USING FINITE ELEMENT STRUCTURAL ANALYSIS TO STUDY RETROREFLECTIVE RAISED PAVEMENT MARKERS

A Thesis

by

JIAXIN TONG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2007

Major Subject: Civil Engineering

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Approved by:

Chair of Committee, Yunlong Zhang
Committee Members, Gene Hawkins
Michael Sherman
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ABSTRACT

Using Finite Element Structural Analysis to Study Retroreflective Raised Pavement Markers. (August 2007)

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Chair of Advisory Committee: Dr. Yunlong Zhang

This thesis investigates the stress inside Retroreflective Raised Pavement Markers (RRPMs) under tire-marker impact and laboratory testing scenarios. Many RRPMs have poor durability although they meet certain standards of the existing laboratory tests. It has been suspected that the current testing procedures might not be adequate to decide the field performance of RRPMs. Thus, it is necessary to evaluate the existing laboratory testing procedures and develop additional ones that could simulate the field performance of RRPMs more accurately.

The tire-marker impact on rigid and flexible pavement will be investigated to identify the critical locations and magnitudes of stress inside markers during the impact. Various external factors, such as tire loading, tire speed, contact angle and contact location, might have effects on the stress inside markers during the impact and be considered as critical factors when developing a laboratory test. On the other hand, RRPMs have different profiles in terms of height, lens slope, and size etc, which affect the structure and field performance as well. The study explores the stress inside markers during the impact by varying the external factors and marker profile. In addition, the interface forces between RRPMs and pavement surface will be studied. Furthermore, the tire-marker impact simulation on rigid and flexible pavement will be compared so that specific testing procedures can be distinguished based on pavement

type. Finally, the existing laboratory tests will be examined and additional tests be recommended based on the tire-marker impact analysis.

The researcher found that the critical compressive stress is produced at the top edges of the markers on both types of pavement, while the patterns of critical tensile stress can be different between the two types of pavement. In addition, tire loading and contact location were determined to have effect on the stress inside the markers. Furthermore, different loading rates should be used in laboratory test based on pavement type. Finally, the researcher evaluated four laboratory tests and found that each test has its merit but none of them can test RRPMs comprehensively, so it is recommended that the four tests are used together to test RRPMs.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Yunlong Zhang, for guiding me throughout the completion of my thesis and supervising me on the Texas Transportation Institute (TTI) research project 0-5089 "Improvements of Retroreflective Raised Pavement Markers" on which this thesis is based. I would also like to thank my committee members, Dr. Gene Hawkins and Dr. Michael Sherman, for providing me with guidance and valuable instructions.

Thanks are also given to Dr. Akram Abu-Odeh for helping me develop the initial finite element model. He built the finite element model of a truck tire that is an important part of the tire-marker impact model used in this research. Besides, he offered me valuable instructions on modeling flexible pavement in the tire-marker impact model. I would like to thank Ravi Agrawal for instructing me to use the finite element tools in this research and transferring the project work to me. I want to thank Ryan Alberson, who also assisted me in the modeling process of this research. In addition, I would like to thank Dr. Sheng Hu who gave me valuable advice on how to model flexible pavement structure.

TABLE OF CONTENTS

LIST OF FIGURES

Page

Page

LIST OF TABLES

Page

INTRODUCTION

The Manual on Uniform Traffic Control Devices (MUTCD) defines a raised pavement marker (RPM) as "a device with a height of at least 10 mm (0.4 in) mounted on or in a road surface that is intended to be used as a positioning guide or to supplement or substitute for pavement markings or to mark the position of a fire hydrant" (*1*). Retroreflective Raised Pavement Markers (RRPMs) are used for providing delineation on highways during nighttime or wet conditions when pavement markings lose their effectiveness to provide guidance to motorists. In addition, the rumbling effect of RRPMs reminds drivers to remain appropriate position in their lanes.

It is expected that RRPMs would remain in the installed locations and have sufficient retroreflectivity over time. However, markers would lose most of their effectiveness on highways with high traffic volume in a short period of time after installation due to poor retention and durability. The major problems of marker failure are poor retention on pavements (adhesive failure), breaking of marker body or lens and loss of retroreflectivity (*2*). Various factors responsible for these failures include high traffic volume, high loading (such as trucks), sand abrasion and environmental factors like ultra-violet radiation (*2*). Several research agencies suggest that poor manufacturing and inadequate application quality may have contributed to the poor durability of markers as well (*2*).

This thesis follows the styles of *Transportation Research Record*.

PROBLEM STATEMENT

In addition to marker quality and various external factors, the under performance of RRPMs can be attributed to the lack of appropriate laboratory testing standards that can test the adequacy of markers to perform well in the field. The existing laboratory testing procedures recommended by American Society of Testing and Materials (ASTM) have problems in several areas (*3*). First of all, RRPMs are generally only tested to some loading levels (pass or fail). Moreover, the existing testing procedures are unable to simulate all the scenarios of tire-marker impact in the field, i.e. contact with angle and offset. Some researchers have tried to demonstrate the capability of certain laboratory tests, i.e. ASTM compression test (*2, 3*). The problem remains, however, that RRPMs passing the tests have displayed markedly different field performance. Therefore, it is necessary to examine the existing testing procedures and develop new testing procedures that could better simulate certain field scenarios. The evaluation and recommendation of laboratory testing procedures require that the critical locations and magnitudes of stress inside RRPMs to be identified during the tire-marker impact in the field. Therefore, the dynamic process of tire-marker impact needs to be studied to determine the stresses inside markers during the impact.

BACKGROUND

Some researches have been conducted to study the tire-marker impact, but none of them were able to analyze the impact dynamically and microscopically until the idea of utilizing the finite element simulation tools to study the stress inside RRPMs arose (*2, 4*). The finite element computational techniques are able to simulate the tire-marker impact in the field dynamically and thus solve the difficulty of measuring the stress inside RRPMs instantaneously in the field and provide the flexibility when various external factors need to be varied. The finite element simulation is able to capture every microscopic step of the tire-marker impact and indicate the critical locations and magnitudes of stress inside RRPMs during the impact.

However, the current tire-marker impact simulation is performed on rigid pavement, so it is not adequate to determine the critical locations and magnitudes of stress inside markers during the tire-marker impact without simulating the impact on flexible pavement. In fact, it has been observed in the field where testing RRPMs were installed on both rigid (concrete) and flexible (asphalt) pavement that several RRPM brands had different damage types between two types of pavement. Such field observation especially highlights the necessity of further examining the stress inside markers during the tire-marker impact on flexible pavement. Considering the wide application of flexible pavement on roadways in the United States, it is valuable to include the pavement properties into the simulation model such that the existing and new laboratory testing procedures can be investigated and developed on a more comprehensive basis.

RESEARCH OBJECTIVES

The primary goal of this research is to identify the critical locations and magnitudes of the stress inside markers during the tire-marker impact on both rigid and flexible pavement and investigate the difference between the stress inside markers on both types of pavement in order to help recommend laboratory testing procedures that could better simulate the field conditions. This research is specifically aimed at the following tasks:

- To model stress inside markers during the tire-marker impact on flexible pavement;

- To evaluate the external factors of tire-marker impact on flexible pavement;
- To identify the factors that need to be evaluated while recommending a laboratory testing procedure;
- To compare the stress and interface forces generated from the tire-marker impact on both rigid and flexible pavement;
- To investigate if a same test is suitable for markers on both rigid and flexible pavement and if there is a need to distinguish laboratory testing procedures for RRPMs based on the pavement type;
- To study the effect of RRPM profile on the stress inside markers;
- To evaluate the existing laboratory testing procedures and recommend testing procedures based on the achievements of the prior objectives.

RESEARCH BENEFITS

This research is an extension of a Texas Transportation Institute (TTI) project, Project 0-5089 Improvements of Raised Pavement Markers, sponsored by the Texas Department of Transportation (TxDOT). It will provide comprehensive information on the critical locations and magnitudes of stress inside RRPMs during the tire-marker impact, and thus help determine whether the same laboratory testing procedures can be applied to RRPMs to be installed on both rigid and flexible pavement. Furthermore, this research will contribute to the laboratory testing standards for RRPMs to assure the quality and hence improve the durability of markers.

THESIS ORGANIZATION

This thesis consists of five sections. The first section introduces the research problem, background information, and the objectives as well as benefits of this research. The second part reviews the RRPM-related state-of-the-art, including the general practice of RRPMs, research on the durability of RRPMs using traditional method, and the latest research on RRPMs using finite element simulation. The next part of the thesis focuses on the methodology adopted in this research and it provides insight into the constitution of tire-marker impact model, the modeling of flexible pavement and the study design. The fourth section gives the results and analysis of the tire-marker impact simulation and laboratory test simulation. The final section concludes with findings, remaining issues, and recommended future research.

STATE-OF-THE-ART AND -PRACTICE

This section of the thesis reviews the state-of-the-art and state-of-the-practice related to RRPMs. It first introduces the current practice of RRPMs, which is then followed by a review of the previous research on the causes of the deterioration of RRPMs. Furthermore, it provides insight into the previous and latest study on tire-marker impact and laboratory testing procedures.

OVERVIEW OF CURRENT RRPM PRACTICE

RRPMs work in complement to pavement markings to provide the overall guidance to motorists on highways. RRPMs have a number of key functions and there are a variety of RRPM types on the market.

Functions

RRPMs are able to offer delineation over a wider range of environmental conditions, i.e. in low-light conditions at night or during inclement weather, than standard pavement markings, which might lose their effectiveness in such situations. According to a study on pavement markings, the accumulated rain on painted markings will reduce the retroreflectivity of the paint and thus affecting the effectiveness of standard marking lines (*5*), while RRPMs stand above the pooled rain water and can provide the needed retroreflectivity to motorists. Besides, lighting is often not available along most rural highways, so the pavement markings are insufficient to meet motorists' visibility needs in the darkness in the absence of effective RRPMs. In addition, the rumbling sound of RRPMs as they are hit by vehicles tires can serve as a "wake up call" to those motorists who are not aware of their vehicle position or driving situation.

RRPMs in different colors work in supplement to the pavement marking stripes of the same color. Yellow RRPMs with yellow lens are installed with the yellow centerlines to underline the stripes. White RRPMs are often installed with white lane lines as the white lens provides reflectivity to motorists while red lens convoys warning message to motorists who enter the wrong way.

Types

Generally, there are two types of RPM: retroreflective and non-retroreflective. This research only focuses on RRPM, which can be separated into two subcategories: non-snowplowable RRPM and snowplowable RRPM. The RRPMs studied in this research are all non-snowplowable. Non-snowplowable RRPMs are widely installed in warm climate states such as Texas and California where snowfall is not a concern, while other states with cold winter climate, such as Massachusetts, New Jersey, Illinois etc, use only snowplowable RRPMs to reduce the damage to markers during the snowplow activity (*6*). Figures 1 and 2 show the typical non-snowplowable and snowplowable RRPMs (*7*).

FIGURE 1 Typical non-snowplowable RRPM.

FIGURE 2 Typical snowplowable RRPM (*7*).

Currently, there are many models of RRPMs, developed with various configurations and characteristics. Some markers are wedge-shaped, and some are round and oval. Some markers are made of acrylic shell and polyurethane-resin filler, and some have a body composed of impact graded acrylonitrile butadiene styrene (ABS) instead of filler. Some markers have lens on both sides, serving both directions of traffic, and some only on one side, serving only one direction of traffic. Some markers are in yellow color with yellow lens, which are usually used along yellow centerlines, and some are in white color with white lens or white-red lens, which are designed for both directions of traffic with red lens warning the motorists not to enter the wrong way. Some markers are even in blue, indicating the position of fire hydrant (*1*). Figure 3 shows some RRPMs with different shapes. Figure 4 shows a typical RRPM composed of lens, shell and filler. In general, RRPMs vary in terms of shape, size, color, composition and functionality.

FIGURE 3 RRPMs in various shapes.

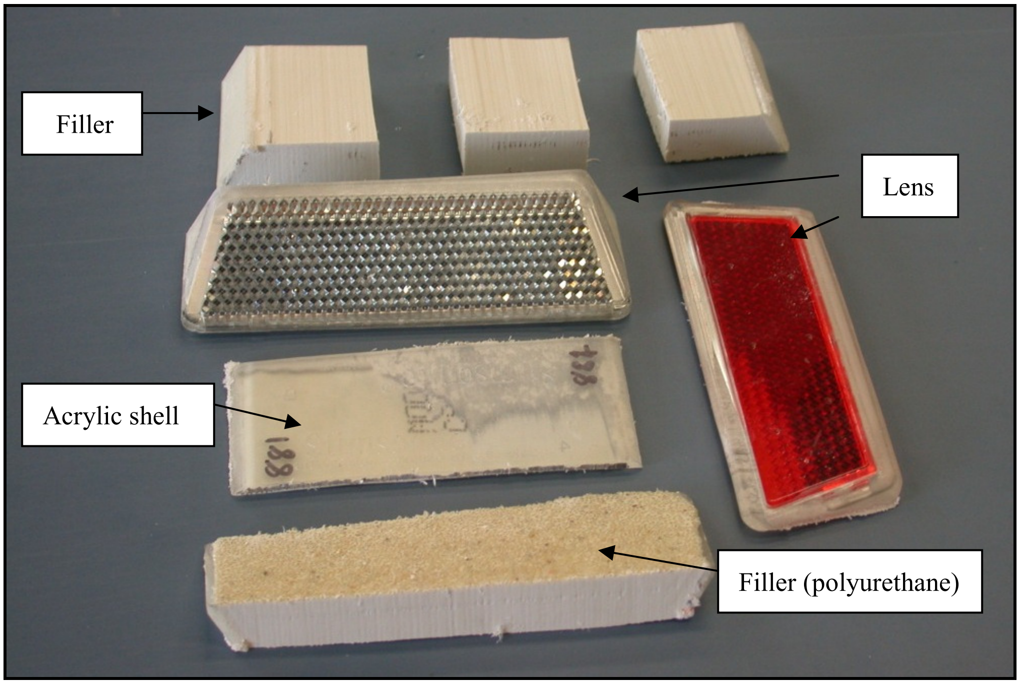


FIGURE 4 Composition of a RRPM.

Implementation

MUTCD states the desired spacing for RRPMs in terms of N, the normal cycle length of a pavement marking used in combination with markers, and the Federal Highway Administration (FHWA)'s *Roadway Delineation Practices Handbook* provides guidelines on the layouts and installation criteria for RRPMs (*1, 8*). According to *MUTCD* and *Roadway Delineation Practices Handbook*, the layout of RRPMs on different sections of roadway, i.e. tangent ramps, curves, and intersections, or on different types of roadway, i.e. two-lane and multi-lane roadway, has specific requirements (*1, 8*). The spacing between two consecutive RRPMs on tangents should be 80 ft (24 m). The spacing between two consecutive RRPMs on horizontal curves between 3 and 15 degrees should be 40 ft (12 m). For those curves larger than 15 degrees a spacing of 20 ft (6 m) is desired. The layout of RRPMs depends on the types of the roadway, and is also related to the configuration of the associated pavement markings. Figure 5 presents the layout of RPM system and RPM/Stripe system for different types of roadway.

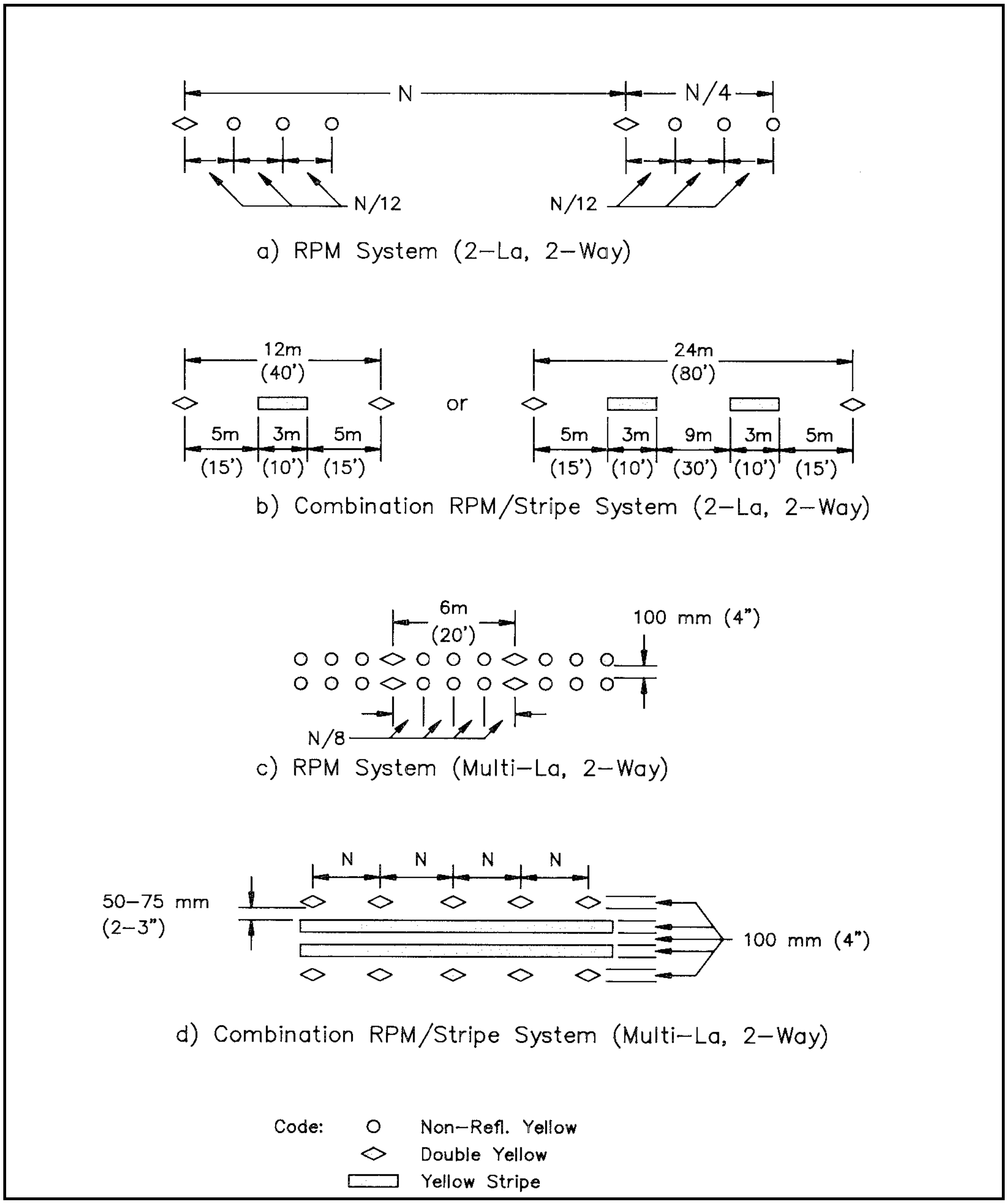


FIGURE 5 Centerline patterns for different roadway types (*8*).

States have their own implementation criteria for RRPMs (*6*). In some states, i.e. Texas and California, RRPMs are installed on all state-maintained highways, while some other states, i.e. Massachusetts, Pennsylvania and Illinois, implement RRPMs non-selectively on freeways, and selectively on other types of roadways based on the following criteria:

- Traffic volume,
- Illumination,
- Safety record,
- Speed limits, and
- Horizontal curves.

The use of adhesive material is also described in *Roadway Delineation Practices Handbook* (*8*). The service life of RRPMs is directly related to the bond strength provided by the adhesives. Epoxy is used to bond RRPMs to rigid pavement, i.e. concrete pavement, while bitumen is used to affix RRPMs to flexible pavement, i.e. asphalt and sealcoat pavement. Some RRPMs that are pressure sensitive can even be installed without adhesives and these markers are usually implemented in work zones. Overall, RRPMs are claimed to be the most expensive marking material to install, which is also the reason why researchers have been trying to find ways to increase the durability of markers (*8*).

PREVIOUS RESEARCH ON RRPM FAILURE

The previous research on the RRPM failure mainly involves investigating the poor durability and loss of retroreflectivity of markers. Besides, some study evaluated the pavement characteristics to correlate them to marker failure. Next, the issues related to these three aspects are reviewed.

Poor Durability of RRPMs

McNees and Noel at Texas Transportation Institute (TTI) conducted research to determine the major problems related to the poor physical durability of RRPMs on roadways (*9, 10*). They found that retention and resistance to wear and shear are two major problems that underlie the poor durability of RRPMs. They also concluded the major factors that cause such problems as the following:

- Traffic volume,
- Truck traffic,
- Service time, and
- Marker location, i.e. at lane line or centerline.

