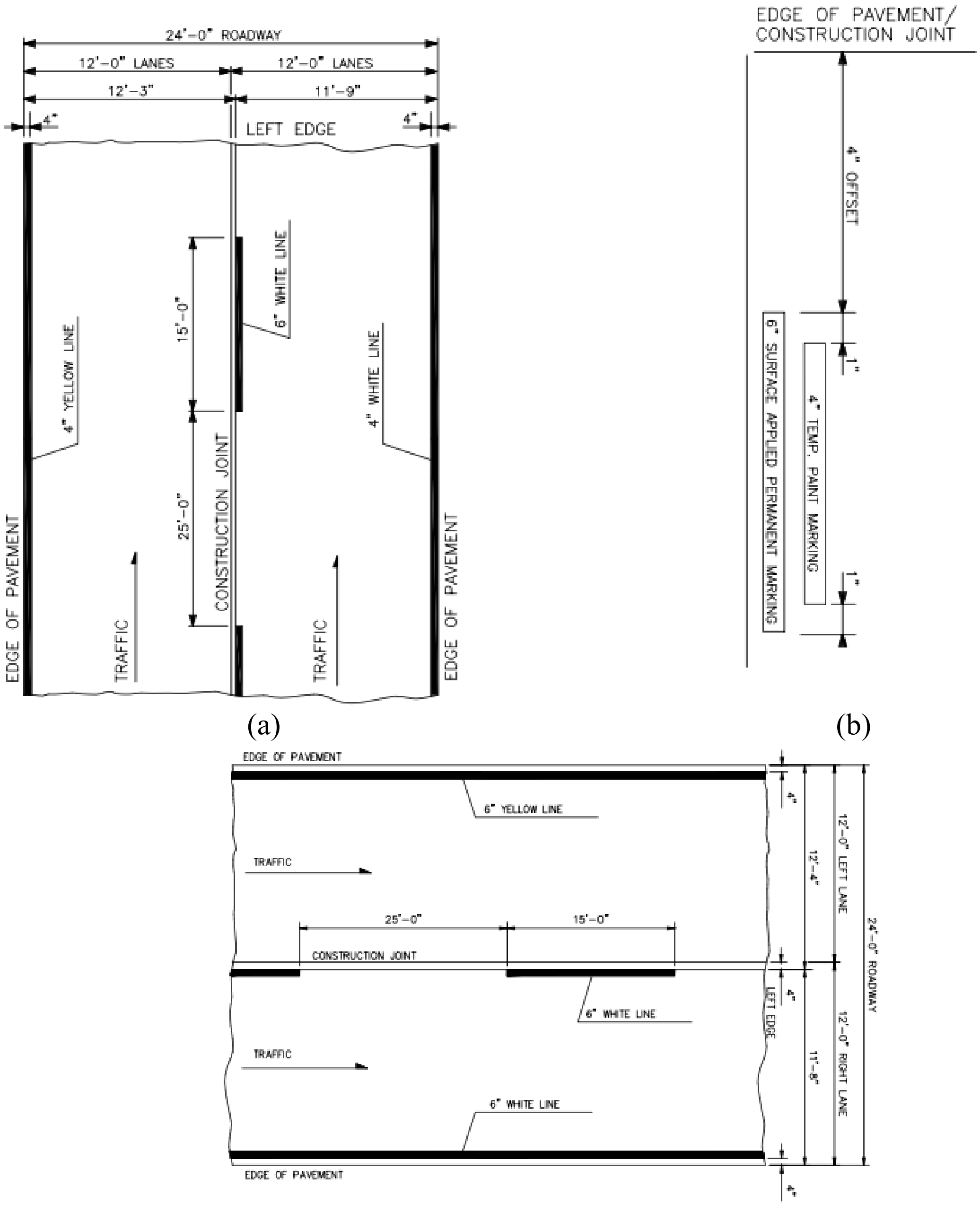
Similar to the previous section, this pavement presents severe cracking at the edge and centerline (Figure 23).

(a) (b)

Figure 23: (a) cracking and potholes in the pavement shoulder joint and (b) cracking at the longitudinal joint

3.3 The Turnpike Commission

The Turnpike Commission initially reported anecdotal issues with distresses around pavement markings. However, upon further investigation, Turnpike informed that those issues were resolved by altering the standards concerning the location of the markings in relation to the longitudinal joint. Standards from 2011 (Figure 24a) show that there was not a recommended offset between the centerline (white marking) and the construction joint [54]. In 2012, an updated standard [55] shows a 4 in. offset for the marking placement (Figure 24b). The 2015 standard [56] which is used currently for permanent markings emphasizes this offset with an additional drawing. The Turnpike Commission informed that since the change in 2012 there were less issues with the durability of pavement markings and the pavement underneath it.



(c)

Figure 24: Turnpike Commission standards regarding offset of centerline marking placement from longitudinal joint in (a) 2011 [54], (b) 2012 [55], and (c) 2015 [56]

4. Nondestructive Ultrasonic Testing

Ultrasonic testing was conducted in the Allegheny County sections. The main objective of this testing was to check different ultrasonic responses between the wheel path region of the lane and the longitudinal joint area. At the longitudinal joint, measurements were taken at the top of each centerline marking and in between markings according to Figure 25. Three measurements were taken at each point. The test was held on a cold, spring morning with an average air temperature of 50°F.