They pointed out that trucks have a more significant effect on the retention than on the loss of retroreflectivity of markers. It was also found that the retention of markers is related to the counts they are hit by the tires, which could be explained by their field observation that RRPMs on lane lines disappear and wear at a faster rate than those on centerlines as they receive twice as many hits as markers on centerlines (*9*). In addition, marker shape was recognized as another primary factor in preserving markers. Other factors that were found to be responsible for the deterioration of markers include: marker type, bond area, vehicle speed, tire pressure, contact location on markers, improper installation, temperature, and moisture.

Loss of Retroreflectivity

McNees and Noel conducted a series of study regarding the retroreflectivity of RRPMs (*10, 11*). They found that RRPMs lose a significant amount of their initial retroreflectivity within two years after installation and over two-thirds of their initial retroreflectivity is lost in the first year. They also concluded that the reflective retention of RRPMs is approximately 2.5 years and markers would remain effective to some extent during this period. The crack of and abrasion on the marker lens caused by tire contacts, the accumulation of road dirt and asphalt on the face of lens, and the residue of water remained near the base of markers due to insufficient drainage on roadways all reduce the retroreflectivity of RRPMs. However, the type of RRPMs, their initial retroreflectivity, and truck traffic have little impact on the loss of retroreflectivity of markers.

Ullman at TTI conducted a two-year evaluation of the RRPMs installed in Texas (*12, 13*). He performed some non-linear regression analyses to study the correlation between RRPM retroreflectivity and traffic volume, and found that the retroreflectivity retention is most related to the cumulative vehicular exposure since the time of installation. Besides, it was slightly less accurate to correlate the retroreflectivity retention of RRPMs to the cumulative truck exposure, but truck traffic was still considered to be a factor for the loss of retroreflectivity according to his research.

Pavement Characteristics

In the study conducted by McNees and Noel on the retention of RRPMs, they found that pavement failure is another significant factor causing the poor retention of markers, especially on asphalt pavement (*9*). All three types of stress, tension, compression and shear tend to be generated in pavement under a marker. Pavement is best at supporting the compressive stress which is predominant among three types of stresses. Adhesives at the opposite edge of marker undergoes tensile stress when the downward force resulted from tire loading is located out of the center one-third of the bonded area between markers and pavement. The shear stress between markers and pavement is caused by non-vertical forces which might be produced by vehicle acceleration or deceleration. Furthermore, they revealed that higher RRPM retention can be obtained using bitumen which gives asphalt pavement longer fatigue life, but such advantage decreases as pavement stiffness grows and input stress level increases.

Ninety-three percent of U.S. paved roadways are surfaced with asphalt material, which is often called flexible pavement, while rigid pavement, surfaced with Portland cement concrete (PCC), comprises seven percent of U.S. paved roadways (*14*). In Texas, about 90 percent of the highways are surfaced with asphalt material (*10*). Flexible pavement has a unique structure consisting of several layers of material, with the highest loading bearing material on the top and the lowest one at the bottom (*15*). A typical flexible pavement structure is shown in Figure 6. On the other hand, rigid pavement typically only consists of two layers, the concrete surface and the subgrade (existing soil). The load from vehicle tire distributes differently inside the two types of pavement, which is shown in Figure 7.

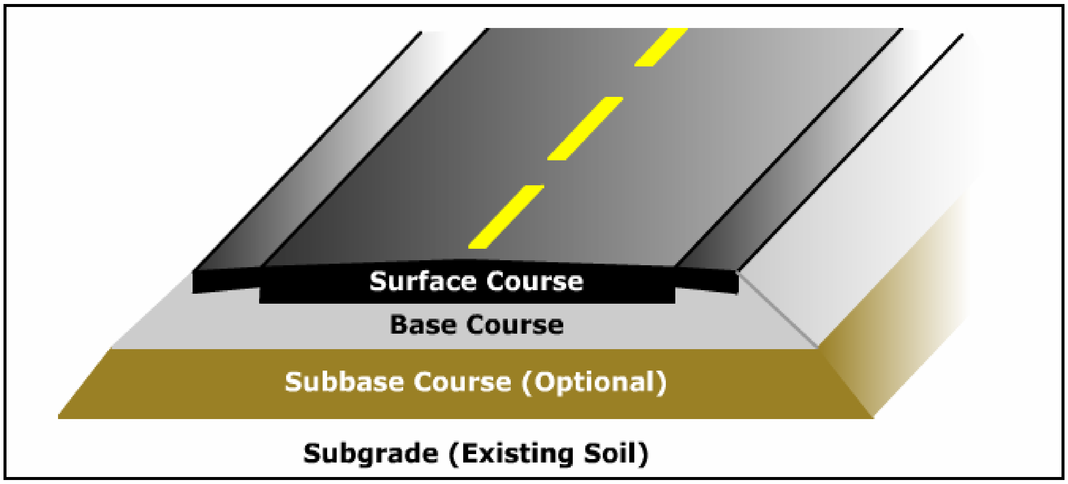


FIGURE 6 Typical flexible pavement structure (*15*).

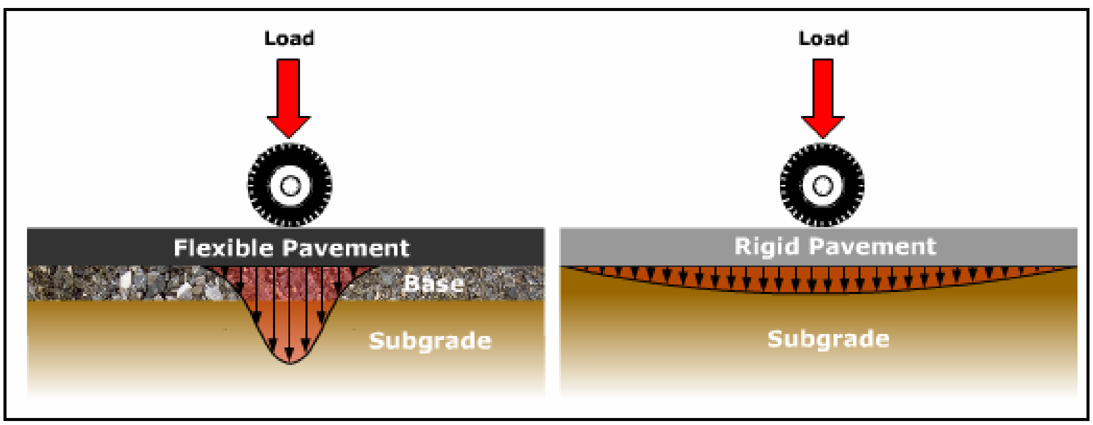


FIGURE 7 Flexible and rigid pavement loading distribution (*14*).

TIRE-MARKER IMPACT

Various methods have been implemented to study the tire-marker impact. Some conventional ways include laboratory tests and high-speed motion picture while the latest research on tire-marker impact utilized the finite element analysis to investigate the tire-marker impact.

Conventional Methods

A tire traveling at 50 mph will traverse a typical RRPM in about 4.5 milliseconds. This duration is too short to visually determine the path the tire is passing over the marker. So, Noel and Tielking did a high-speed photographic study of the path the tire is traversing the marker (*16*). It was found that a passenger car tire with high-pressure had contact with the entire top surface of the marker and remained in contact with a portion of the exit-sloping lens in stead of leaping over the marker. Similarly, a truck tire would stay on top of a marker longer than a passenger car tire.

These findings were used subsequently in a design of a laboratory test to measure the fatigue strength of asphalt sustaining loading from tire-marker impact. During the experiment, Noel and Tielking found that the most significant impact on markers occurs when the sidewall of a tire hits the nearly vertical side (non-lens side) of a marker (*16*). Such impact often occurs during a turning-passing maneuver. This finding is in accordance with the field study carried out in this research as a lot of damages on RRPMs were observed at the non-retroreflective side. They also found that tire speed and tire pressure might be the factors for inducing the dynamic forces on markers.

Zhang, et al have been conducting a two-year field study of RRPMs in four test decks characterized by different traffic conditions, pavement types, etc (*17*). During their field evaluation every six months, they summarized some types of marker damage. The top edges of a RRPM are most frequently damaged and Figure 8 shows this type of damage.

FIGURE 8 A common RRPM damage type.

RRPMs on concrete pavement were more frequently removed than on asphalt pavement by shear force induced by vehicle tires. Besides, some RRPM brands on asphalt pavement were observed with damage of split across the mid-bottom-line of the markers, which was rarely seen for RRPMs on concrete pavement. Figure 9 shows this type of structural damage. In addition, the non-lens side of a RRPM often experienced severe damage as can be seen in Figure 10, indicating that the location of tire-marker contact is critical to marker damage.

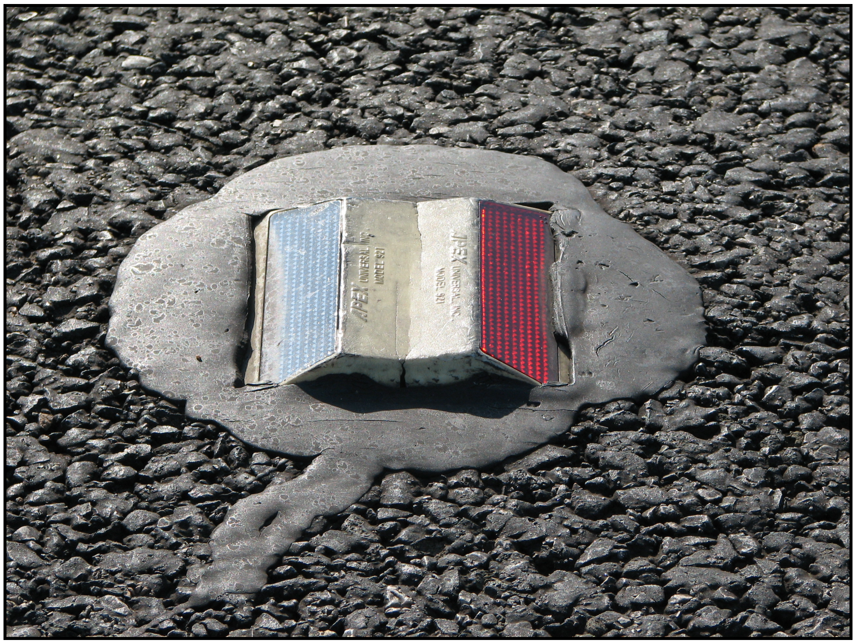


FIGURE 9 A typical damage type for RRPMs on flexible pavement.

FIGURE 10 Damage at the non-lens side of a RRPM.

Finite Element Analysis

Finite element analysis (FEA) applies the finite element method to analyze either static or dynamic problems in various aspects, including structure analysis, thermal analysis, fluid analysis etc (*18, 19*). The computational techniques make FEA even more powerful in simulating the performance of a complex system. The FEA software, Hypermesh and LS-DYNA, is such a computational tool upon which the FEA model can be built and simulated (*20, 21*). The finite element model contains the following information about the device to be analyzed: geometry, which is subdivided into finite element, materials excitation and constraints.

Researchers at TTI developed a finite element model to find out the critical locations and magnitudes of stresses inside markers during the tire-marker impact. Dr. Abu-Odeh, an associate research scientist at the Center of Excellence in Transportation Computational Mechanics of TTI, built the preliminary tire-marker impact model. Figure 11 shows the model.

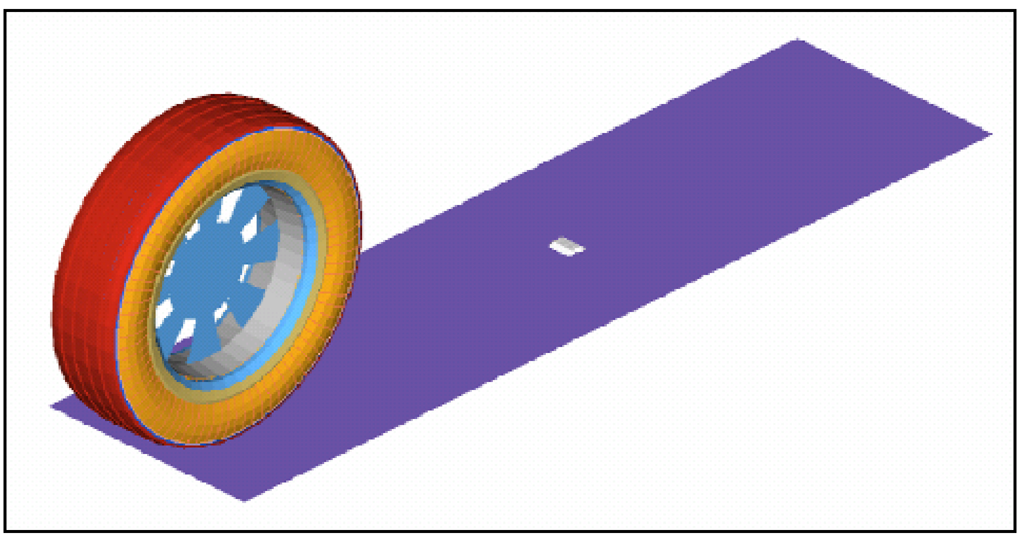


FIGURE 11 Preliminary finite element model of tire-marker impact.

The model consists of three major components: a truck tire (525 mm in radius), a simplified RRPM, and the rigid pavement. The tire in this model was well calibrated by Dr. Abu-Odeh, while the marker originally did not have any constitutive material properties and was only a rigid object. Alberson and Agrawal then worked together to build finite element models of three models of RRPMs, which are similarly structured as the real RRPMs. Agrawal calibrated the material properties of those marker models based on matching measurements and finite element simulation of strains in a laboratory setup (*2*).

After the calibration of constitutive material property, Agrawal simulated the tire-marker impact model in LS-DYNA to generate stress analysis. The simulation was conduct in such a way that the tire passes over the marker in three stages. The first stage represents the scenario when the tire first contacts the front lens face of the marker and is about to ascend the marker. The second stage represents the scenario when the tire stays on top of the marker. The third stage represents the scenario when the tire is still in contact with the rear lens face of the marker and about to descend the marker. He found that predominant compressive stress is produced in the upper half as well as the edge of top surface of the contacted retroreflective side in the first stage. The same pattern was found in the third stage. When a tire sits on top of the marker, compressive stress is concentrated at the edges of top surface of the marker. Tensile stress is observed throughout the marker during the impact and it is especially intense at the opposite side of the location the tire contacts the marker (*2*).

In the further research done by Zhang, et al, the effect of external factors, i.e. tire loading, tire speed, contact angle and contact location, on the critical locations and magnitudes of stress inside markers were identified during the tire-marker impact on rigid pavement (*4*). Based on the simulations, the critical stress is produced on the top edges of the marker (perpendicular to the traffic direction). Studying the various external factors, the researchers found that the stress inside the markers increases as the tire loading is increased and higher stress is seen as the impact location moves away from the center of the marker. Besides, the contact angle was found to affect the tensile stress inside the markers, with larger angles causing more tensile stress. However, no consistent effect of tire speed was found on the stress inside the markers. These findings pointed out that the loading rates and contact location should be considered as important factors in developing the laboratory testing procedures.

However, the studies by Agrawal and Zhang et al. did not consider pavement properties. That is to say, the results from the studies only apply to RRPMs on rigid pavement. The conclusions thus remain incomplete until the impact on flexible pavement is evaluated. It is important to model flexible pavement because not only the external factors can be studied thoroughly to see their effects on the impact but also it allows researchers to investigate the difference between the patterns and magnitudes of stresses inside markers during the impact to distinguish the needs of certain laboratory testing procedures for RRPMs to be installed on rigid and flexible pavement.

LABORATORY TESTING PROCEDURES

American Society of Testing and Materials (ASTM) has standard specification for non-snowplowable RRPM, and it is issued under the fixed designation of D 4280 (*3*). Most state agencies use the testing specification in ASTM to test RRPMs. There are two specific tests in ASTM D 4280 regarding the structure durability of RRPMs, a compression test and a longitudinal flexural test. The next part introduces the common practices of these two tests and the research work conducted to examine the tests.

ASTM Compression and Longitudinal Flexural Tests

The compression test requires the marker being tested have a condition of about 23 degree Celsius (73 degree Fahrenheit) for 4 hours prior to testing. The marker base should be positioned down at the center of a flat steel plate. On top of the marker is placed an elastomeric pad while another flat steel plate is then placed on top of the elastometric pad. All the steel plates and elastomeric pad should be larger than the marker. A load at a rate of 2.5 mm (0.1 inch) per minute is applied on top of the upper steel plate. It tests the compressive strength of RRPMs.

The longitudinal flexural test requires the same temperature condition as the compression test. The marker base should be positioned onto two elastomeric pads which are perpendicular to the lengthwise of the marker (traffic direction) and placed at the two edge sides of the marker. The pads are located on top of two steel bars and both the pads and bars are longer than the bottom width of the marker. Another elastomeric pad and steel bar are placed in the same manner on top of the marker at the center with a load at a rate of 5.0 mm (0.2 inch) per minute applied on it until the marker breaks. It tests the longitudinal flexural strength of RRPMs. Figure 12 shows the configuration of longitudinal flexural tests.

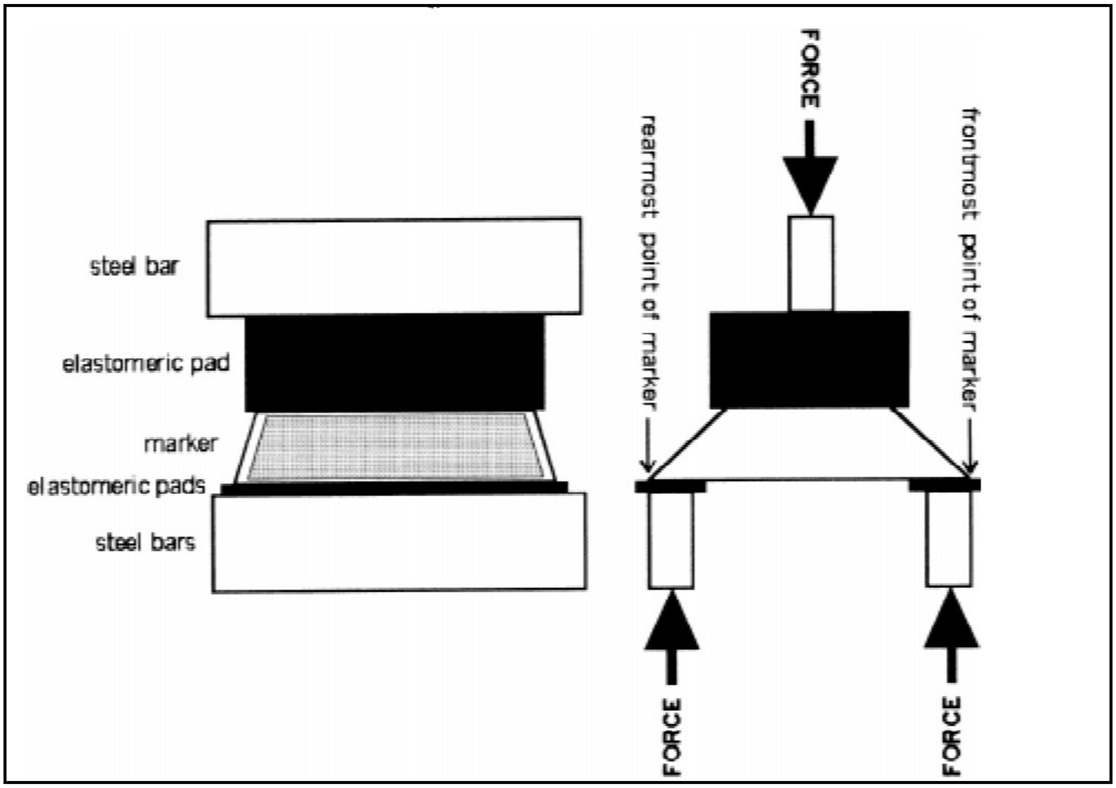


FIGURE 12 ASTM longitudinal flexural test (*3*).

Previous Study of Laboratory Tests

Agrawal simulated five laboratory tests that could replicate the stress conditions during the tire-marker impact simulations using finite element computational techniques (*2*). These tests are ASTM compression test, ASTM longitudinal flexural test, reversed longitudinal flexural test, cylindrical test and offset test. Based on the simulation results between the lab test model and the tire-marker impact model, Agrawal found that the ASTM compression test replicates the second stage of the tire-marker impact well while the ASTM longitudinal flexural test simulation does not produce the same pattern of stress inside markers as is resulted from the tire-marker impact simulation. This might be explained by the fact that the tire-marker impact was simulated on rigid pavement where damage usually occurs on the top edges of markers while the longitudinal flexural test is designed to investigate the structural toughness across the mid-line of the bottom of markers (perpendicular to the traffic direction). Such damage mode as split across the mid-bottom-line of markers was observed for some RRPM brands on asphalt pavement based on the field study conducted by Zhang, et al (*17*). This again underlines the importance to study the tire-marker impact on flexible pavement.