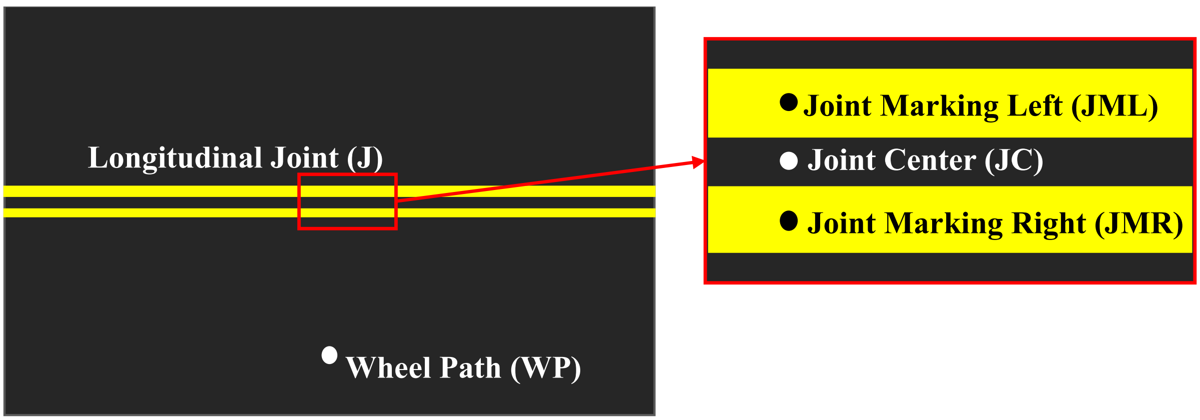
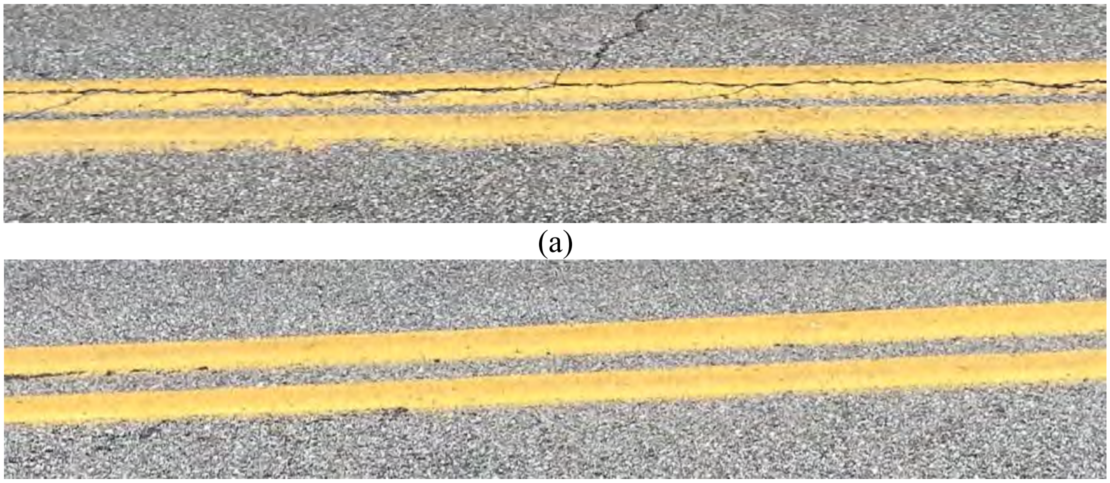


Figure 25: Ultrasonic testing layout

Due to potential traffic interruptions, only three sections were selected for testing. The selected sections, which were detailed previously in this report, were:

- Section 1 - 977 to 1065 Forest Avenue
- Section 2 - 5309 Verona Road
- Section 3 - 3504 Greenburg Pike

Several segments of each section were tested. The segments were selected based on the level of visible deterioration of the longitudinal joint. Segments presenting surface cracks at the longitudinal joint were classified as “deteriorated” whereas segments without surface distress were classified as “intact”. Figure 26 shows this classification in two segments from Section 1. It should be noted that even if there are no clear distresses on the pavement surface, the pavement structural integrity may still be affected by potential underlying distresses (for example bottom-up cracking).



(a)

(b)

Figure 26: Segments presenting (a) deteriorated and (b) intact longitudinal joint area in Section 1

4.1 Ultrasonic Device

The device used in the nondestructive testing was the UK1401 “Surfer” ultrasonic tester (Figure 27a). This handheld device was designed for measurements of time and propagation (pulse) velocity of longitudinal ultrasonic waves in solid materials, mainly concrete. The device has two dry contact transducers which allows testing directly on the surface without the need for a coupling material (Figure 27b). Ultrasonic pulse velocity testing has been used to estimate Portland cement concrete strength accurately [57-59]. More recently, researchers have used pulse velocity to estimate asphalt concrete properties such as dynamic modulus with mixed results [60-62]. The primary issues using ultrasonic testing for asphalt concrete is the materials’ viscoelastic properties and high dependency on temperature and loading time. However, ultrasonic pulse velocity can be used to roughly estimate density differences between pavement areas using the same asphalt mixture tested simultaneously in the same temperature. As with Portland cement concrete, testing a stiffer material will result in higher velocity propagation for the ultrasonic waves.

(a)

(b)

Figure 27: (a) Ultrasonic device [63] and (b) field testing

4.2 Ultrasonic testing results

Figure 28 through Figure 30 shows the comparison between ultrasonic pulse velocity at the wheel path and at the longitudinal joint for each segment in the three sections. Pulse velocity at the joint was calculated as the average between the three joint measurements as illustrated in Figure 25.

Direct comparison between sections is not recommended as these sections might have very different design characteristics regarding age, materials, traffic exposure, and construction practices. With this, results were analysed with focus on segments in the same section.

Section 1 (Figure 28) presents higher pulse velocity for the wheel path (average of 3628 m/s) than for the longitudinal joint (average of 3187 m/s). This indicates that the asphalt concrete density at the joint is lower than at the lane center (wheel path). Issues with achieving high levels of density at the longitudinal joint are common in asphalt paving [64] and are known to be the reason for several joint related distresses [65-67]. Results also show that joints without surface distresses (intact) also present higher pulse velocity than deteriorated joints confirming the greater presence of distresses in the latter.

Similar results were obtained from Section 2 (Figure 29) where the wheel path presents high, uniform pulse velocity with an average of 3870 m/s. The longitudinal joint was so heavily deteriorated that no intact segments could be scanned for this section. This longitudinal joint showed a much lower pulse velocity than the lane center with an average of only 3044 m/s.

Section 3 differed from the previous sections by showing similar pulse velocity between the wheel path and the longitudinal joint with averages of 3479 and 3498 m/s, respectively. This can indicate that the construction of the longitudinal joint for this section was more successful in achieving similar density levels when compared to the center of the lane. However, from all the tested sections, Section 3 segments present significantly more deterioration at the wheel path (Figure 30) even when the longitudinal joint area seemed intact. The presence of distress in the wheel path, as seen in Figure 31 can also help explain the lower pulse velocity in comparison with the other Sections although comparison between sections can be misleading.

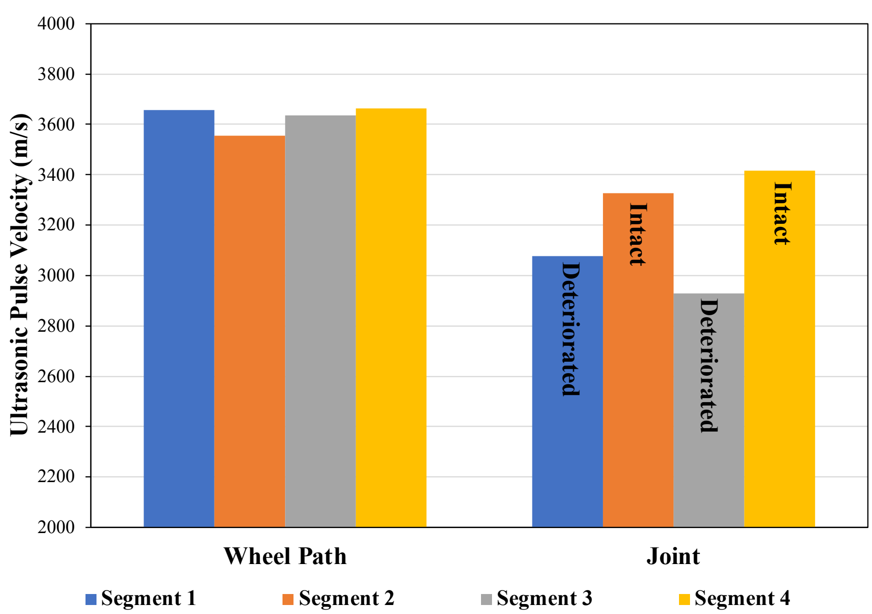


Figure 28: Ultrasonic pulse velocity at wheel path and longitudinal joint in Section 1