Agrawal also found that a test that could produce compressive stress on one retroreflective side of the marker while producing tensile stress in the other areas of the marker would be a good test to simulate the stages of the tire-marker impact where the tire ascends or descends the marker. The offset compression test developed by Agrawal was such a test. It was found that the offset compression test with a higher loading rate could replicate the first stage of the tire-marker impact well (*2*).

One of the unsolved problems regarding Agrawal's work on evaluating the laboratory tests is attributed to the absence of pavement properties in the tire-marker model. As all the stress results from the simulated laboratory tests were compared with those from the tire-marker impact simulation on rigid pavement, it is questionable whether these tests can be applied to RRPMs to be installed on flexible pavement. Besides, different loading rates were not exercised in the experiment by Agrawal while Zhang, et al have found that loading rates should be an important factor in recommending laboratory testing procedures.

METHODOLOGY

This research follows the path of the previous research, which is incorporated in the same research project as this one, utilizes finite element computational tools to simulate the tire-marker impact and laboratory testing set-up, and analyzes the tire-marker impact in an even more comprehensive perspective by taking flexible pavement into account. Hence, this research is able to evaluate the existing laboratory tests thoroughly and recommend necessary improvements or new standards. The implementation of the finite element computational tool in this research involves three procedures: pre-processing, processing and post-processing. Hypermesh is used to set up the finite element model, which is processed by LS-DYNA, and finally Hyperview is responsible for analyzing the simulation results (*20, 21, 22*). The details of these finite element tools can be found in the previous research or research in other fields using these tools and will not be elaborated here.

This section of the thesis primarily demonstrates the study design of this research. It first introduces the previous work on finite element modeling of markers this research is based on as well as the original work on tire-marker impact simulation. Furthermore, the study design of the tire-marker impact analyses is described. Finally, it explains how to evaluate the laboratory testing procedures.

FINITE ELEMENT MODELING

It is fundamental to build a finite element model before processing and analyzing it. This research not only utilizes the finite element model of tire-marker impact set up in the research project this thesis is based on, but also models flexible pavement in the current tire-marker impact model. The next part will introduce the procedures of setting-up these models.

RRPM Models

The finite element models of two RRPM brands evaluated in this research were built by the predecessors who also worked in the project this thesis is based on. The pictures of the two RRPM brands, which are named as Type A and B in this research, are shown in Figures 13 and 14, respectively.

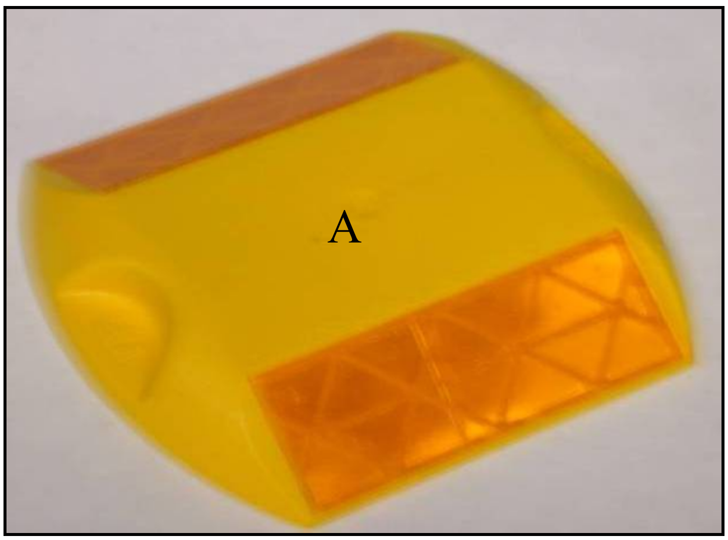


FIGURE 13 RRPM type A.

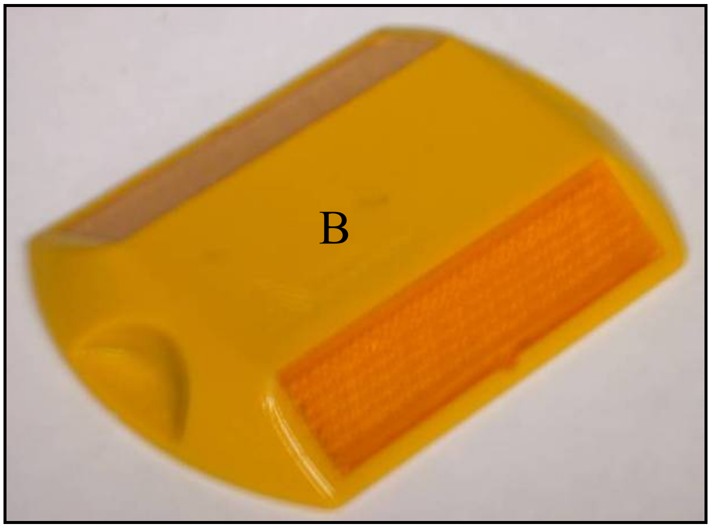


FIGURE 14 RRPM type B.

The finite element models of the two marker brands were built to replicate the real markers both geometrically and structurally. The real markers were dissected for better modeling their inner structures. The marker models were constructed and meshed in Hypermesh, and the completed mesh of marker models of Type A and B are shown in Figures 15 and 16, respectively.

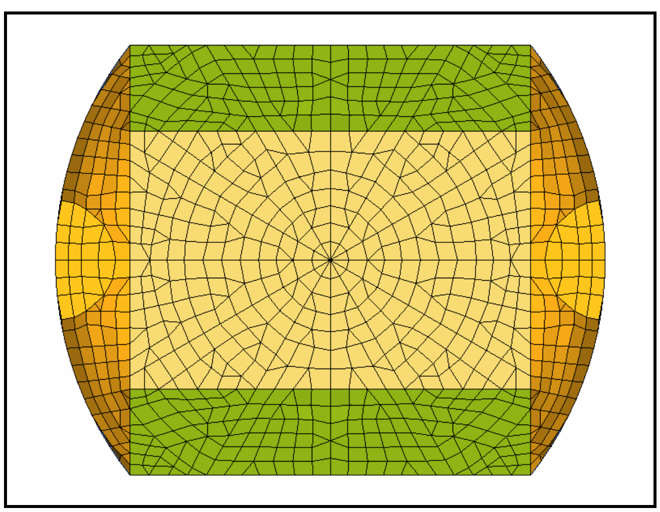


FIGURE 15 RRPM type A model.

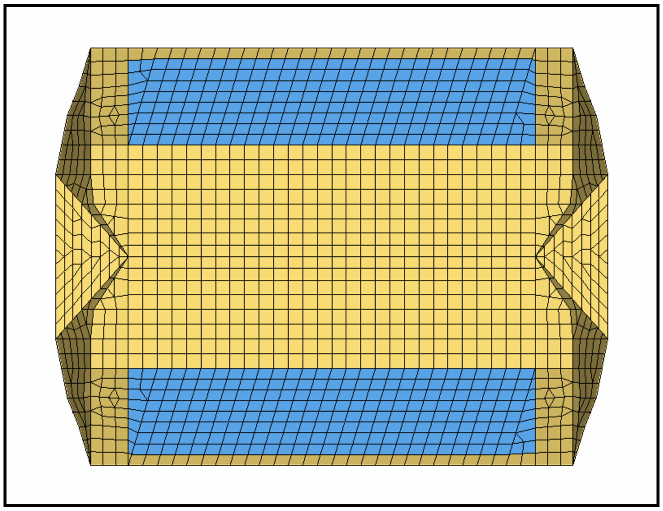


FIGURE 16   RRPM type B model.

One thing that needs attention here is that the geometry of RRPM B at the middle part of the non-lens side does not exactly replicate that of the real RRPM. For real maker, there is a curve in the middle of the non-lens side instead of straight lines there on the meshed marker model. Initially, the marker models were built without material properties. The predecessor of this research then calibrated the material properties using an ASTM longitudinal flexural test both in finite element simulation and laboratory setup to correlate both the stress and strain results from the two approaches. The material properties were then obtained and input into the tire-marker model which will be described in the next part. The details of the calibration process and material properties of the markers can be found in the previous research (*2, 4*).

Tire-Marker Impact Model

The basic information of the preliminary tire-marker impact model was provided in the review of the state-of-the-art. The existing tire-marker impact studied based on this model is only valid for rigid pavement, which is a constraint to a comprehensive understanding of the tire-marker impact. Therefore, the next part will describe how flexible pavement is built in the current finite element model.

As was introduced in the review of the state-of-the-art, flexible pavement is structurally different from rigid pavement, and is usually composed of three layers, which are surface course, base course, and subgrade. An optional sub-base layer may be constructed between base course and subgrade. The surface course for flexible pavement mostly uses asphalt concrete, which is harder than the material used in base course. Subgrade is actually the existing soil, which is the softest among the three layers.

In order to model flexible pavement as closely as what it is in the real world, the researcher inquired some specialists working on flexible pavement in Texas Transportation Institute, and acquired some valuable information as well as common data they usually use to model flexible pavement in finite element analysis. The thickness and material properties of an average flexible pavement are summarized in Table 1 according to the researchers at TTI. The numbers in the parentheses are for flexible pavement on interstate highways with a large percentage of truck traffic. Later, the researcher will do a simple sensitivity analysis of pavement thickness regarding the critical locations and magnitudes of stress inside the markers during the tire-marker impact. Besides, the results between the average flexible pavement and the flexible pavement on interstate highways will be compared as well.

TABLE 1 Pavement Profiles and Properties

Layer Name	Thickness (m)	Mass Density (kg/m^3)	Poisson Ratio	Modulus (MPa)
Surface	0.08 (0.20)*	2322	0.35	3000 (3000)
Base	0.30 (0.30)	2162	0.35	150 (300)
Subgrade	5.00 (5.00)	2001	0.35	50 (10)

*The numbers in the parentheses are for flexible pavement on interstate highways with a large percentage of truck traffic.

The material card for the three layers of flexible pavement is chosen to be elastic in the finite element modeling software of Hypermesh, although the elastic-plastic card should be more accurate in terms of the material characteristics of flexible pavement. Because modeling elastic-plastic material is much more complex than modeling elastic material and requires comprehensive data input for the flexible pavement, it is not advised by the researchers at TTI. Elastic Modulus is the key material property that determines the stiffness of the pavement layer and plays a more important role than density and Poisson ratio in finite element modeling. The area of the pavement course should be large enough so that elastic deformation inside the pavement can be produced during the tire-marker impact.

Taking all these issues into consideration, the researcher modeled three layers of pavement block to form the typical flexible pavement, according to the profiles and material properties listed in Table 1, to replace the rigid ground which was originally built in the model. Hence, the tire-marker impact takes place on flexible pavement. The tire-marker impact model on flexible pavement is shown in Figure 17. Later, the tire-marker impact analysis will be based on both this model and the original model designed on rigid pavement.

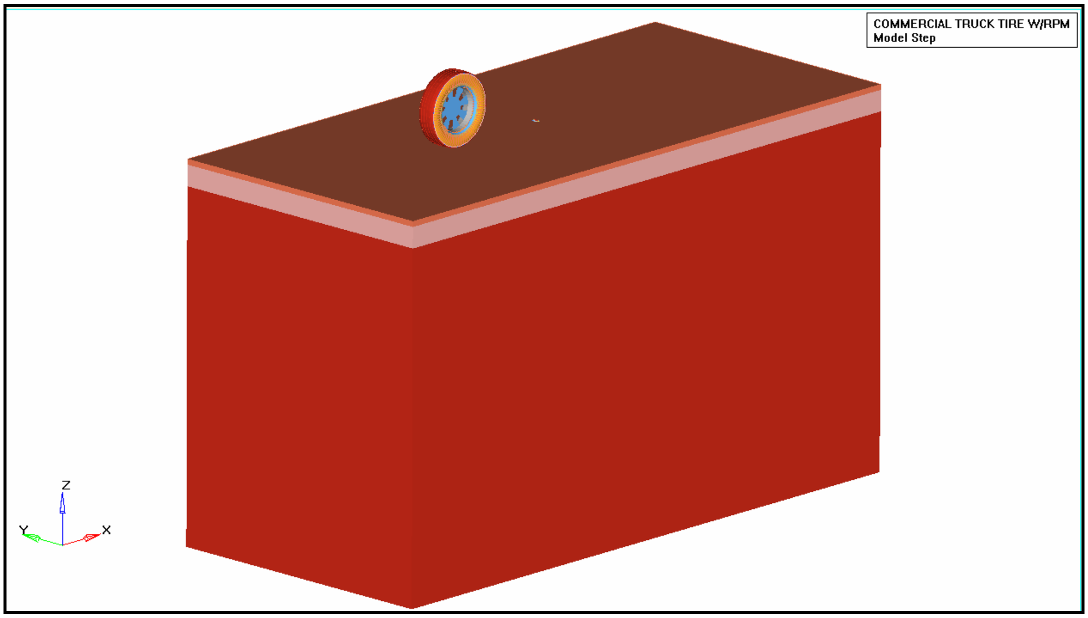


FIGURE 17 Tire-marker impact model with flexible pavement.

TIRE-MARKER IMPACT ANALYSIS

After the finite element model this research studies was introduced, this section of the methodology demonstrates the study design of the research which involves both tire-marker impact models with rigid and flexible pavement. The study design explains how stresses and interface forces for markers are analyzed and compared between two pavement types. Besides, it covers the evaluation of marker profiles based on the tire-marker impact model on rigid pavement.

Stress

There are two types of stress generated insides markers during the tire-marker impact, compressive and tensile stress, which are distributed differently and have different magnitudes as well. As for finite element analysis, the common stress evaluated is Von Mises stress, which is a scalar function of the components of the stress tensor that gives an estimation of the overall magnitude of the tensor according to the definition on the encyclopedia (*23*). The mathematical equation of Von Mises stress is given as follows:

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}},$$

where σ_1, σ_2, and σ_3 are the principal stress (*23*). The finite element modeling software used in this research is able to evaluate all the three types of stress introduced above, Von Mises, compressive and tensile stress, and they are selected to be evaluated for the purpose of the analysis.

First of all, the researcher will identify the critical locations and magnitudes of stress inside the markers during the tire-marker impact on flexible pavement. The researcher will model and simulate multiple scenarios of tire-marker impact with the combination of all the base external factors on flexible pavement. The Von Mises stress plots as well as the stress tensor plots generated from these simulations will be examined to identify the critical locations and magnitudes of stress inside the markers.

Next, the effects of external factors, tire loading, tire speed, contact angle and contact location, on the critical Von Mises stress identified in the previous task will be examined on flexible pavement in the same way as the researchers did on rigid pavement. Specifically, the researcher will study each external factor separately by varying the scenario of one external factor while keeping the others constant in the tire-marker impact simulation. The trend of the critical Von Mises stress over different scenarios of each individual external factor will be plotted for both types of markers. More details on how to evaluate the effects of external factors can be found in the research done by Zhang, et al (*4*).

Furthermore, the compressive and tensile stress inside the markers will be chosen as measurement of effectiveness to compare the impact between rigid and flexible pavement. The reason why these two types of stress are chosen is because the compressive strength and tensile strength of the pavement differ significantly as compressive strength is much larger. The two types of stress are also produced at different locations inside markers and cause different types of structural damage to RRPMs. As was reviewed, compressive stress tends to damage the top edges and non-lens sides of markers, while tensile stress inclines to bend markers and cause fracture from the mid-bottom of markers. On the other hand, marker damages caused by tensile stress are more frequently observed on flexible pavement, while compression-caused damages are more predominant on rigid pavement. Therefore, it is essential to compare these two types of stress both qualitatively and quantitatively between rigid and flexible pavement.

Specifically, the critical locations, patterns and magnitudes of compressive and tensile stress inside the markers will be compared. Based on the tire-marker impact simulations on flexible pavement and the corresponding ones on rigid pavement, the researcher will examine the stress tensor plots from these simulations to compare the critical locations and patterns of compressive and tensile stress. Furthermore, the magnitudes of the critical compressive and tensile stress at the same locations inside the markers will be averaged, respectively, to plot the comparison over the three stages of the tire-marker impact between the two types of pavement.

Interface Force

The interface force studied in this research refers to the force produced between the marker base and pavement surface during the tire-marker impact. There are two types of interface force evaluated in this research in terms of the direction of the force, which are x-direction interface force, also known as the shear force, and the z-direction interface force, which is perpendicular in nature. Both of them can be obtained from the tire-marker impact simulation. The shear force has been considered critical to the retention of PPRMs on the road.

Similarly, this research will compare the interface forces between rigid and flexible pavement, as more RRPMs have been observed to be removed from the road surface by traffic on rigid pavement than on flexible pavement (*17*). Such comparison is solely based on the magnitudes of interface forces, for the trend of forces over time during the tire-marker impact is pretty much the same between the two types of pavement. By varying the external factors on both rigid and flexible pavement, the researcher will be able to obtain multiple scenarios of simulation, which makes the study more representative. As for example, typical plots of shear (x direction) and perpendicular (z direction) interface forces between marker base and flexible pavement surface over time are shown in Figure 18.

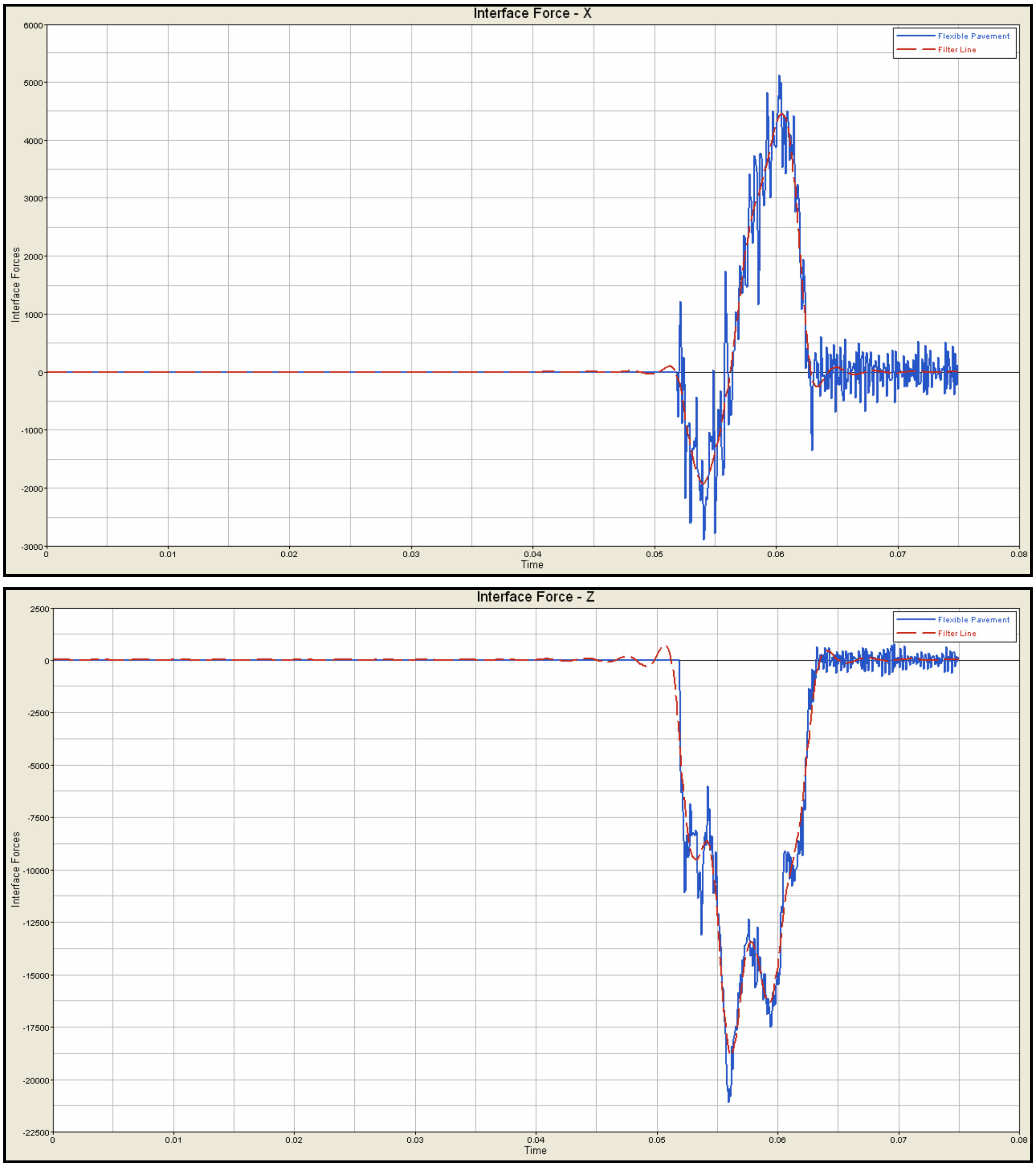


FIGURE 18 Shear and perpendicular interface force plots over time.