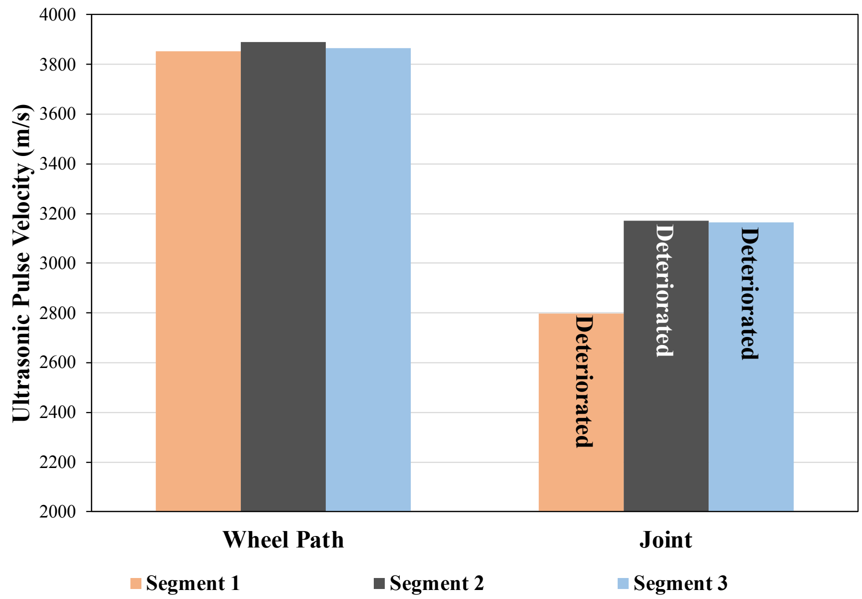


Figure 29: Ultrasonic pulse velocity at wheel path and longitudinal joint in Section 2

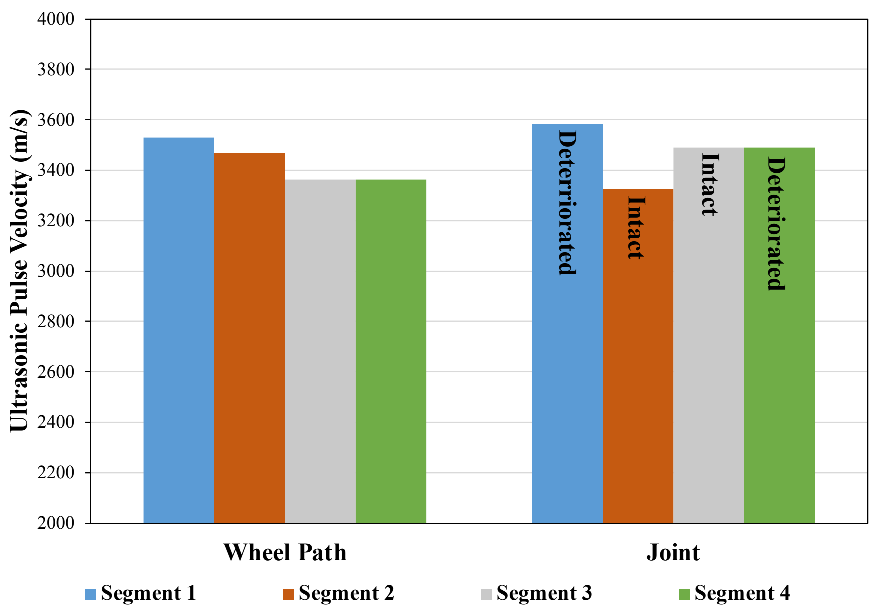


Figure 30: Ultrasonic pulse velocity at wheel path and longitudinal joint in Section 3

Figure 31: Pavement deterioration at the wheel path in Section 3

To evaluate the effect of markings on the ultrasonic pulse velocity, measurements at the longitudinal joint on top of the markings (joint marking right - JMR and joint marking left - JML) and between markings (joint center - JC) were analysed. Figure 32 presents the results for the three sections. As can be seen in the figures, results are inconclusive. There is no indication that measurements on top of the marking produces higher or lower pulse velocity.

Overall results indicate that pulse velocity is more affected by the proximity to the longitudinal joint regardless of the presence of pavement markings. An extra set of measurements was performed in segment 3 of Section 2 in which the ultrasonic device was positioned with an offset of 10 cm from the outer centerline marking. Results (illustrated in Figure 33) show that pulse velocity and potentially asphalt concrete density increases significantly right outside of the joint. This could help explain the success in avoiding premature marking deterioration by the Turnpike Commission when changes in standards for marking placement in relation to longitudinal joints were put in place.