The blue lines are the simulation results of interface forces over time, and the red lines are the plots after filtering the noises of the results. The minus shear force indicates the opposite direction in which a tire travels, while the minus perpendicular force represents the downward force. Based on the plots, there are two peak shear forces which are produced in opposite directions. The first one is generated at the point when the tire is about to ascend the marker, and the other one occurs when the tire is about to descend the marker. The peak of the perpendicular force is produced approximately when the tire sits on top of the marker, which actually explains why the overall maximum Von Mises stress is produced at the second stage of the tire-marker impact, and which also demonstrates that the perpendicular force can be used to validate the credibility of the results of Von Mises stress comparison at the second stage of the impact.

Marker Profile Study

The profile of RRPMs has been regarded to affect marker durability. So, it is necessary to study the effect of marker profile on the stresses inside markers during the impact using the existing tire-marker impact model. The marker profile here is defined as the height, lens slope, length, and width of a marker. The researcher varies these factors in the finite element model to find out how they affect the magnitudes of maximum Von Mises stress inside the markers during the impact.

There is an issue associated with the modeling work – as the mesh of an individual marker is based on the whole geometry of the marker, a re-mesh is required whenever the shape of a marker is changed, which is very time-consuming. So, the researcher decided to use another approach to fulfill the study, which is varying the scale of the marker in the directions of x, y and z in a coordinate system, to get the same effect of changing the profile of a marker while reducing the time burden to conduct the study. The only limitation is that it is unable to study the marker height and lens slope separately as the scale variation in z direction will change the height and lens slope simultaneously. The compromise nevertheless does not affect the results the researcher expects to achieve. Another issue which needs to be considered is that MUTCD requires a minimum height of RRPM to be 10 mm (0.4 in) (*1*). For the sake of simplicity, the study is conducted only on rigid pavement. The coordinate system of x, y and z in which a marker model locates is shown in Figure 19.

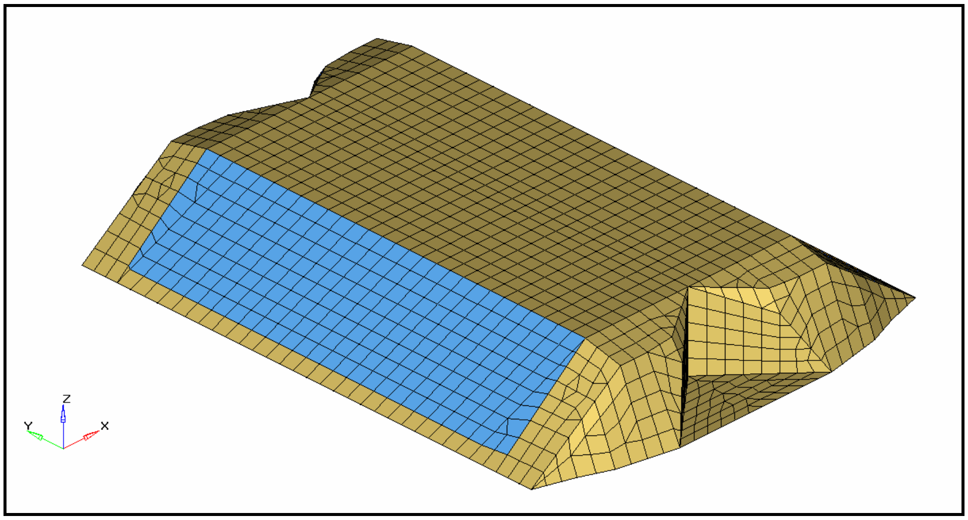


FIGURE 19 RRPM type B in x, y, z coordinate system.

LABORATORY TEST EVALUATION

The laboratory test evaluation consists of two tasks. One is to evaluate the existing standard laboratory tests which are the ASTM compression test and the longitudinal flexural test. The other one is to recommend additional laboratory tests which could better simulate the tire-marker impact in some specific scenarios that are proved to be critical in this research. The laboratory tests are built in Hypermesh and simulated by LS-DYNA as well.

The evaluation of the ASTM laboratory tests and the recommended ones is conducted by comparing the tensor plots of compressive and tensile stress inside the markers in the laboratory test simulation against the tire-marker impact simulation to see whether the simulated laboratory tests can generate the stress in the similar pattern and close magnitude as the simulated tire-marker impact does. The researcher believes that it is better than comparing the Von Mises stress, because the tensor plots of compressive and tensile stress are more specific in describing the stress distribution and more precise in correlating to the tire-marker impact on both types of pavement. So, the criteria of selecting a qualified laboratory testing procedure rely on the capability of the test to produce the critical stress at the same place inside the markers and to produce the similar pattern of critical stress as well as an appropriate loading rate to approximate the magnitude of the critical stress generated from the designated tire-marker impact.

Specifically, different laboratory tests have different weights of importance in terms of compressive and tensile stress. Compressive stress should attract more attention in the ASTM compression test against the tire-marker impact simulation, while tensile stress should be a more critical measurement in the ASTM longitudinal flexural test. The researcher considers it reasonable to weigh a measurement of effectiveness over another according to the nature of a laboratory test, and not a single test is expected to replicate the tire-marker impact completely. Overall, compressive stress is an important measurement for tire-marker impact on both types of pavement as it is predominant inside markers during the impact in terms of the magnitude, and tensile stress might be more critical to the impact on flexible pavement, as was demonstrated by the unique damage type previously described.

In addition, the tire-marker impact simulation used to compare with the laboratory test simulation consists of the external factors with specific values. Base values are used for the external factors that are proved to be insignificant to the impact while the largest values are used for the external factors that are demonstrated to have effects on the impact. In this way, the laboratory tests can be examined to their limit for evaluating the field performance of RRPMs. Different loading rates are tried in the laboratory tests until the best one that generates the approximate critical stress compared with the tire-marker impact is determined. The researcher endeavors to differentiate the loading rates for RRPMs to be installed on different types of pavement.

RESULTS AND ANALYSIS

The researcher ran a large number of simulations in LS-DYNA for the study design described in methodology part. This section of the thesis presents the results of these simulations and the related analysis and discussions.

TIRE-MARKER IMPACT ANALYSIS

The researcher utilized the advantage of finite element simulation to investigate multiple scenarios of tire-marker impact based on the combination of four external factors defined previously for the study design, making the results of the study more representative. The researcher is able to evaluate 3^4 scenarios of tire-marker impact simulation to the extreme extent with the combination of four variables each having three scenarios. The configuration of these scenarios is shown in Table 2.

TABLE 2 External Factors and Their Scenarios

External Factors	Base	Value 1	Value 2
Tire Loading (N)	22,200	13,300	31,100
Tire Speed (m/s)	31.3	26.8	35.7
Contact Angle (Degrees)	0	5	10
Contact Location (mm offset from center)	0	25	51

The values of tire loading and tire speed correspond to the values in English unit at 3000, 5000, 7000 lbs and 60, 70, 80 miles per hour, respectively. The reasons for selecting these values are explained next. For tire loading, 5000 lb was chosen as the base value because the federal government limits vehicle weights on Interstate highways to a maximum of 20,000 lb for a single axle, averaging 5000 lb for a single truck tire (*24*). Since the load may not be equally distributed among the four tires of an axle, 3000 and 7000 lbs were picked up as the lower and upper values. For tire speed, 70 mph was chosen as the base value due to the speed limit on most Interstate highways and 60 and 80 mph were used as the lower and upper values.

The entire process of tire-marker impact was categorized into three stages (*2, 4*). The first stage is defined as when the tire first contacts the front lens face of the marker and is about to ascend the marker. The second stage represents the scenario when the tire stays on top of the marker. At the third stage the tire is still in contact with the rear lens face of the marker and about to leave the marker. Either the critical Von Mises stress, or critical compressive and tensile stress at each stage will be selected as the measurement of effectiveness for each simulation. The following results and analysis are based on the evaluation of tire-marker impact in three stages.

Tire-Marker Impact on Flexible Pavement

The researcher modeled and simulated 9 scenarios of tire-marker impact with the combination of all the external factors with base values. In simulation, the tire rolls over the markers in the same manner as it does on rigid pavement, but the markers tied with the pavement surface were found to sink at approximately 1 mm, which is reasonable as RRPMs on flexible pavement, to some extent, have sunk into the pavement over time (See Figure 8) (*17*). Reviewing the Von Mises stress plots, the researcher found that the critical Von Mises stress was produced at the top edges of the markers, identical to the critical locations identified on rigid pavement. Figures 20 and 21 show the critical locations and magnitudes of Von Mises stress at the three stages of impact on flexible pavement for RRPM type A and B, respectively, which were both generated from the simulation consisting of all base external factors.

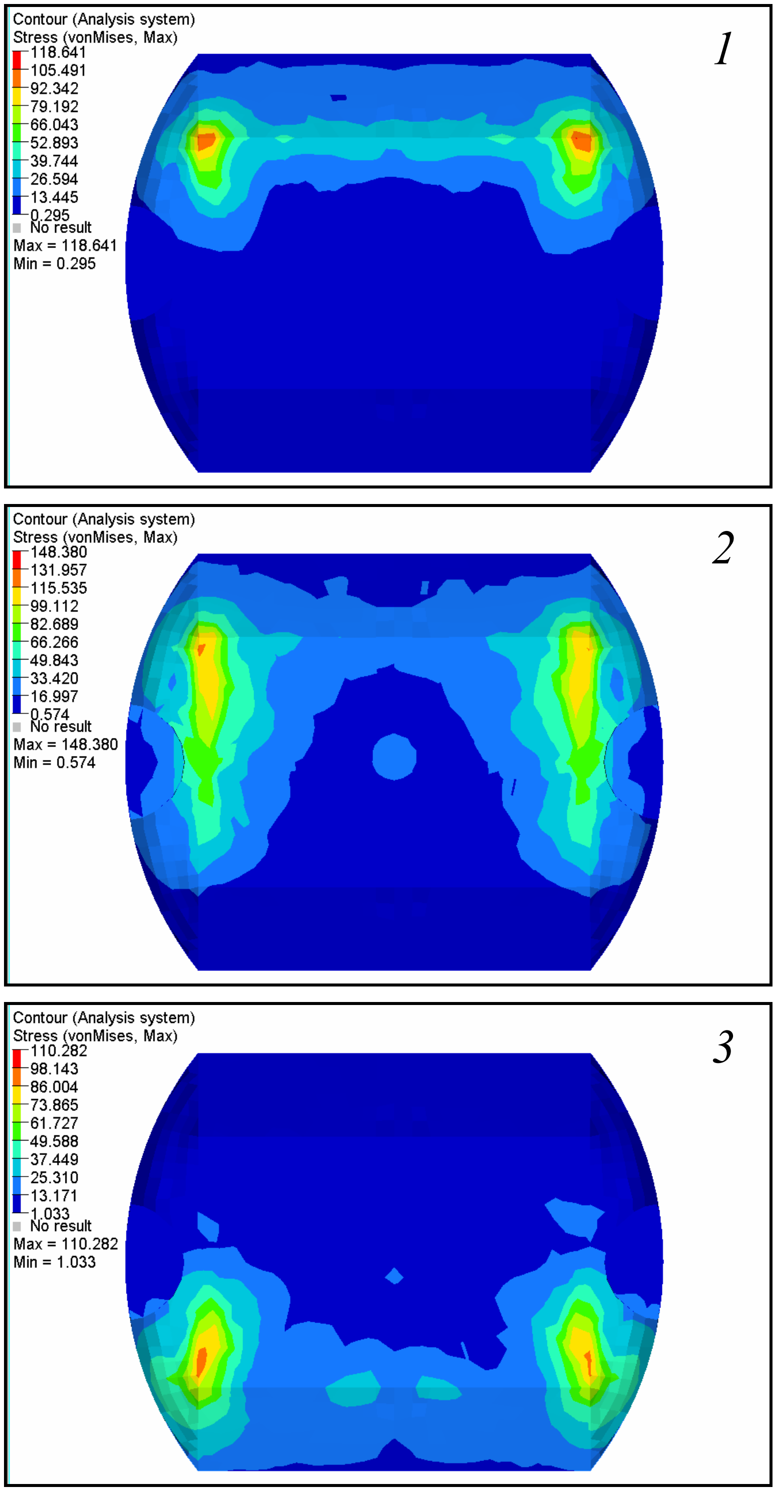


FIGURE 20 Von Mises stress plot for RRPM type A.

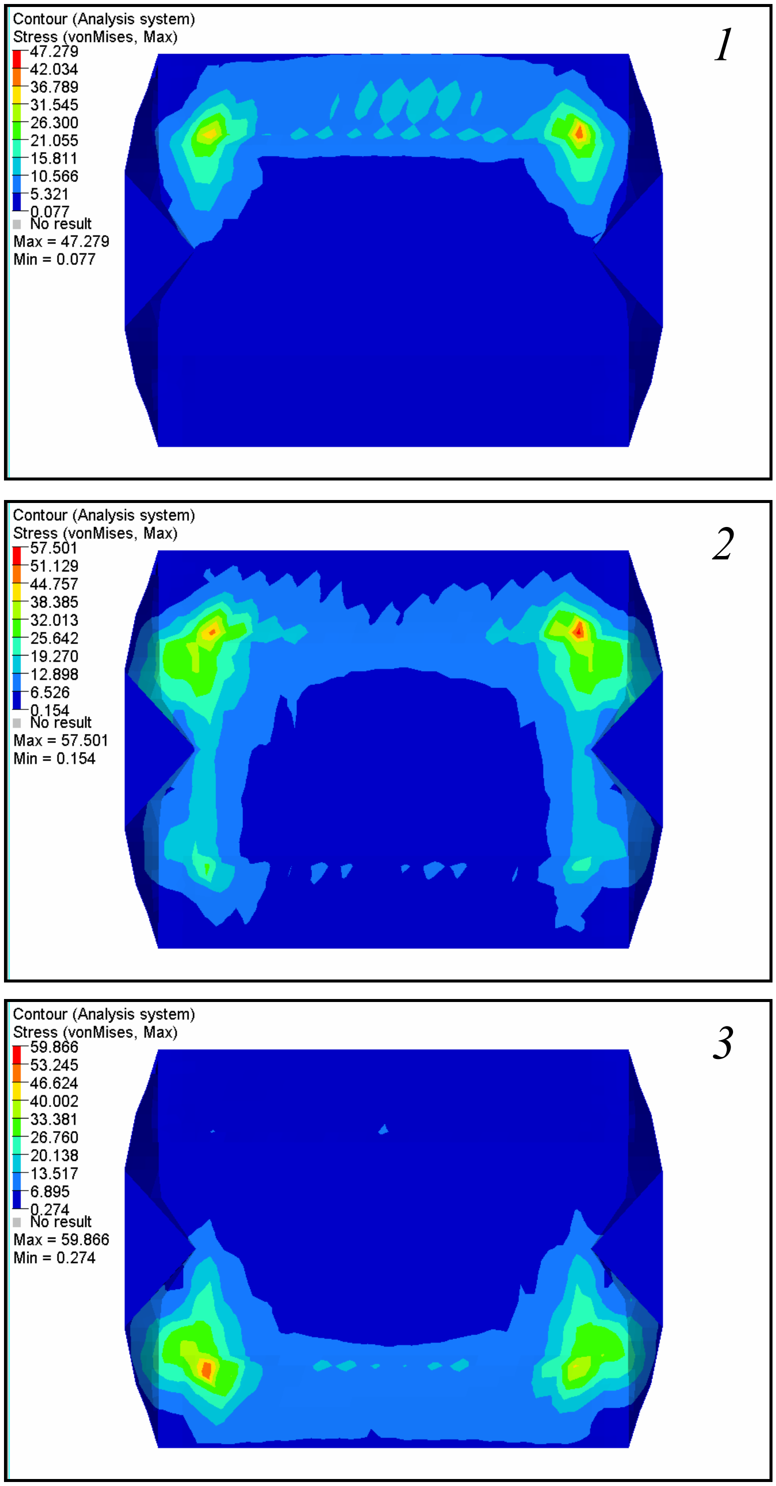


FIGURE 21 Von Mises stress plot for RRPM type B.

The maximum Von Mises stresses in the first stage are 118.641 and 47.279 MPa for RRPM type A and B, respectively. In the second stage, the maximum Von Mises stresses for maker type A and B are 148.38 and 57.501 MPa, respectively. In the third stage, the maximum Von Mises stresses for maker type A and B are 110.282 and 59.866 MPa, respectively. The reason why there is a large discrepancy between the results of two marker models is that the yield strength set for the material of these two marker models is significantly different.

Reviewing the compressive and tensile stress inside the markers during those tire-marker impact simulations, the researcher found that when the tire was about to ascend the markers, tensile stress was produced all over the opposite side of the markers where the tire contacted the markers while compressive stress was generated at the top of the lenses and especially intense at the top edges of the markers. The same pattern occurred when the tire was about to descend the markers. When the tire sat on top of the markers, compressive stress was seen at the non-lens side of the top surface of the markers and especially intense at the top edges of the markers while tensile stress was found throughout the body of the markers and significant close to the mid-bottom of the markers. In terms of the magnitude, compressive stress was predominant, but tensile stress was speculated to damage the inner structure of the markers more severely. The typical tensor plots of compressive and tensile stress for RRPM type A and B are shown in Figures 22 and 23, based on the tire-marker impact simulation with all the base scenarios of external factors. The compressive stress is represented by negative values and tensile stress by positive values.

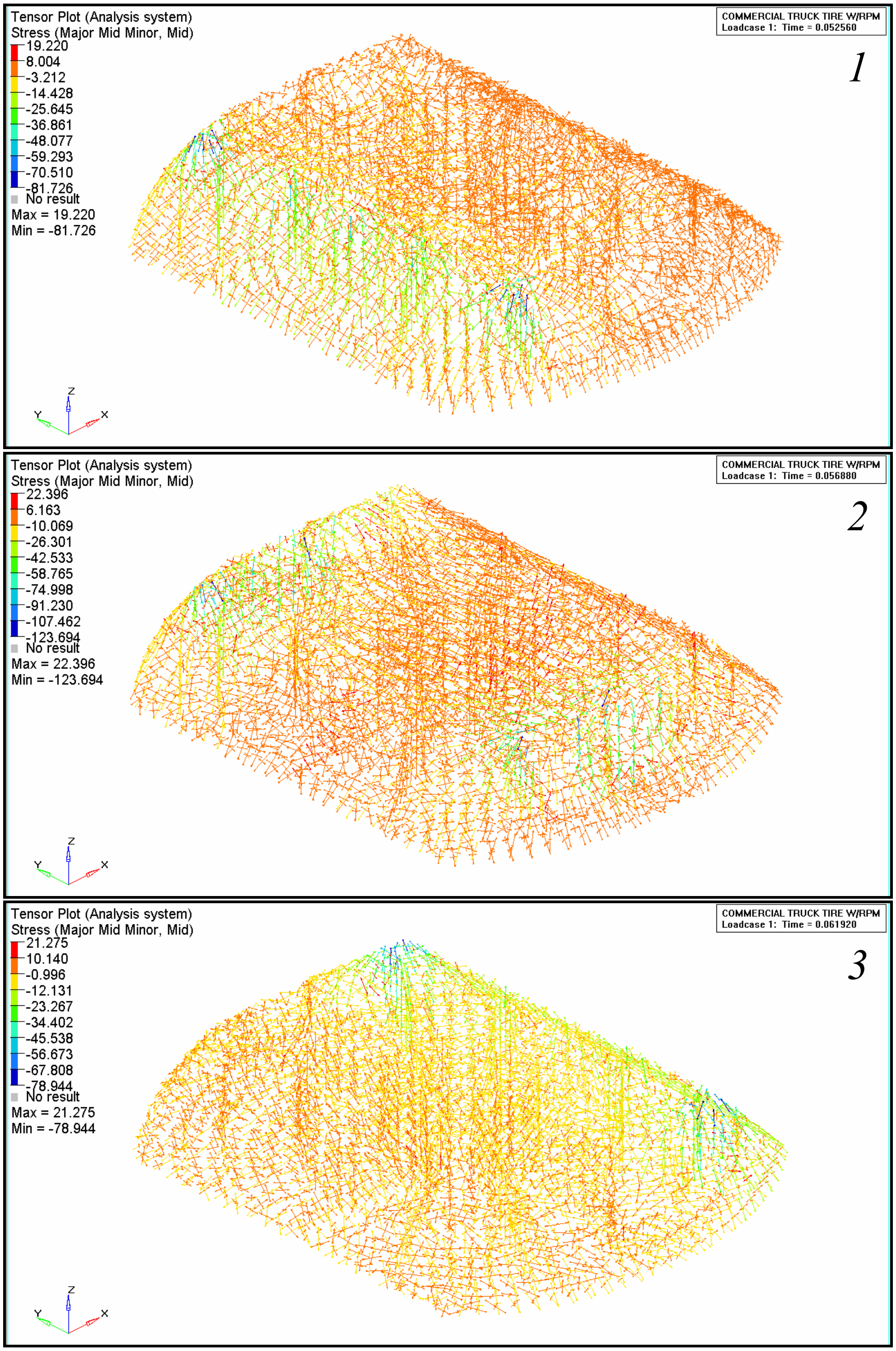


FIGURE 22 Tensor plot for RRPM type A.

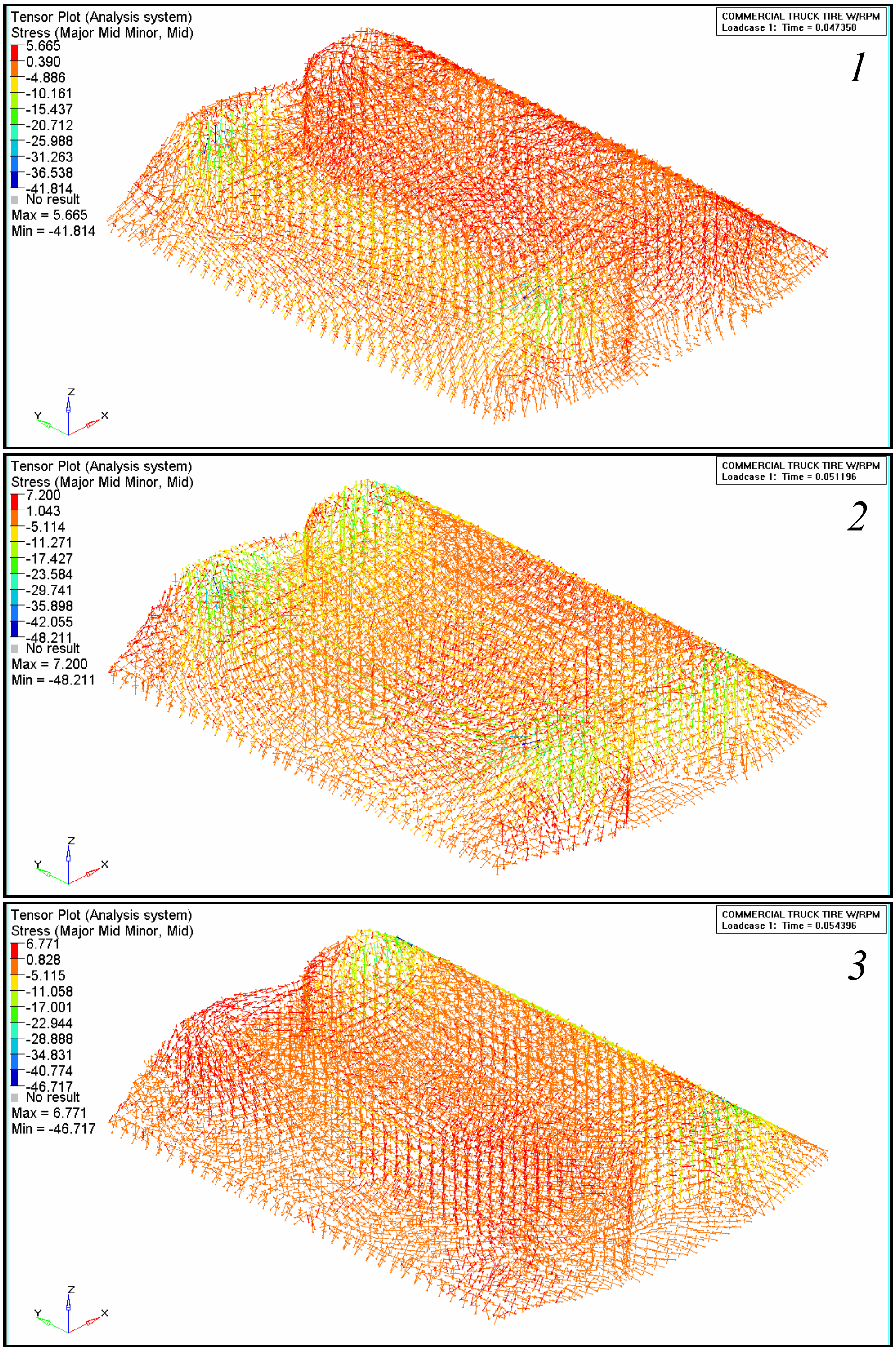


FIGURE 23 Tensor plot for RRPM type B.

The researcher then did a sensitivity analysis of pavement thickness regarding the critical locations and magnitudes of stress inside the markers during the impact. Besides the pavement thickness in Table 1, two other groups of pavement thickness were used to simulate the tire-marker impact. The researcher found that the critical locations of stress are similar among the three groups of pavement thickness. Furthermore, the magnitudes of the critical stress are not much different. Table 3 shows the results of the sensitivity analysis.

TABLE 3 Sensitivity Analysis of Pavement Thickness

Critical Stress (Mpa)	Pavement Thickness (mm) Surface/Base/Subgrade	RRPM Type A			RRPM Type B		
		Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Von Mises	80/300/5000	118.641	148.38	110.282	47.279	57.501	51.882
	120/450/5000	118.989	149.774	112.131	47.647	57.613	52.219
	160/600/5000	119.023	150.403	113.076	47.648	57.775	52.868
Compressive	80/300/5000	113.281	136.107	89.286	41.814	52.356	46.717
	120/450/5000	113.706	137.295	92.013	41.963	52.45	46.931
	160/600/5000	113.931	137.975	93.188	41.954	52.527	47.181
Tensile	80/300/5000	18.951	26.867	30.121	5.665	8.411	6.771
	120/450/5000	18.325	27.421	26.025	5.589	8.504	6.873
	160/600/5000	18.441	27.764	24.605	5.628	8.575	7.074

In addition, the researcher compared the critical locations and magnitudes of stress between the average flexible pavement and the flexible pavement on interstate highways whose pavement thickness and material properties are shown in Table 1. The critical locations of stress are the same between the two and the magnitudes of the critical stress are close as well, which are shown in Table 4. All these demonstrate that the thickness and material properties of an average flexible pavement can be used in the tire-marker impact model to conduct the following research tasks as there is not much variation in stress inside the markers between an average asphalt pavement and one for extremely heavy loads.

TABLE 4 Sensitivity Analysis of Average and Interstate Flexible Pavement

Critical Stress (Mpa)	Flexible Pavement	RRPM Type A			RRPM Type B		
		Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Von Mises	Average	118.641	148.38	110.282	47.279	57.501	51.882
	Interstate	119.145	150.815	113.316	47.662	57.871	52.36
Compressive	Average	113.281	136.107	89.286	41.814	52.356	46.717
	Interstate	114.125	138.264	93.35	41.995	52.727	47.185
Tensile	Average	18.951	26.867	30.121	5.665	8.411	6.771
	Interstate	19.886	22.871	27.321	5.621	8.669	7.121

Next, the effects of the external factors, tire loading, tire speed, contact angle and contact location, on the critical Von Mises stress previously identified were examined on flexible pavement. The researcher was able to study each external factor separately by varying the scenario of one external factor while keeping the others constant in the tire-marker impact simulation. Figures 24 and 25 show the trend of the critical Von Mises stress over different scenarios of each individual external factor for marker type A and B, respectively.

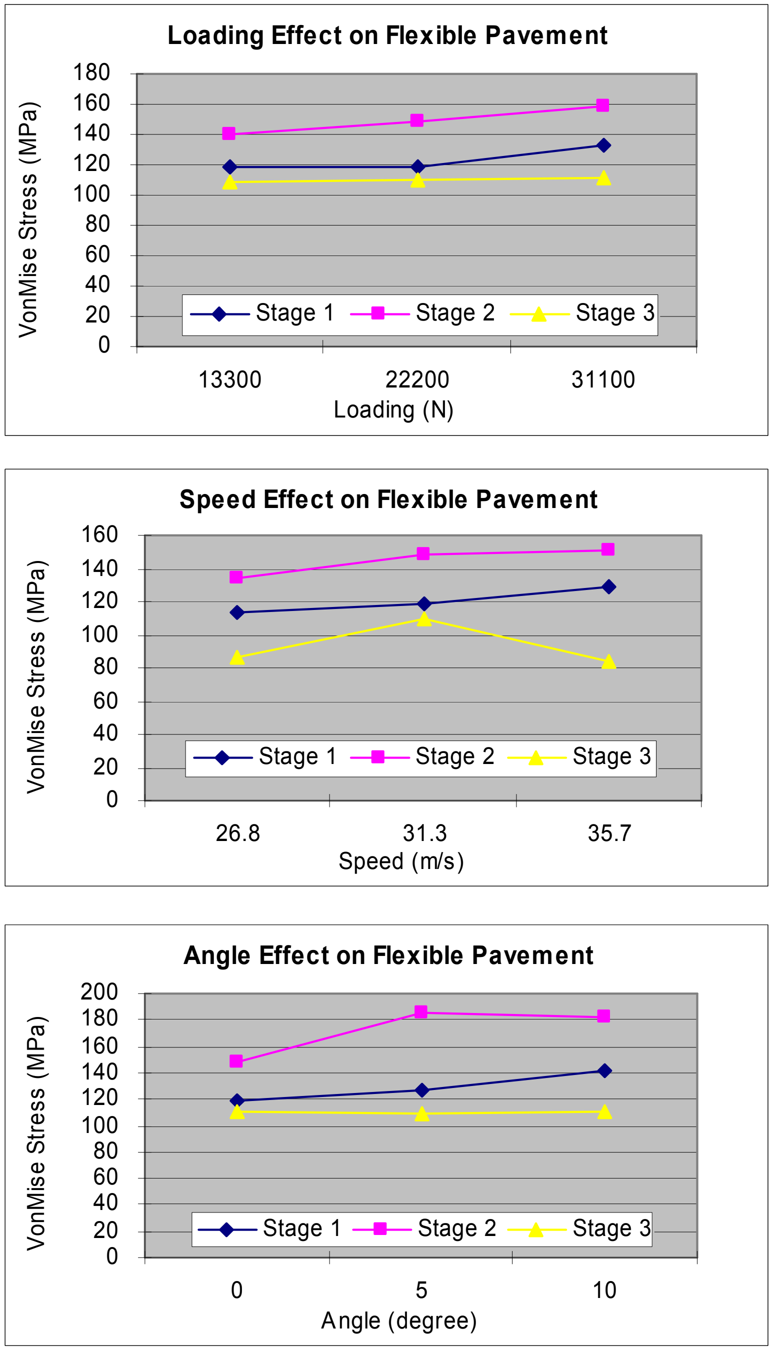


FIGURE 24 Effect of external factors on Von Mises stress for RRPM type A.

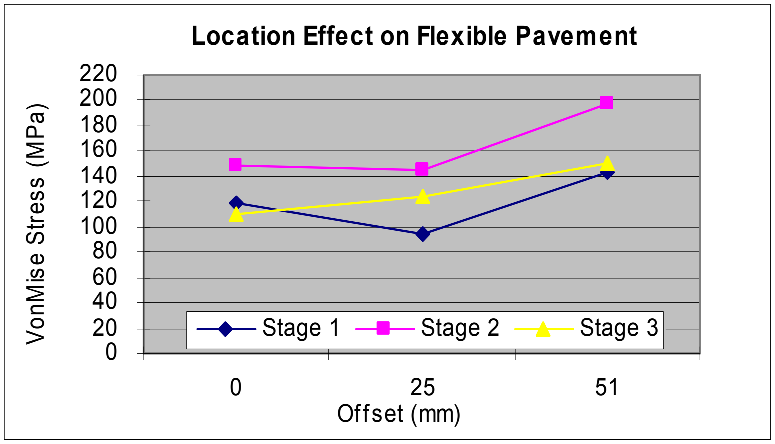
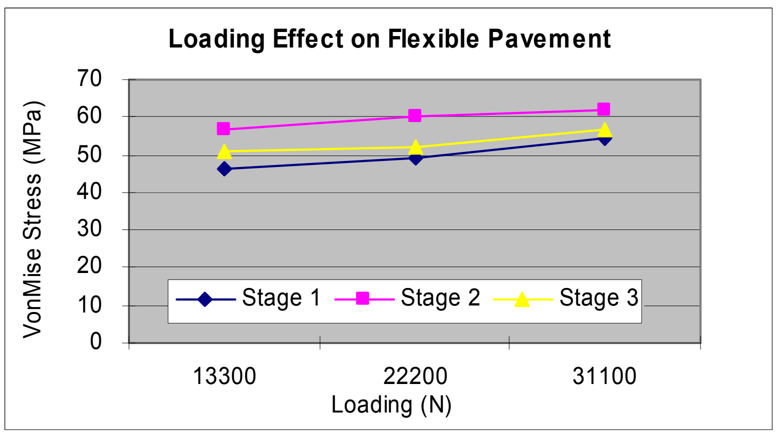


FIGURE 24 Continued.



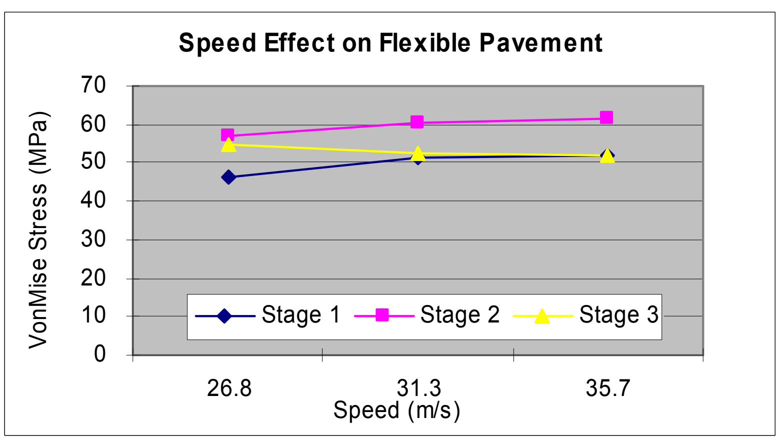
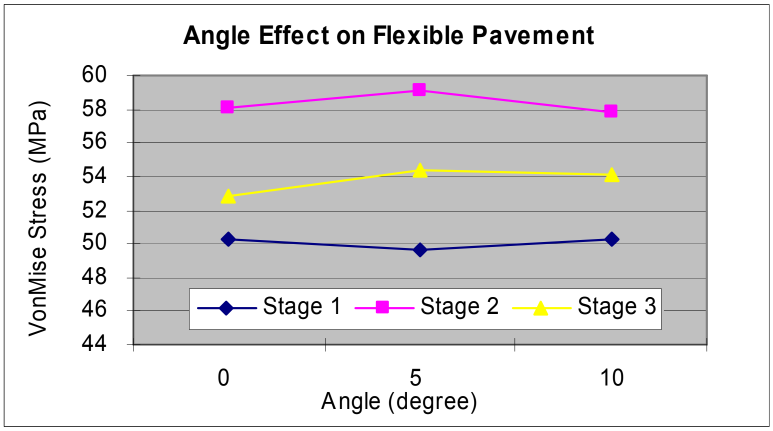


FIGURE 25 Effect of external factors on Von Mises stress for RRPM type B.



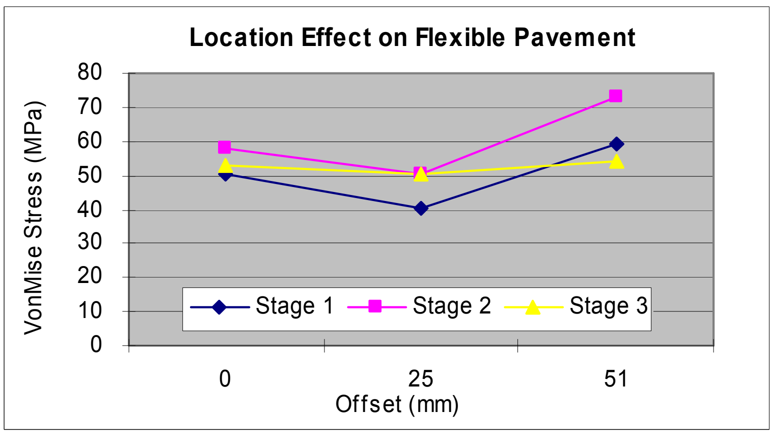


FIGURE 25 Continued.

Based on the trend plots for two marker models, the researcher found that the tire loading and contact location have consistent effects on Von Mises stress during the impact on flexible pavement. In addition, contact angle has some effect on the stress for marker type A, but such effect is inconsistent for marker type B. Tire speed does not have consistent effect on Von Mises stress for both types of marker. This conclusion is in accordance with what was previously reached by researchers in evaluating the external factors on rigid pavement. Therefore, loading and contact location should be considered as important factors when developing a laboratory test.

More detailed comparisons and discussions between two pavement types are provided in the next section.

Comparison between Rigid and Flexible Pavement

The critical locations and magnitudes of Von Mises stress as well as compressive and tensile stresses were compared between tire-marker impact on rigid and flexible pavement. Based on the Von Mises stress plots in Figures 20 and 21, the critical locations of Von Mises stress inside the markers are almost identical between the two types of pavement in that they are all located at the top edges of the markers. However, in terms of the magnitude of critical Von Mises stress at those locations, it is about 10% larger on rigid pavement than on flexible pavement. Figures 26 and 27 show the comparison of the average magnitudes of critical Von Mises stress based on the 9 scenarios of simulation for marker type A and B, respectively.

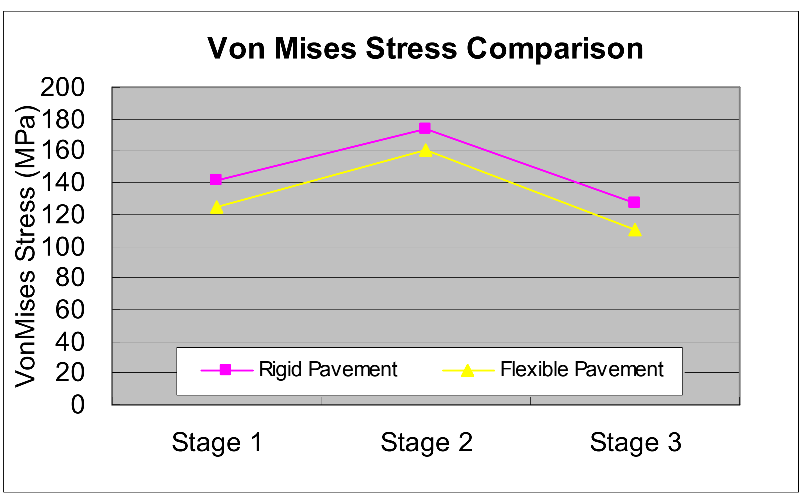


FIGURE 26 Von Mises stress comparison for RRPM type A.

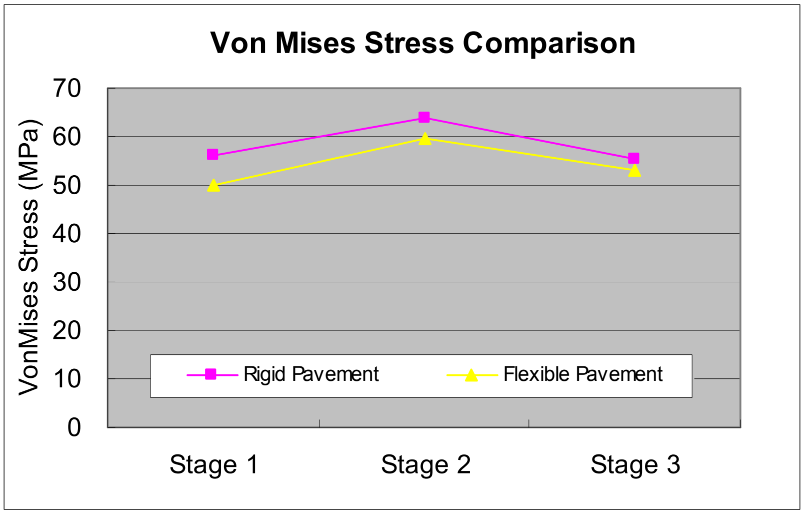


FIGURE 27 Von Mises stress comparison for RRPM type B.

Examining the stress tensor plots in Figure 22 and 23, the researcher found that the critical locations of compressive stress inside the markers are the same on two types of pavement, both are at the top edges of the markers, but the average magnitude of compressive stress at those critical locations is about 11% larger on rigid pavement than on flexible pavement. Figures 28 and 29 show the comparison of the average magnitudes of critical compressive stress based on the 9 scenarios of simulation for marker type A and B, respectively.