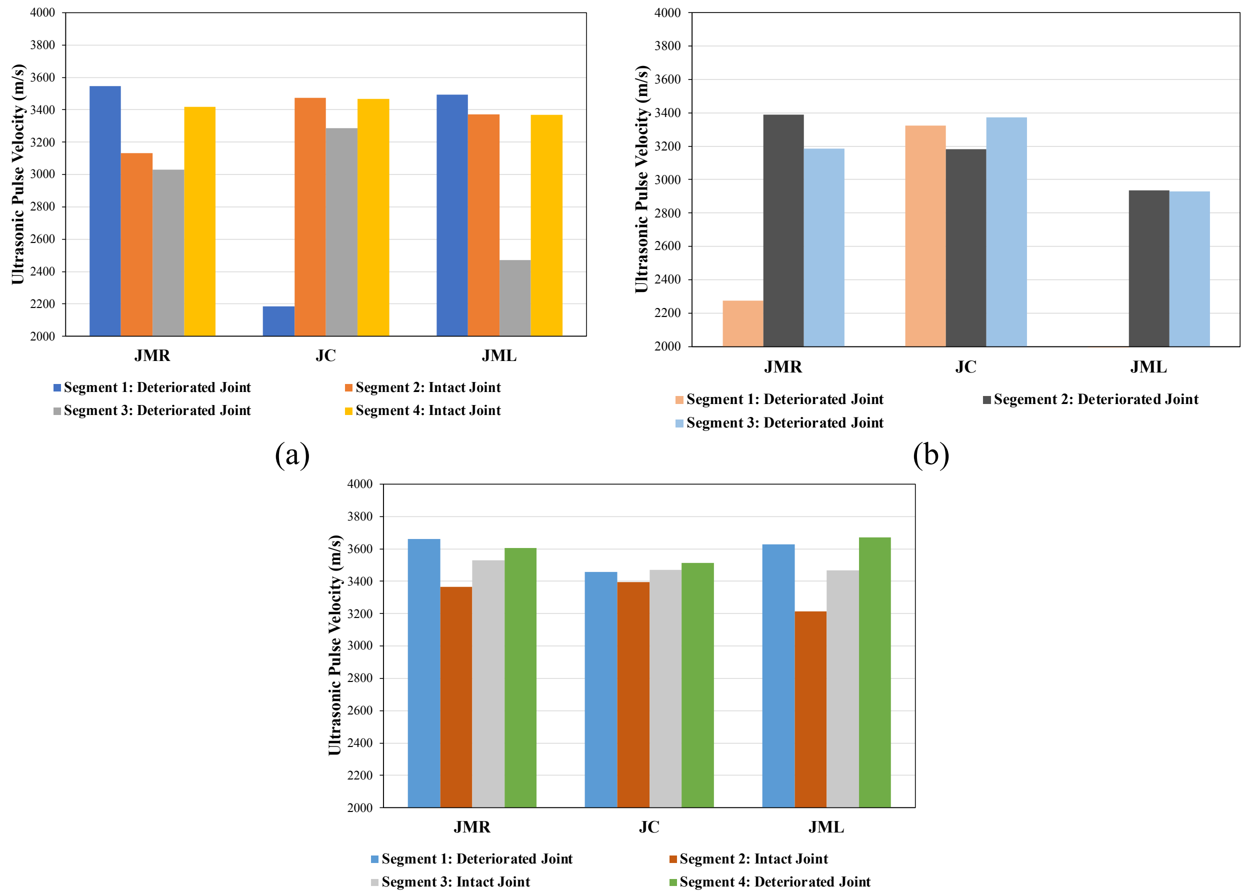


Figure 32: Ultrasonic pulse velocity at the joint for (a) Section 1, (b) Section 2, and (c) Section 3

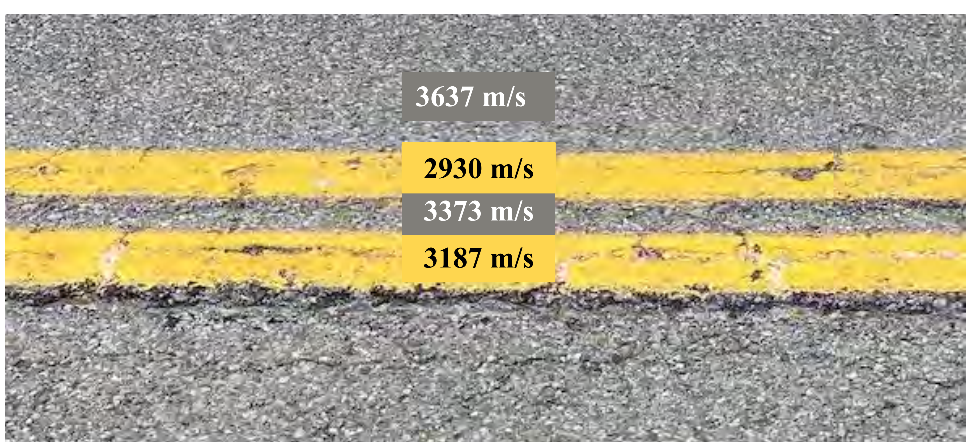


Figure 33: Ultrasonic pulse velocity at the longitudinal joint in different locations

5. Finite Element Modeling of Temperature Differences

Asphalt materials are widely influenced by temperature because of its viscoelastic thermo- and time-dependent properties [68]. Due to the temperature sensitivity of asphalt mixtures, the temperature-dependent response of asphalt pavements are significant because of their potential influence on pavement performance, particularly in areas that experience large temperature fluctuations. These temperature fluctuations may lead to contraction in asphalt mixtures, which can cause a build-up of tensile stress, also known as thermal-induced stress [69]. Cracks may initiate once the development of thermal stress exceeds the tensile strength of the asphalt material. Consequently, the propagation of thermal-induced cracks will damage the pavement structure while also providing paths for infiltration of surface water. Thus, accurate evaluation of the initiation of thermal induced fracture is critical for designing and maintaining durable asphalt pavements.

The significance of temperature with relation to crack opening of asphalt pavement has been confirmed for many years [70]. A number of studies have also been conducted to evaluate the climate related crack opening [71]–[77]. However, few have investigated the effect of pavement marking on pavement distresses. Asphalt pavements have a high solar absorptivity due to its typically dark color, especially in a young pavement [68]. Pavement markings have highly contrasting colors (white or yellow) compared to the pavement and therefore have a high solar absorptivity. During the day when the temperature is high, the significant difference in absorptivity can cause a large temperature difference around the marking edge, leading to thermal crack initiation. Prolonged summers and higher extreme temperatures of recent years [68] can further worsen the effect of pavement markings.

The objective of this chapter is to investigate the effect of temperature differentials between the pavement and marking surfaces. Models were developed to predict the damage inflicted on the asphalt surface caused by temperature differences. Finite element models were developed using ABAQUS and the stress gradient in the asphalt surface was calculated under a variety of temperature differentials.

5.1 Pavement and pavement marking model

A model of a three-layered asphalt pavement system was developed (Figure *34*). The input parameters of material properties of asphalt, base and subgrade layers are listed in Table *4*.