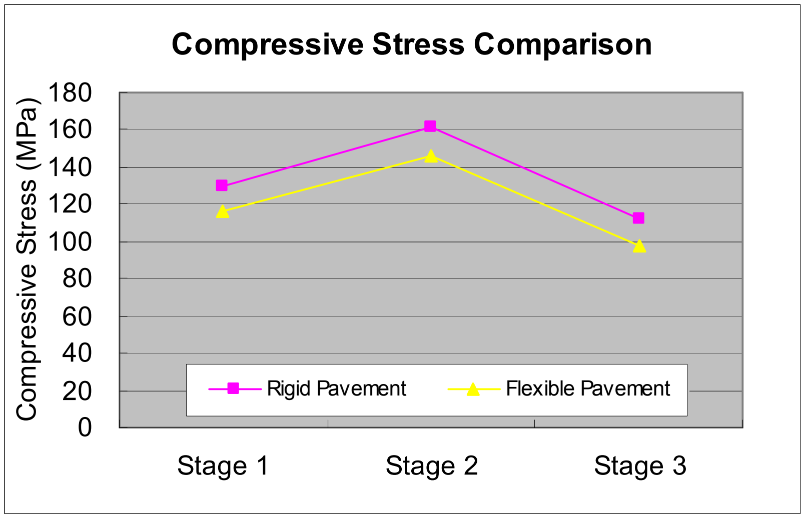


FIGURE 28 Compressive stress comparison for RRPM type A.

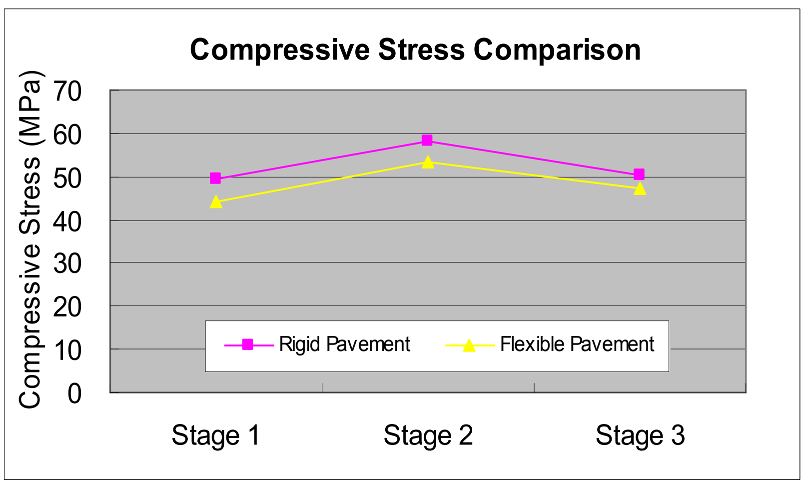


FIGURE 29 Compressive stress comparison for RRPM type B.

As for tensile stress, it is generally distributed in the same way on both types of pavement. However, for RRPM A, the patterns of the critical tensile stress are different between the two types of pavement based on the side view of stress tensor plots from the same stage of the simulation, which is shown in Figure 30. But for RRPM B, the patterns of the critical tensile stress look similar, shown in Figure 31.

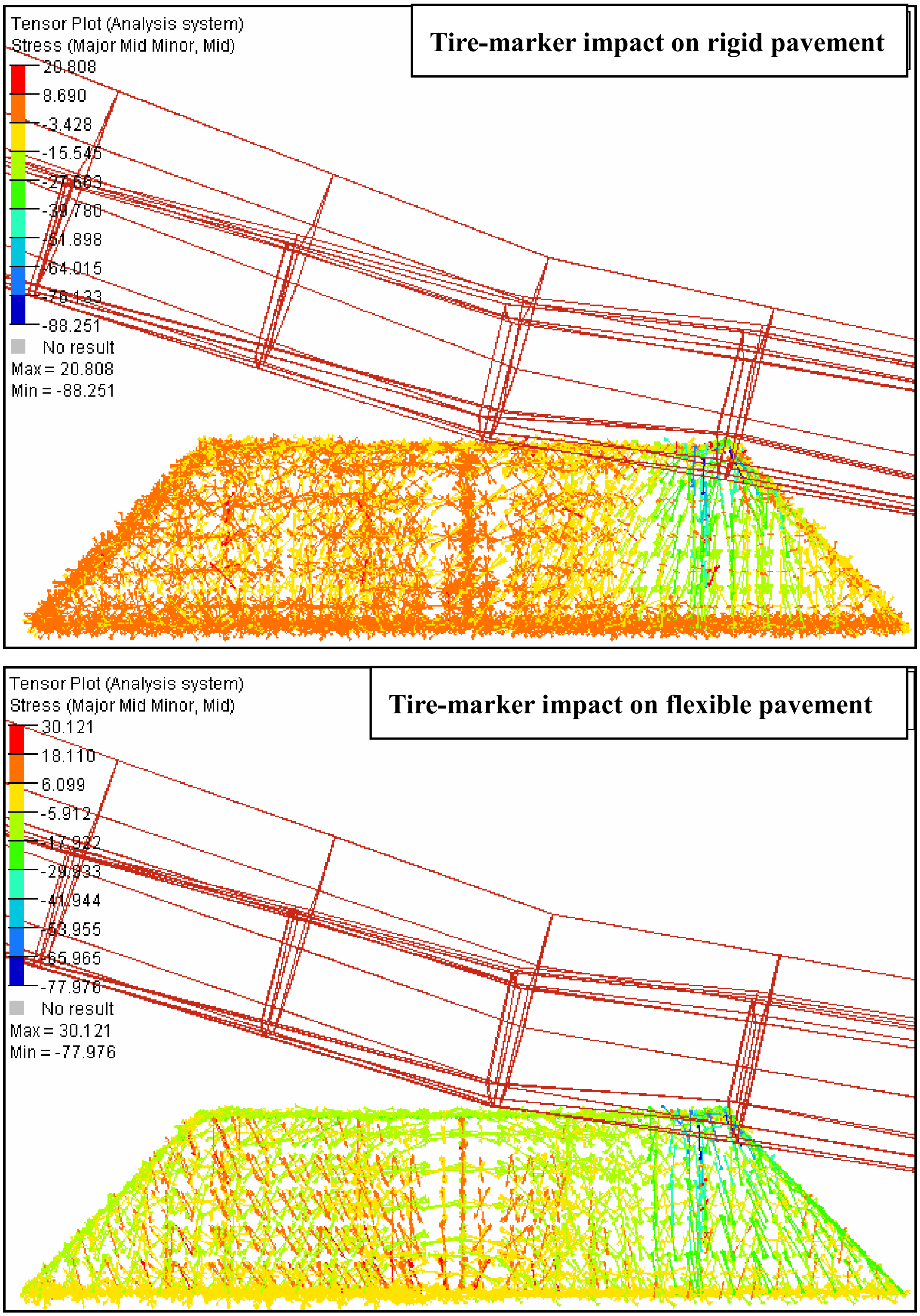


FIGURE 30 Tensile stress pattern comparison for RRPM type A.

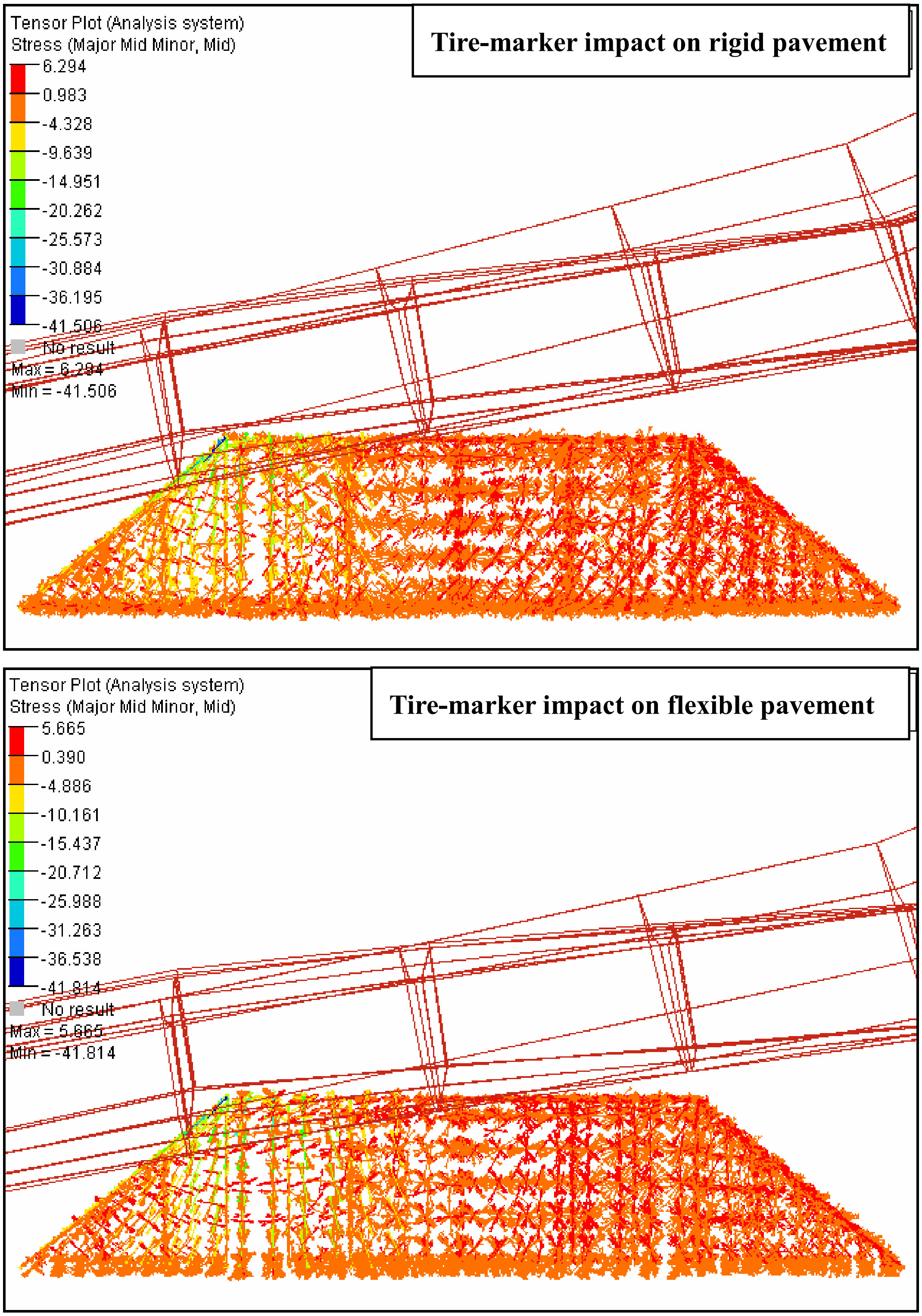


FIGURE 31 Tensile stress pattern comparison for RRPM type B.

For marker type A, the critical tensile stress scatters inside the marker on rigid pavement while on flexible pavement it is generated from the mid-bottom of the marker and going upward with certain angle consistently. The average magnitudes of this group of critical tensile stress are not significantly different between rigid and flexible pavement for both types of markers during the first and second stage of the impact. However, the critical tensile stress during the third stage of the impact on flexible pavement is significantly larger than that on rigid pavement. Nevertheless, such difference is slight for marker type B. Figures 32 and 33 show the comparison of the average magnitudes of the critical tensile stress based on the simulations for marker type A and B, respectively.

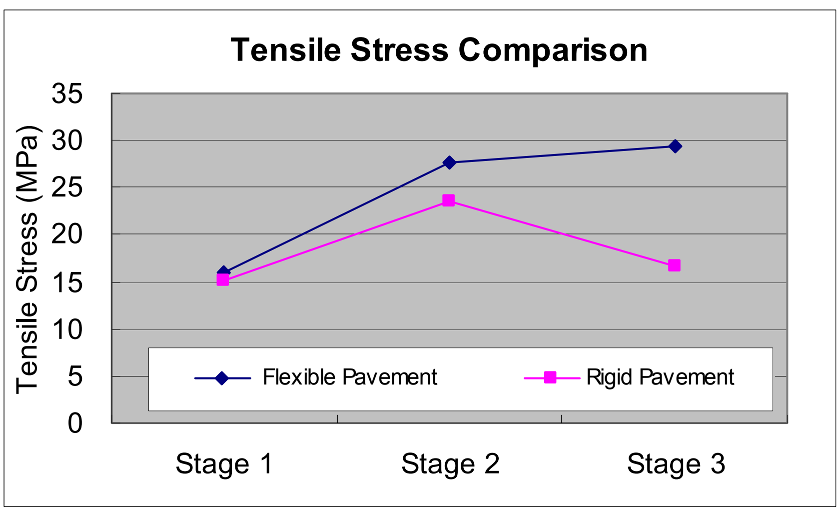


FIGURE 32 Tensile stress comparison for RRPM type A.

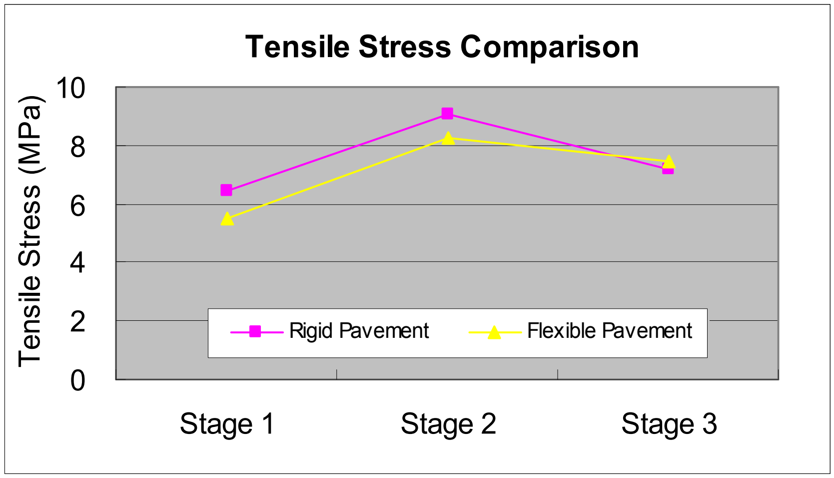


FIGURE 33 Tensile stress comparison for RRPM type B.

Based on the results and plots above, it is evident that there tends to be a larger magnitude of critical Von Mises stress at the top edges of the markers during the tire-marker impact on rigid pavement than on flexible pavement, and the critical compressive stress, which is predominant in terms of the magnitude compared to the critical tensile stress, demonstrates this relationship as well. Such results are expected by the researcher as the field study conducted by Zhang, et al shows that RRPMs on rigid pavement have more severe damages at the top edges, upper lens, and the non-lens sides, which are caused by compressive stress, than those on flexible pavement at the same test deck (*17*).

On the other hand, the side view of stress tenor plots for marker type A demonstrates that the patterns of the critical tensile stress inside the markers are different between the two types of pavement although the general distribution of tensile stress is similar. For the impact on rigid pavement, the critical tensile stress scatters in the body of the markers, while the critical tensile stress is produced from the mid-bottom of the markers on flexible pavement. But for marker type B, the critical tensile stress is generated from the mid-bottom of the markers on both types of pavement. Furthermore, the magnitude of the critical tensile stress during the third stage of the impact on flexible pavement is larger than that on rigid pavement, as was proved by both types of makers, although such difference was considered to be insignificant for marker type B. In fact, the tensile stress for marker type B is relatively small in magnitude, which might be a reason for the slight difference between two types of pavement. Overall, it is supportive to the field observation at the test deck on flexible pavement that some RRPMs have fracture across the mid-bottom of the markers (See Figure 9), which is resulted from the critical tensile stress shown in Figures 30 and 31 for the impact on flexible pavement, and such structural failure was rarely observed at any test deck on rigid pavement.

The finding that different magnitudes of critical compressive and tensile stress exist inside the markers between rigid and flexible pavement point out that different standards on loading rate should be implemented in laboratory tests designed to test RRPMs to be installed on the two types of pavement. Furthermore, a laboratory test specialized in examining tensile stress is necessary for RRPMs on both types of pavement, but more critical to RRPMs on flexible pavement, while a test that is good at testing compressive stress should be important to RRPMs on both types of pavement.

Interface Force Comparison

Forty-five scenarios of tire-marker impact simulation were set up and run by the researcher on both types of pavement. They are combined with all the scenarios of external factors except for the scenarios having contact angle and offset at the same time. After obtaining all the results of peak forces in x and z direction, the sample means were used to examine the relationship between the peak interface forces on rigid and flexible pavement. The comparison of the sample means of interface forces in x and z direction (Unit: Newton) between two types of pavement is shown in Table 5.

TABLE 5 Comparison of Interface Forces between Two Types of Pavement

	Interface Forces (RRPM A)			Interface Forces (RRPM B)		
Average Peak Force (N)	x(+)	x(-)	z	x(+)	x(-)	z
Rigid Pavement	4656	2550	20536	3117	1753	19976
Flexible Pavement	4244	1718	18886	2821	1438	18530

In addition to this comparison, the researcher also plotted the interface forces over the entire impact process on both types of pavement simultaneously for marker type A and B, respectively, which are shown in Figures 34 and 35. The blue lines represent results on rigid pavement, while red lines are for flexible pavement. It is evident that the interface forces between markers and pavement surface on rigid pavement are statistically larger than those on flexible pavement in both x and z direction. The result of perpendicular interface force (z direction) further proves the credibility of the comparison of Von Mises stress at the second stage of the impact between the two types of pavement. Furthermore, the researcher believed that RRPMs on flexible pavement should undergo less shear interface force (x direction) than those on rigid pavement, as can be explained by the fact that RRPMs on flexible pavement have sunk into the pavement more or less over a period of time, and was also supported by the field study conducted by Zhang, et al who found that much more RRPMs had been removed by traffic on rigid pavement than on flexible pavement over time at the same test deck (*17*). Therefore, the execution of improved procedure or the use of stronger binding material to install RRPMs on rigid pavement, especially at places where traffic volume or truck percentage is high should be attached with importance.

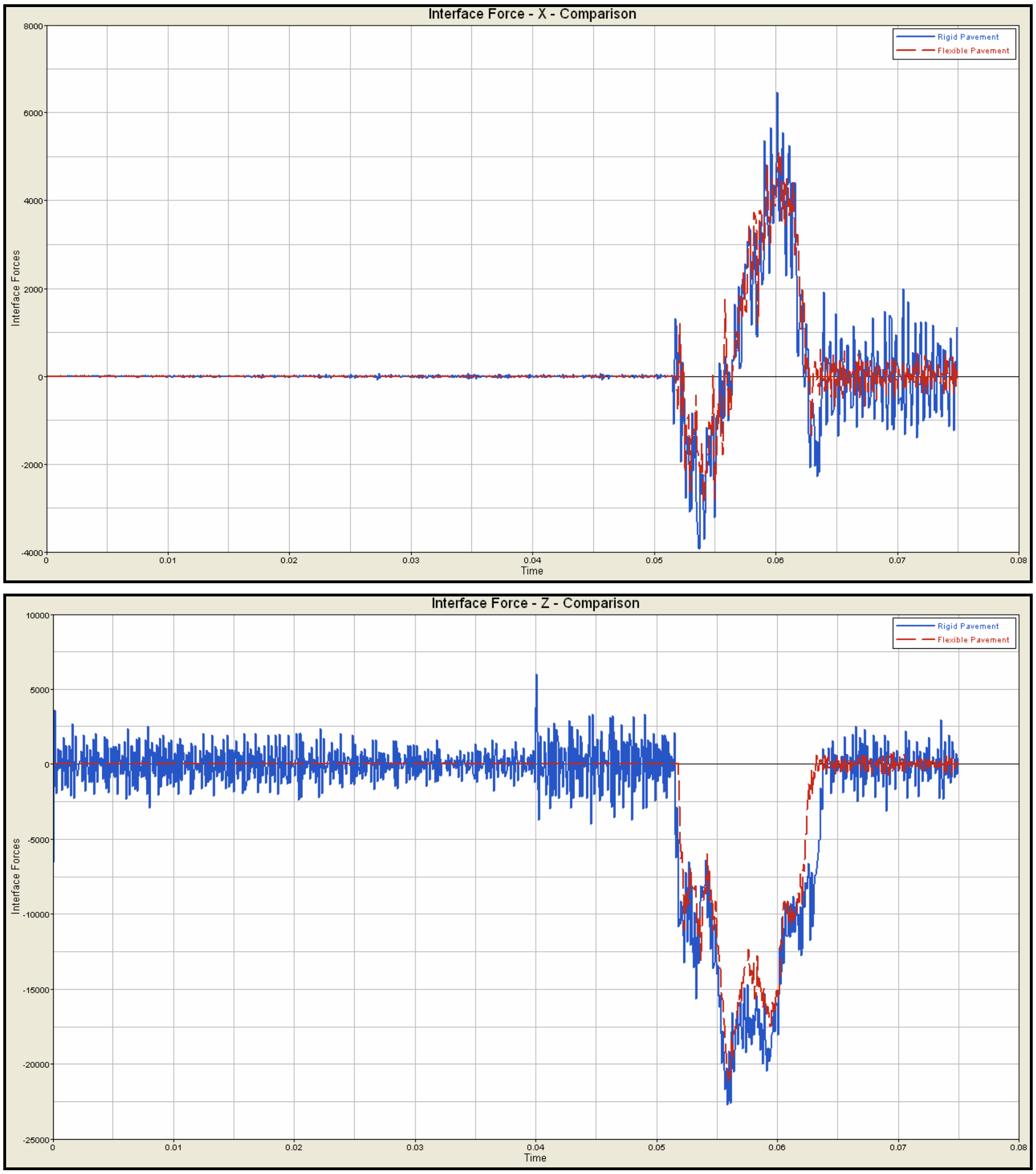


FIGURE 34 Comparison of the magnitudes of interface forces between the two types of pavement for RRPM type A.

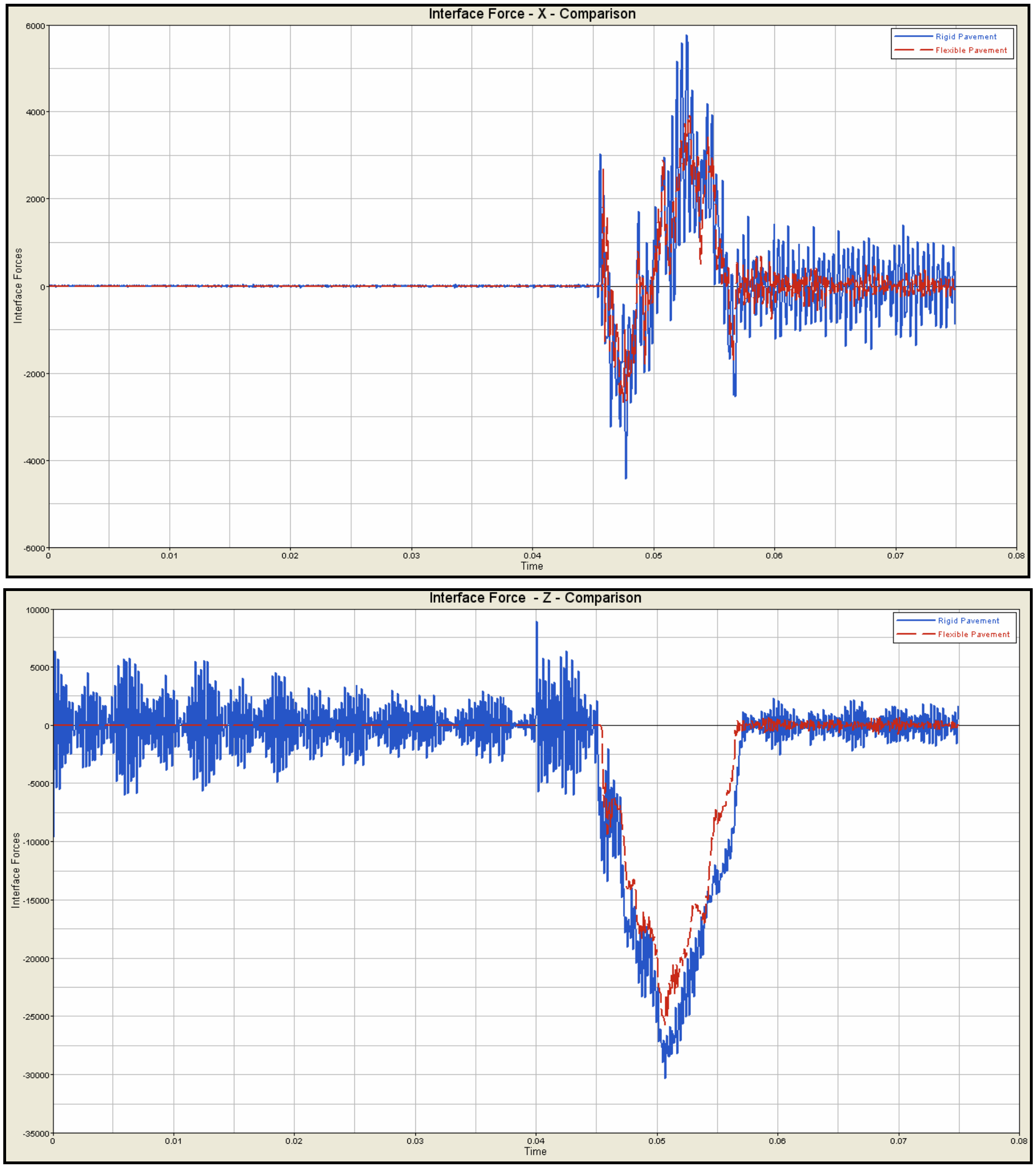


FIGURE 35 Comparison of the magnitudes of interface forces between the two types of pavement for RRPM type B.

Marker Profile Study

By varying the scale of the marker in z, x and y direction, the researcher got different profiles of the two marker models. All the marker profiles meet the minimum height of 10 mm (0.4 in) required by MUTCD. Tables 6 and 7 show the profiles of maker model A and B in commensurate with the scales.

TABLE 6 RRPM Type A Profiles (Unit: mm)

RRPM A		height	length	width			slope
Direction	Scale	(z)	(x)	(y)	upper x	upper y	(degree)
Z	0.8	12.2	74.997	96	45	70	39
	0.9	13.725	74.997	96	45	70	42
	1	15.25	74.997	96	45	70	45
	1.1	16.775	74.997	96	45	70	48
	1.2	18.3	74.997	96	45	70	51
X	0.8	15.25	59.9976	96	36	70	52
	0.9	15.25	67.4973	96	40.5	70	48
	1	15.25	74.997	96	45	70	45
	1.1	15.25	82.4967	96	49.5	70	43
	1.2	15.25	89.9964	96	54	70	40
Y	0.8	15.25	74.997	76.8	45	56	45
	0.9	15.25	74.997	86.4	45	63	45
	1	15.25	74.997	96	45	70	45
	1.1	15.25	74.997	105.6	45	77	45
	1.2	15.25	74.997	115.2	45	84	45

TABLE 7 RRPM Type B Profiles (Unit: mm)

RRPM B		height	length	width			
Direction	Scale	(z)	(x)	(y)	upper x	upper y	slope
	0.8	10.8	71	95	38	83	33
	0.9	12.15	71	95	38	83	36
	1	13.5	71	95	38	83	39
	1.1	14.85	71	95	38	83	42
Z	1.2	16.2	71	95	38	83	44
	0.8	13.5	56.8	95	30.4	83	46
	0.9	13.5	63.9	95	34.2	83	42
	1	13.5	71	95	38	83	39
	1.1	13.5	78.1	95	41.8	83	37
X	1.2	13.5	85.2	95	45.6	83	34
	0.8	13.5	71	76	38	66.4	39
	0.9	13.5	71	85.5	38	74.7	39
	1	13.5	71	95	38	83	39
	1.1	13.5	71	104.5	38	91.3	39
Y	1.2	13.5	71	114	38	99.6	39

After running the base tire-marker impact simulation on rigid pavement with different scenarios of marker profile, the researcher got the maximum Von Mises stress generated at the top edges of the markers for each profile scenario. The researcher was able to investigate the effect of marker height combined with lens slope (z direction scale), marker length combined with lens slope (x direction), and marker width (y direction scale) on the maximum Von Mises stress. Figure 36 and 37 show such effect for marker type A and B, respectively.

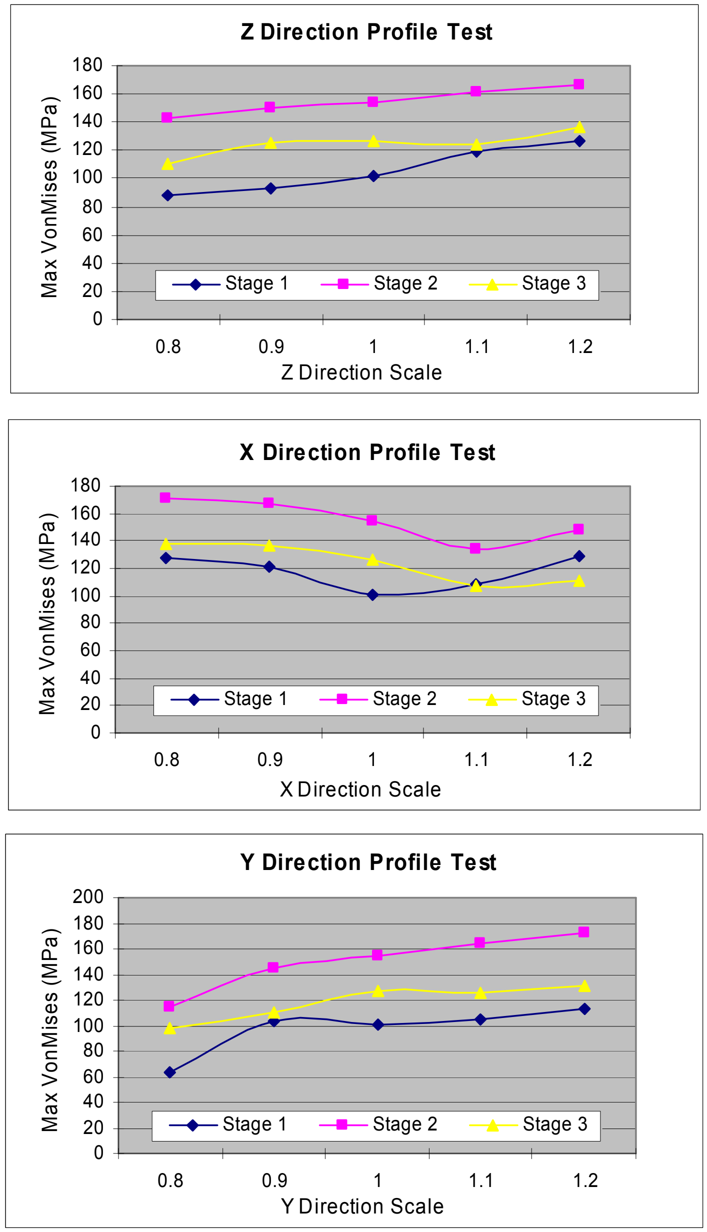
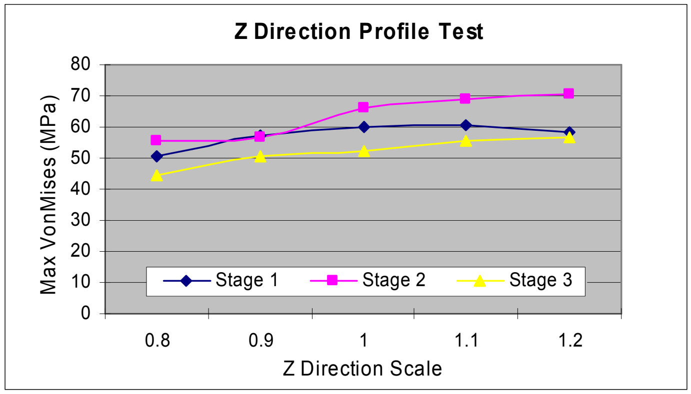
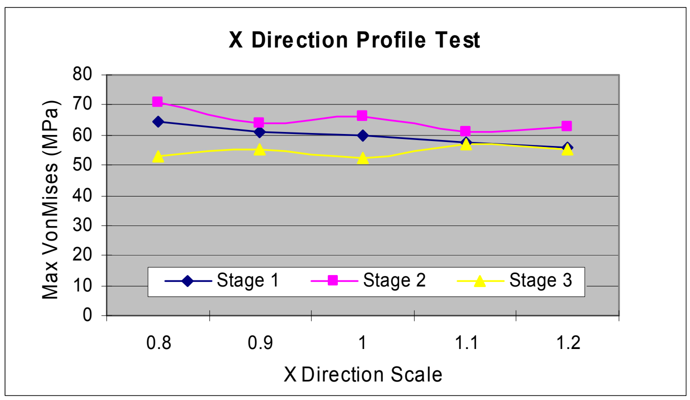


FIGURE 36 Effect of profile scale on Von Mises stress for RRPM type A.





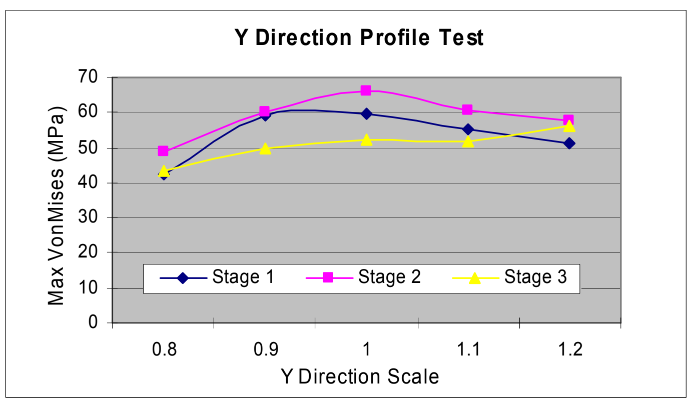


FIGURE 37 Effect of profile scale on Von Mises stress for RRPM type B.

Based on the plots, the variation of marker scale in z direction has the most consistent effect on the stress inside the markers during the tire-marker impact. As the marker scale in z direction increases, the maximum Von Mises stress increases consistently for both types of markers, indicating that the increase of marker height and lens slope will result in more stress inside the markers during the tire-marker impact. No consistent effect was found in terms of the variation of marker scale in x direction (marker length and lens slope) for both types of markers. As for the scale in y direction (marker width), the result from marker type A shows that increasing the width of marker will cause more stress inside the marker, which however is not reflected in the result for marker type B. Generally, the marker height and lens slope are more critical to the durability of markers, and from this perspective it is better to have RRPMs designed with height and lens slope as small as possible. However, a minimum marker height is required by MUTCD, but lens slope can be small to some extent as the new technology allows the lens with small slope to provide adequate retroreflectivity to the drivers.

LABORATORY TEST EVALUATION

Four specific laboratory tests were evaluated in this research: two of them are the ASTM compression test and longitudinal flexural test, and the other two are the additionally recommended ones, offset test and location offset test, which were developed based on the tire-marker impact study conducted in this research. The criteria for selecting a laboratory testing procedure consist of two things. One is that the test should be able to replicate any stage of the tire-marker impact on either type of pavement in terms of the critical locations of the stress and the pattern of the critical stress, while the other one is that the least loading rate being able to produce the stress at those critical locations within 50% of the range larger than that generated from the designated tire-marker impact will be selected. The results of the evaluation are presented in the next part.

ASTM Compression Test

The ASTM compression test was simulated and evaluated quantitatively against the second stage of the tire-marker impact simulation with tire loading of 31,100 N, tire speed of 31.3 m/s and without contact angle and offset. The simulated setup of the test is shown in Figure 38.

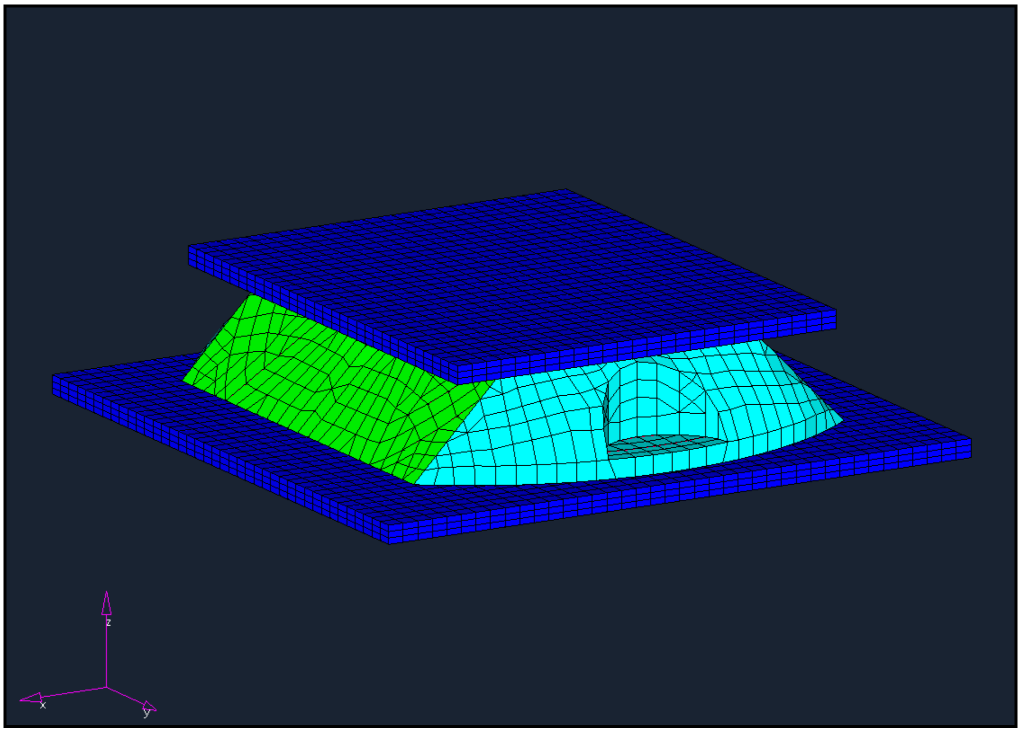


FIGURE 38 Simulated ASTM compression test.

Based on the tensor plots of compressive stress, the ASTM compression test is able to produce maximum compressive stress at the four corners of the upper surface of the marker, similar to the critical location of compressive stress generated by the tire-marker impact. So, as long as the magnitudes of compressive stress are close between the test and tire-marker impact, ASTM compression test is good at testing the compressive stresses inside the markers during the tire-marker impact. The tensor plots of the stresses inside the markers for the test in a loading rate of 4.0 mm/min are shown in Figure 39 for maker type A and B, respectively.

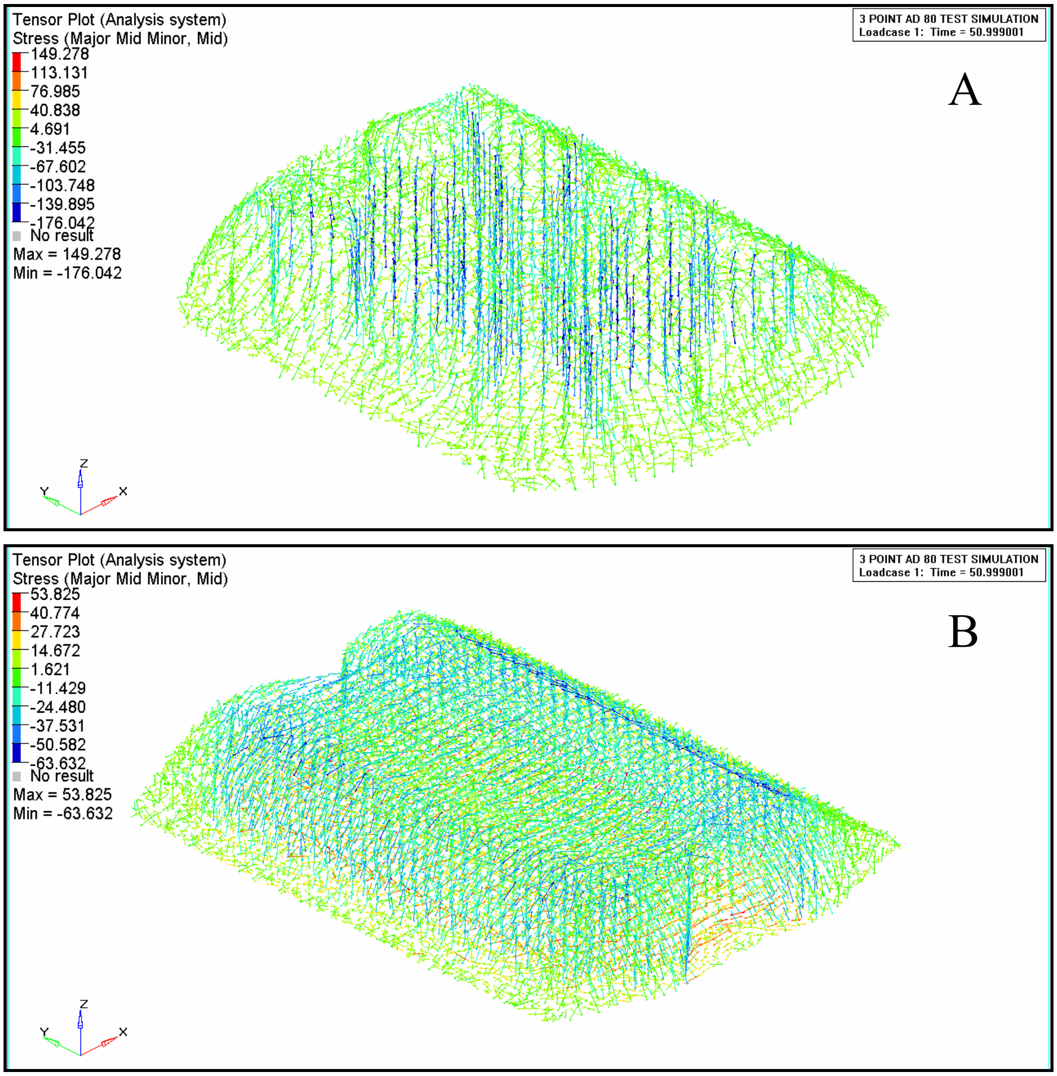


FIGURE 39 Stress tensor plots for RRPM A and B in ASTM compression test.