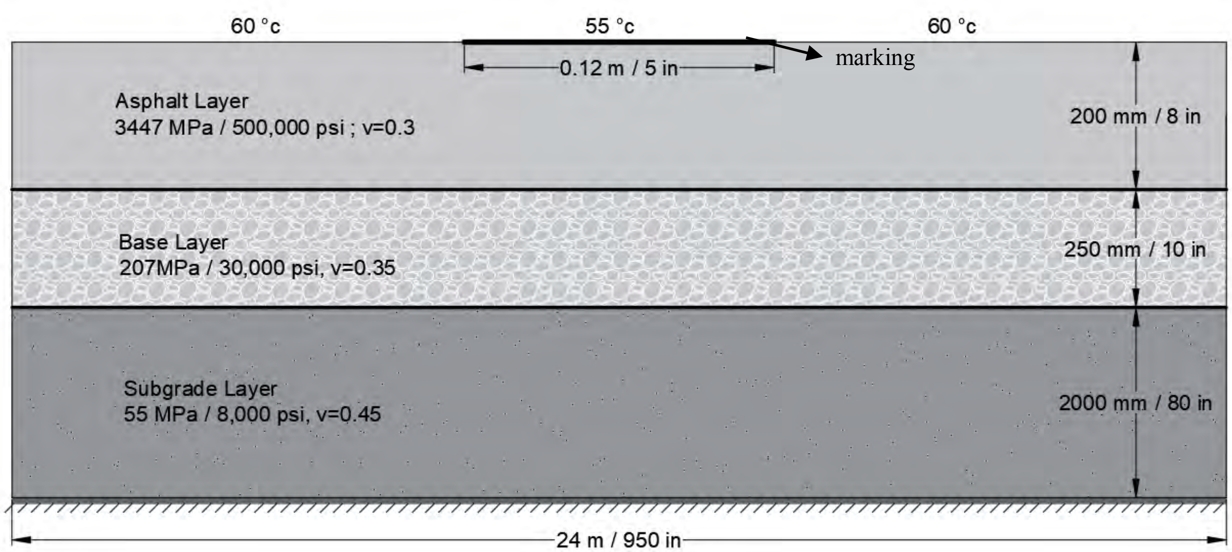


Figure 34: Three-layered asphalt pavement model

Table 4. Material properties of pavement layers

	Asphalt Layer	**Base Layer**	**Subgrade Layer**
Coefficient of thermal expansion (/ °C)	4×10^{-5}	1×10^{-5}	9×10^{-6}
Resilient modulus (MPa)	3447	207	55
Density (kg/m^3)	2240	1880	1530
Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)	900	800	600
Thermal conductivity (W/m K)	1.5	0.7	0.8

Note: The initial temperature is 20°c for all layers

The developed ABAQUS model used a biased mesh method to discretize the model meaning the mesh size is finer close to the pavement marker and becomes coarser farther away (Figure *35*). A coupled thermal-displacement simulation was performed in a steady-state analysis. The initial field temperature of the model was set as 68°F (20°C) for all three layers. The boundary conditions were set as 140°F (60°C) and 130°F (55°C) for asphalt and marking surfaces, respectively. On the left and right sides of the model, the horizontal displacement was fixed and at the bottom of the model, the vertical displacement was fixed. Interfaces between asphalt/base and base/subgrade were tied. A static analysis was performed with the results shown in next section.

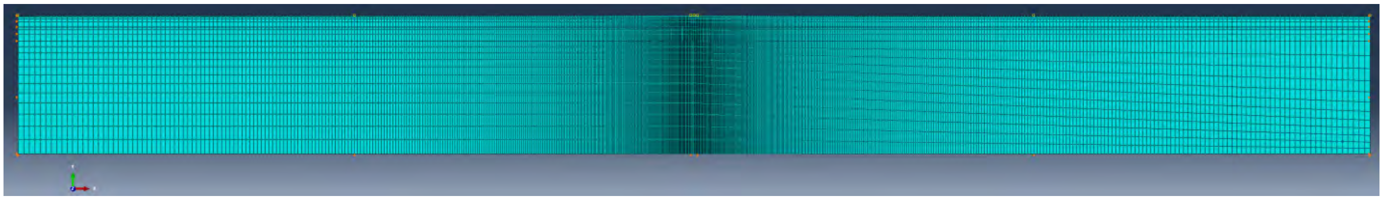
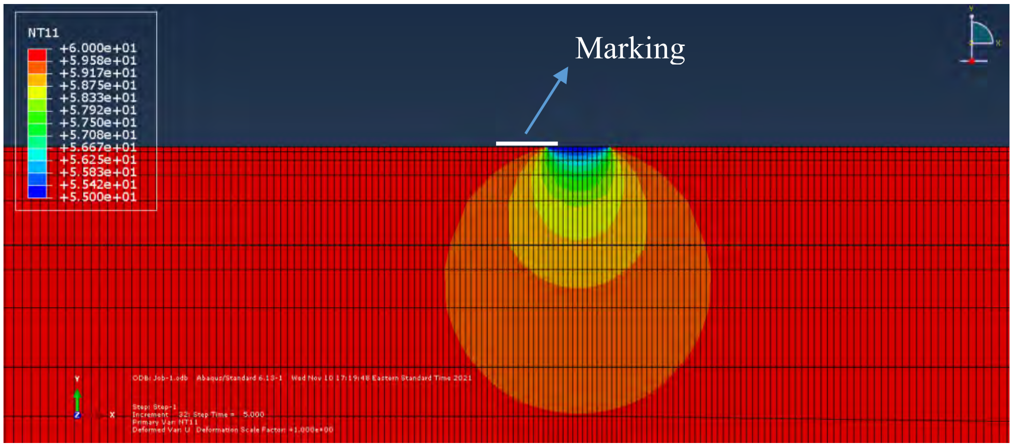


Figure 35: The developed ABAQUS model

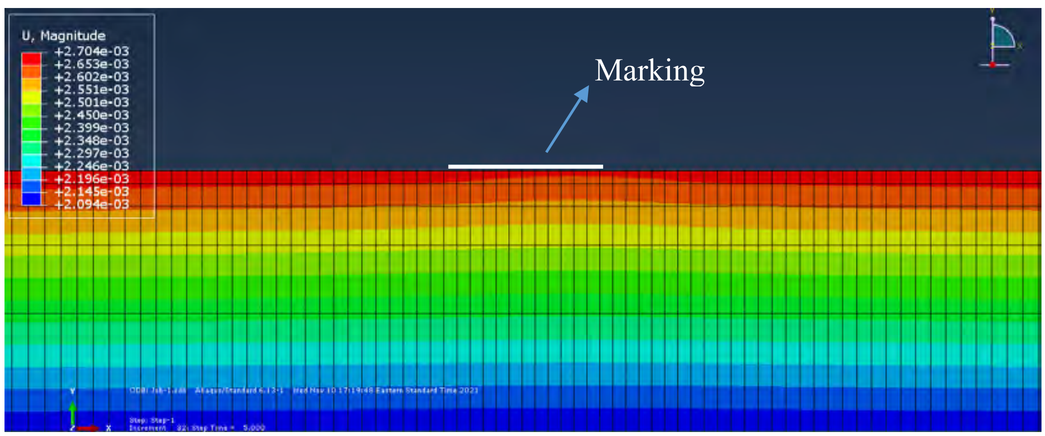
5.2 Simulation of temperature differential effects

The temperature distribution, vertical displacement, stresses in transverse (x direction) and vertical (y direction) directions cause by the temperature differential are shown in Figure *36* and Figure 37. The temperature distribution in Figure *36*a shows a decreasing gradient, with a lower temperature closer to the marking area. Figure *36*b shows the surface temperature differential effect on deformation decreases with an increase of asphalt depth. These results are as expected based on previous hypotheses outlined in this report.

High-stress gradients in both horizontal and vertical directions are observed between marking and asphalt surfaces as shown in Figure 37. Since stresses are calculated assuming elastic behavior, very high values are observed between marking and asphalt surfaces (details can be seen in magnified plot in Figure 37). These high stresses are stress singularities that do not exist in practice. When stresses increase beyond the tensile strength of an asphalt layer, cracks would initiate and the stresses would be released. Since asphalt material has viscoelastic behavior and presents healing properties in the field, the results presented using this elastic model might not be representative. In any case, points with high stresses represent locations which can develop cracking exposing the effect of thermal differentials between pavement and marking surfaces.

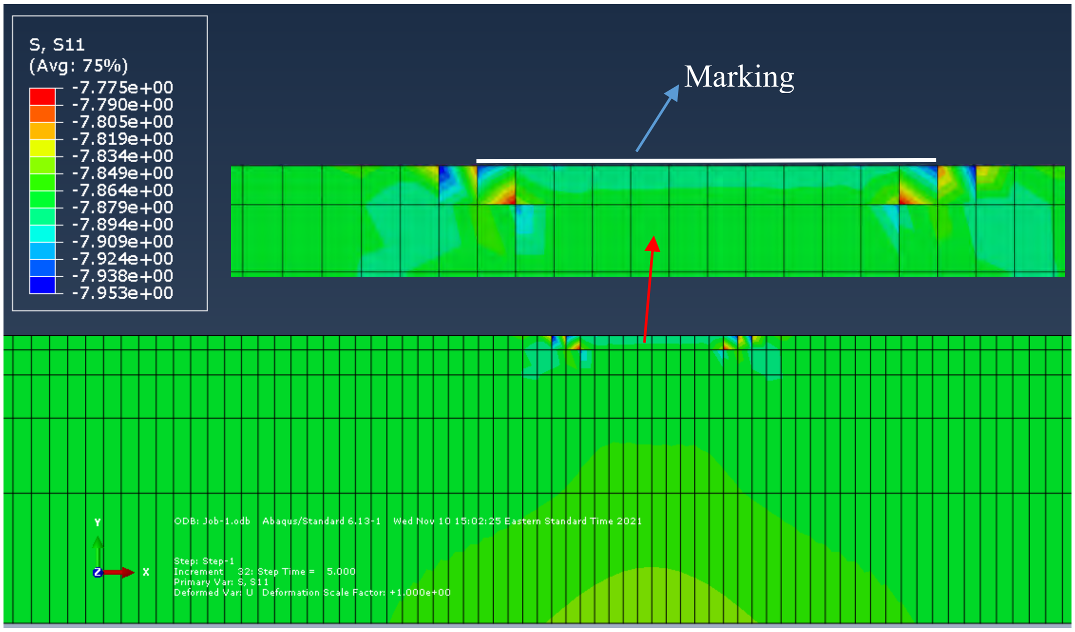


(a)

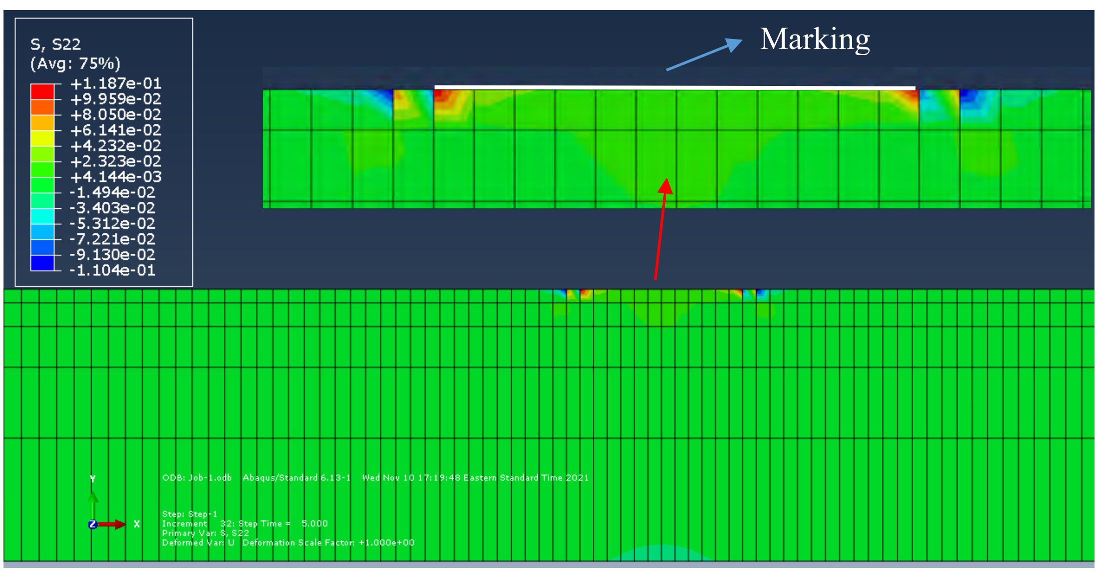


(b)

Figure 36: (a) Temperature distribution and (b) displacement in vertical direction



(a) stress in transverse direction (x-direction, MPa)

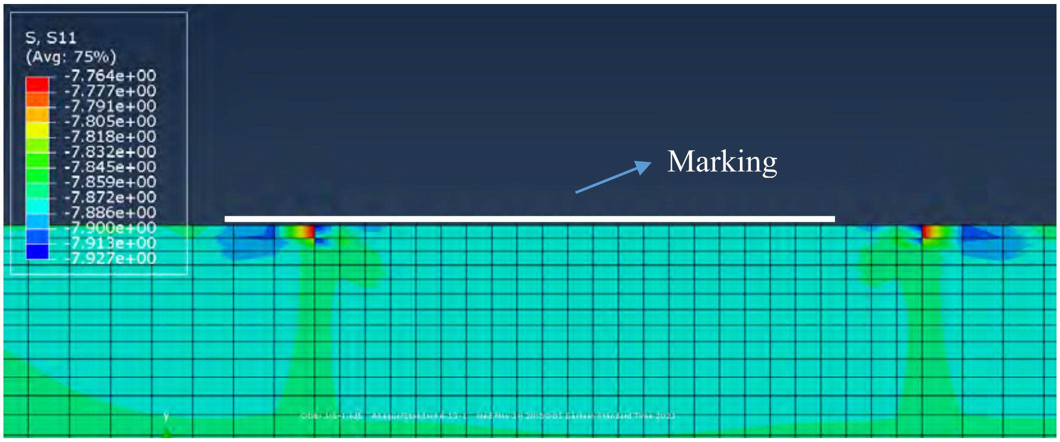


(b) stress in vertical direction (y-direction, MPa)

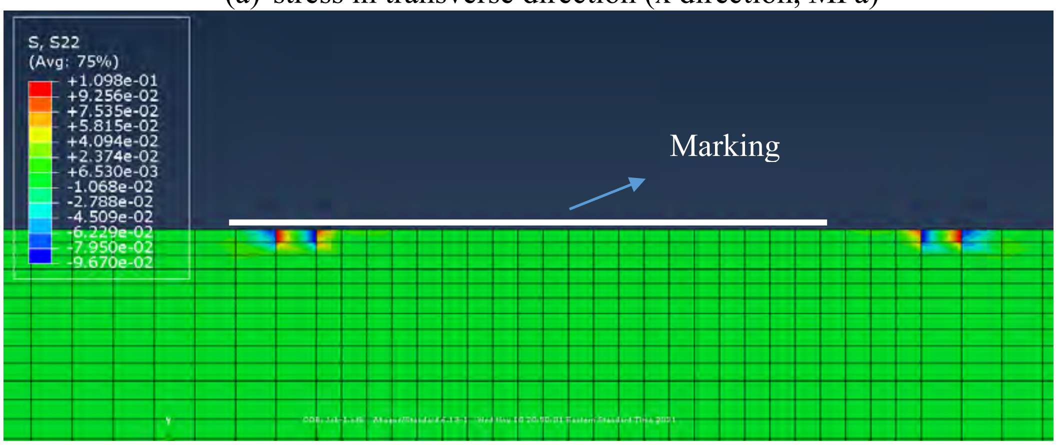
Figure 37: Stresses in the (a) transverse and (b) vertical direction

5.2.1 Convergence Analysis

To demonstrate the numerical analysis convergence, the same model was analyzed with a finer mesh using half of the initial mesh size. The results of the stresses in transverse and vertical directions are shown in Figure 38. Comparing Figure 37 with Figure 38 shows the effect of a smaller mesh size. Maximum stresses (in x and y direction) are still observed, which proves that the stresses are stress singularities or point stresses.



(a) stress in transverse direction (x direction, MPa)



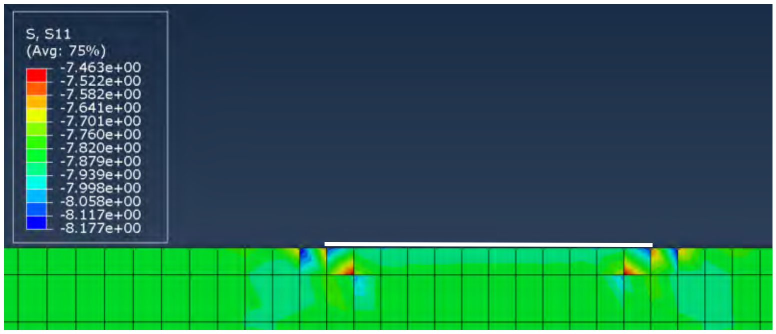
(b) stress in vertical direction (y direction, MPa)

Figure 38: Simulation results using a finer mesh

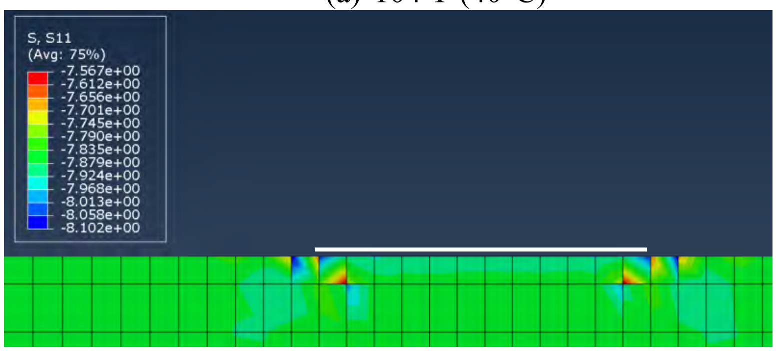
5.3 Sensitivity Analysis

To further investigate the temperature differential effect on stress development, a sensitivity analysis was performed. The temperature of the marking was changed to 131°F (55°C), 122°F (50°C), 113°F (45°C), and 100°F (40°C), while the temperature of asphalt surface remained 140°F (60°C). Critical stresses in the transverse direction, which are responsible for cracking, are shown in Figure 39.

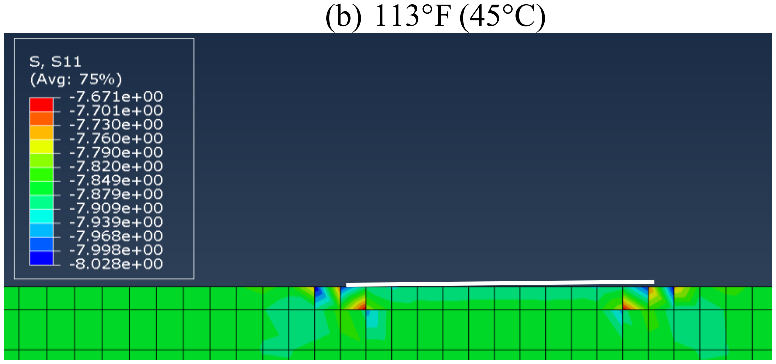
With the increase in temperature of the marking area, the temperature difference between asphalt surface and marking surface decreases and the magnitude of tensile stress singularities decrease as well. This further indicates the potential damaging effect of the temperature difference caused by the different absorptivity of the pavement and marking.



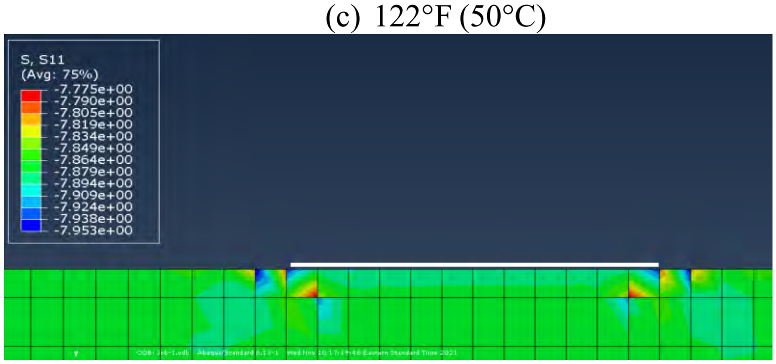
(a) 104°F (40°C)



(b) 113°F (45°C)



(c) 122°F (50°C)



(d) 131°F (55°C)

Figure 39: Transverse stress (MPa) variation with marking temperature

6. Summary and Recommendations

Reports from several transportation agencies and contractors showed the presence of pavement distresses on or around pavement markings raising the concern that the interaction between pavement markings and pavement surface was causing pavement deterioration. This project aimed at investigating the root of this issue.

The literature review on marking types and marking distresses resulted in the analysis of three hypotheses that could help explain the distresses localized around pavement markings:

- Trapped moisture: moisture trapped beneath a less permeable pavement marking accelerates asphalt stripping beneath the marking,
- Longitudinal joints issues: pavement markings influence distress when located around vulnerable low-density asphalt due to joint construction difficulties.
- Temperature differences: differences in reflective and absorption qualities between marking and pavement surface create a thermal gradient.

Visual and nondestructive surveys were conducted in sections presenting pavement distresses located at or around pavement markings. Visual surveys were conducted to locate distresses in relation to pavement lane and longitudinal joints. Nondestructive surveys used a handheld ultrasonic device to measure pulse velocity which can be an indicative of material density.

Visual surveys indicated that the distresses are related to construction issues with longitudinal joints which is a well-known problem for asphalt paving. These distresses are due to insufficient compaction in the unconfined side of the longitudinal joint. Since the centerline markings are placed at the longitudinal joints, the distresses deteriorate the markings as well. Trapped moisture was not observed in the field.

Nondestructive ultrasonic surveys in selected sections were able to confirm the compaction issues using a comparative analysis of measurements between the wheel path and the longitudinal joint. Measurements on marked and unmarked pavement sections in the same area (longitudinal joint) presented similar results indicating that markings do not contribute locally to pavement deterioration. In fact, ultrasonic pulse velocity increased significantly just outside of the joint area which helps explain the success in avoiding marking distresses by the Turnpike Commission when their design procedure was changed to include an offset between markings and the longitudinal joint.

Results from the finite element simulation showed that high-stress gradients are observed at the area between asphalt and marking when there is a temperature difference between the two surfaces. Results indicate that the temperature differences have an impact on pavement responses and that temperature difference-induced stress could be high enough to contribute to the cracking of the asphalt surface. However, further investigation (non-linear simulation or field test), outside of the scope of this project, is required for the proper analysis of the temperature effect.

6.1 Mitigation Strategies

The proposed mitigation strategies are based on two approaches: reduce pavement distresses related to poor compaction at the longitudinal joint and reduce pavement marking deterioration by altering the marking placement. Combining these strategies can help preserve both the pavement surface and markings.

6.1.1 Improving longitudinal joint compaction

As discussed previously, proper longitudinal joint compaction is still a major challenge for the asphalt paving industry. Several studies analyzed the detrimental effect of poor joint compaction on pavement performance. This led to various transportation agencies, including the Pennsylvania Department of Transportation (PennDOT), to develop stricter standards to improve longitudinal joint compaction. Since the change in PennDOT specifications, significant improvement of joint compaction compared to compaction at the center of the lane has been reported.

Despite the improvements seen by PennDOT, other agencies and contractors report that compaction at the longitudinal joint still tends to be significantly lower than at the wheel path or at the center of the lane. Results from ultrasonic testing conducted in the streets and roads of Allegheny County showed that a decrease in asphalt density (estimated by pulse ultrasonic velocity) between the joint and the wheel path areas is correlated with distresses at the longitudinal joint and marking.

To improve longitudinal joint construction, it is recommended to use the recent guidelines from the National Road Research Alliance (NRRA) Flexible Team [78]. This short-term research project highlights best practices from six Departments of Transportation and summarizes a state of practice for proper joint construction. The project focus on five key points to improve joints as listed below. The guidelines also present a discussion on quality control/quality assurance as performed by each state.

1) Paver reference line
2) Type and arrangement of compacting rollers
3) Paver screed placement
4) Compacting methods
5) Notched and tapered design wedge alternatives

To evaluate longitudinal joint construction quality, it is recommended to use real-time measurements of compaction levels. Devices like the Density Profiling System (DPS – Figure 40) can provide fast, accurate, and easy to interpret compaction levels for asphalt paving. Compaction levels are measured automatically and appear on the device screen for real-time compaction assessment. The DPS can be used as soon as final roller compactor pass is concluded which allows for corrections to be made immediately while the asphalt mat is still hot.

Additional information on the device functionality and implementation can be found elsewhere [79].

Figure 40: Density Profiling System (DPS) for real-time compaction assessment

6.1.2 Pavement marking placement

In combination with improvements to longitudinal joint construction or if these improvements cannot be achieved, the marking material can be protected from joint related distresses by changing the placement of the marking as illustrated in Figure 41.

If possible, regarding the geometric design of the road, the marking should be placed on the confined or “hot” side of the joint, i.e., the side which was constructed last. This will ensure the marking is placed over the joint side which presents significantly higher levels of compaction and is less likely to present premature distresses.

In addition, like current practices adopted by the Turnpike Commission, the marking should be placed 3 to 5 in outside of the joint. Results from the ultrasonic testing showed an increase in asphalt density 3 in from the longitudinal joint indicating that higher levels of compaction can be achieved in the near proximity of the joint.

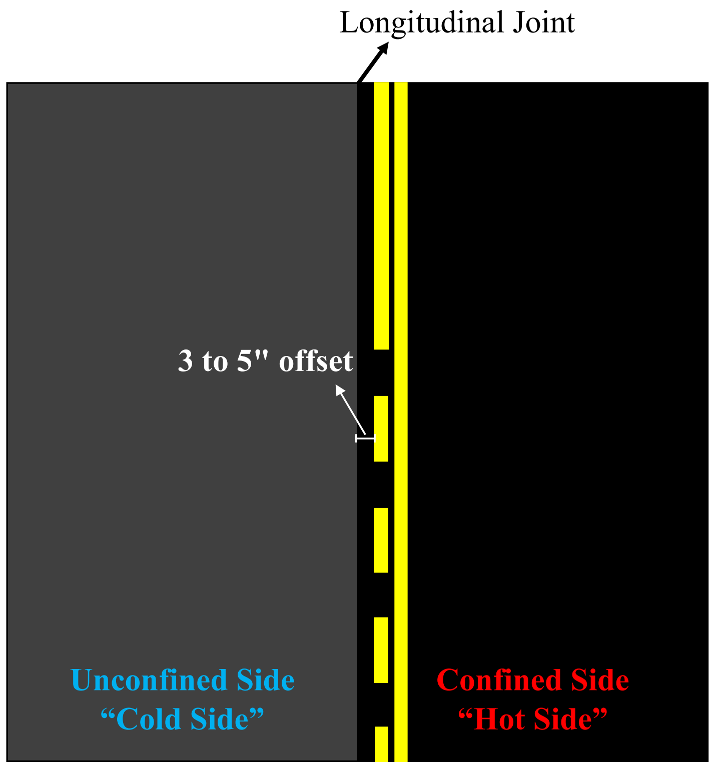


Figure 41: Suggested pavement marking placement

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