Different loading rates were tried for the test. The magnitudes of the critical compressive and tensile stress in accordance with the loading rates of the test as well as those from the designated tire-marker impact simulation are presented in Table 8. Only compressive stress was evaluated to determine the appropriate loading rate. Based on the criteria of selecting a loading rate, the loading rates of 3.0 and 4.0 mm/min are selected for ASTM compression test for RRPMs to be installed on flexible and rigid pavement, respectively.

TABLE 8 Evaluation of ASTM Compression Test in Different Loading Rates

Laboratory Test		ASTM Compression Test				Tire-Marker Impact	
Loading Rate (mm/min)		2.5	3.0	4.0	5.0	Flexible	Rigid
Compressive Stress (Mpa)	RRPM Type A	105.183	129.785	176.042	184.736	124.131	150.201
	RRPM Type B	55.258	57.749	63.632	64.936	56.954	63.558
Tensile Stress (Mpa)	RRPM Type A	25.88	30.811	37.39	45.738	32.598	25.141
	RRPM Type B	13.187	16.886	22.587	33.111	8.098	9.049

ASTM Longitudinal Flexural Test

The ASTM longitudinal flexural test was simulated and evaluated quantitatively against the second or third stage of the tire-marker impact simulation with tire loading of 31,100 N, tire speed of 31.3 m/s and without contact angle and offset. The simulated setup of the test is shown in Figure 40.

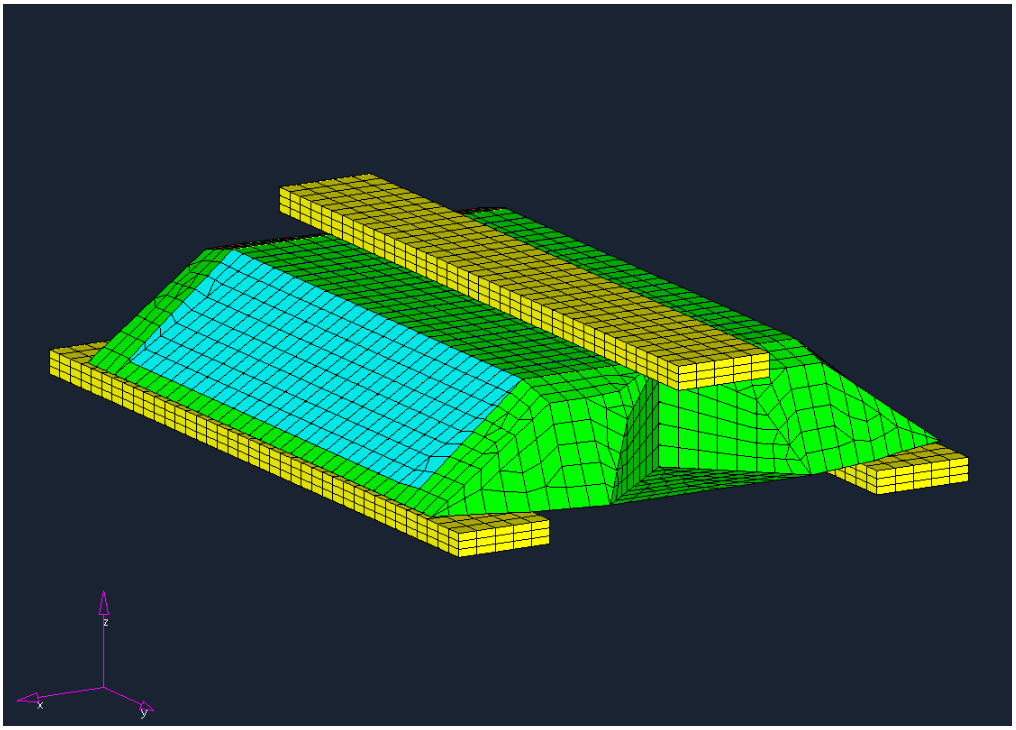


FIGURE 40 Simulated ASTM longitudinal flexural test.

The test generates a similar pattern of tensile stress inside the markers compared to that produced during the entire process of the tire-marker impact on flexible pavement. A significant group of tensile stress is generated from the marker base and approaching upward inside the markers, which is considered critical in this study. The side view of the stress tensor plots for marker type A and B in the ASTM longitudinal flexural test with a loading rate of 2.5 mm/min is shown in Figure 41.

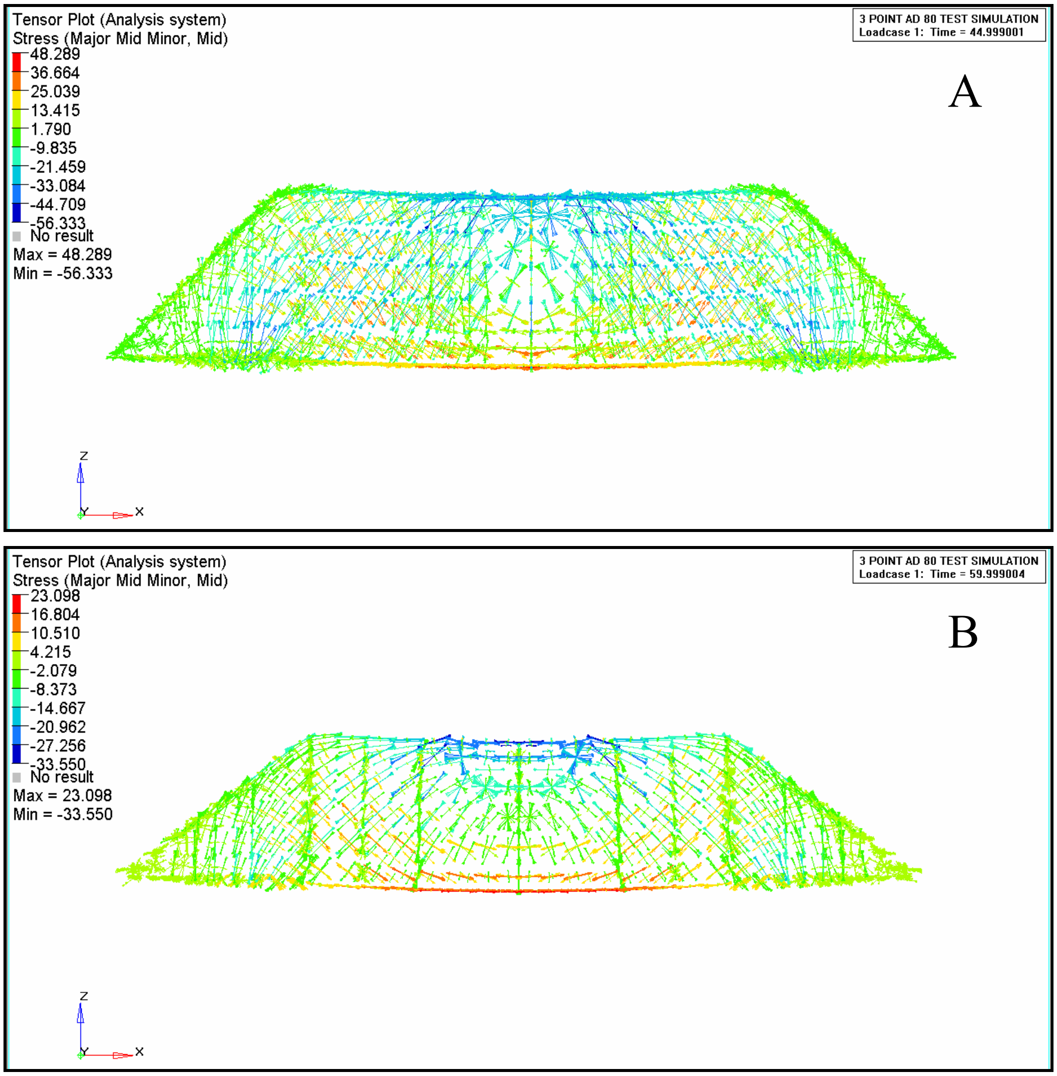


FIGURE 41 Side view of the stress tensor plots for RRPM A and B in ASTM longitudinal flexural test.

After executing different loading rates, the researcher determined that a loading rate of 2.5 mm/min was selected for the ASTM longitudinal flexural test for RRPMs to be installed on both types of pavement, as a loading rate of 5.0 mm/min might be too large for the RRPMs. The magnitudes of the critical tensile and compressive stress along with the corresponding loading rates of the test as well as the critical stress from the designated tire-marker impact simulation are presented in Table 9. Only tensile stress was evaluated to determine the suitable loading rate.

TABLE 9 Evaluation of ASTM Longitudinal Flexural Test in Different Loading Rates

Laboratory Test		ASTM Longitudinal Flexural Test		Tire-Marker Impact	
Loading Rate (mm/min)		2.5	5.0	Flexible	Rigid
Tensile Stress (Mpa)	RRPM Type A	36.664	87.441	32.598	25.141
	RRPM Type B	16.804	35.21	8.098	9.049
Compressive Stress (Mpa)	RRPM Type A	84.323	166.926	124.131	150.201
	RRPM Type B	33.55	55.088	56.954	63.558

Offset Test

The offset test was first developed by Agrawal and used to simulate the first or third stage of a tire-marker impact (*2*). The researcher re-evaluated it against the first or third stage of the tire-marker impact simulation with tire loading of 31,100 N, tire speed of 31.3 m/s and without contact angle and offset. The simulated setup of the test is shown in Figure 42.

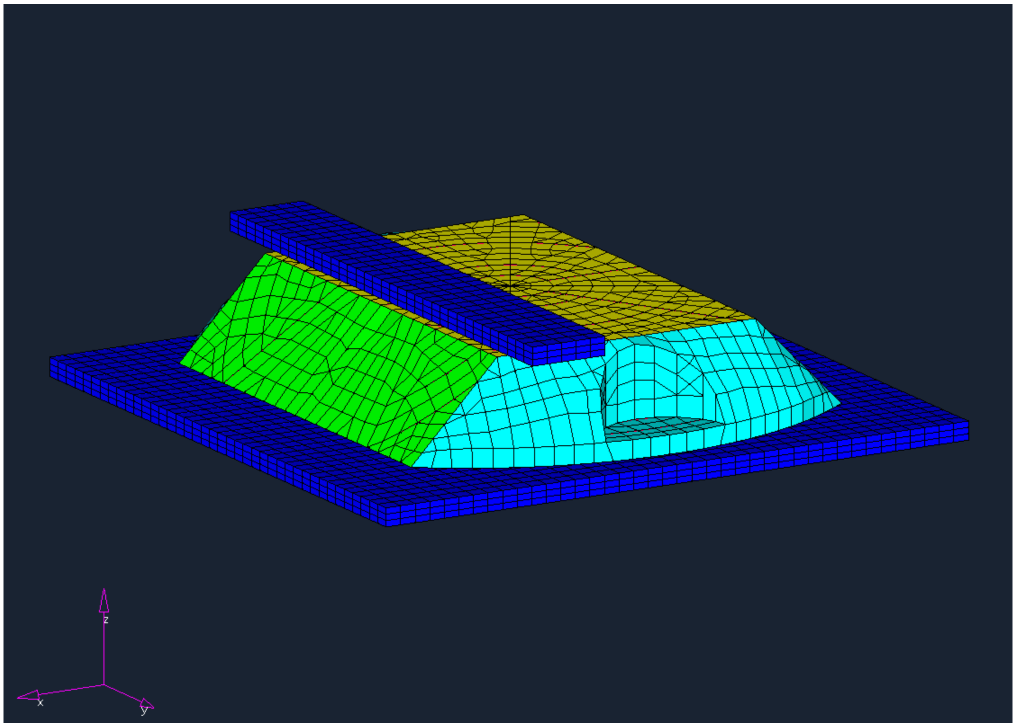


FIGURE 42   Simulated offset test.

Based on the tensor plots of compressive and tensile stresses inside the markers, the test is able to replicate the first or third stage of tire-marker impact in that maximum compressive stress is generated at the two upper corners of the marker where the steel bar contacts the marker while a significant amount of tensile stress is produced in the rest part of the marker and a lot of them going up from the bottom of the marker is evaluated in this study.   Figures 43 and 44 show an isolated and a side view of the tensor plots of the stresses inside marker type A and B during the test in a loading rate of 4.0 mm/min.

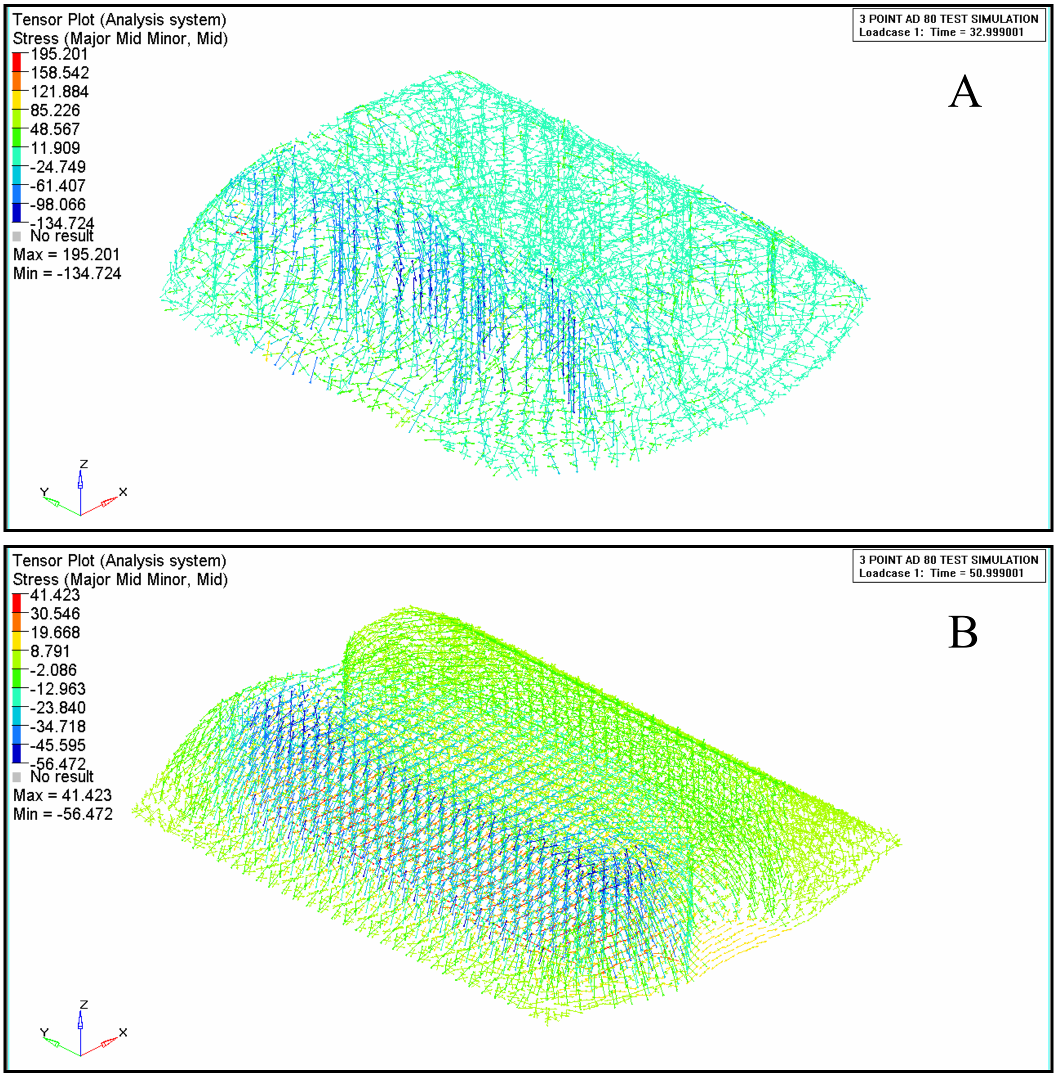


FIGURE 43 Stress tensor plots for RRPM A and B in offset test.

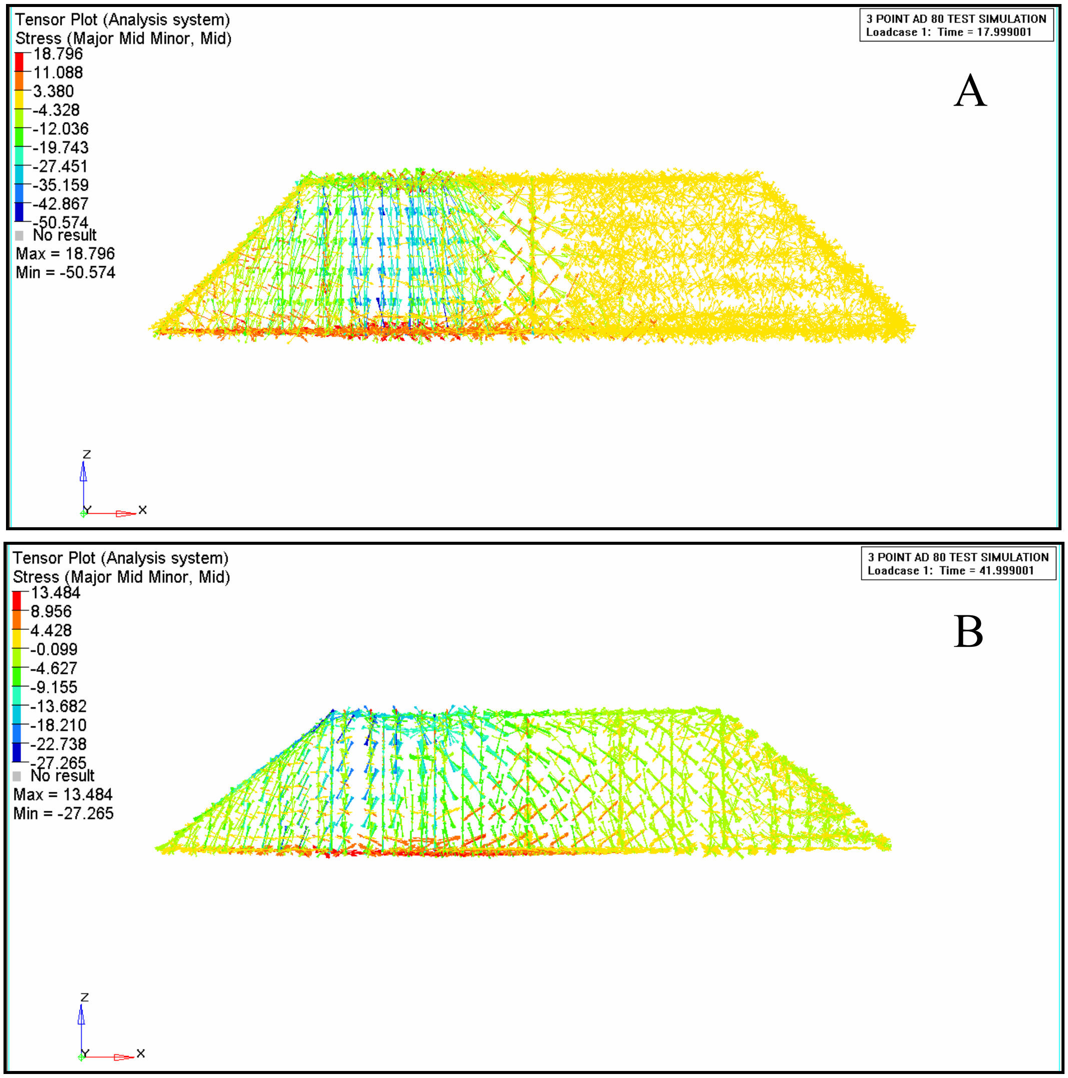


FIGURE 44 Side view of stress tensor plots for RRPM A and B in offset test.

By varying the loading rate in the test, the researcher compared both the critical compressive stress and tensile stress introduced above with those generated from the designated tire-marker impact. The comparison is shown in Table 10. Based on the evaluation criteria, a loading rate of 4.0 mm/min best satisfies the criteria for both compressive and tensile stress, and thus is selected as the loading rate for the offset test for RRPMs to be installed on both types of pavement.

TABLE 10 Evaluation of Offset Test in Different Loading Rates

Laboratory Test		Offset Test			Tire-Marker Impact	
Loading Rate (mm/min)		3.0	4.0	5.0	Flexible	Rigid
Compressive Stress (Mpa)	RRPM Type A	65.082	134.724	146.935	111.878	131.998
	RRPM Type B	33.106	56.472	62.807	51.151	55.064
Tensile Stress (Mpa)	RRPM Type A	12.853	34.707	50.621	32.598	18.618
	RRPM Type B	10.788	17.563	22.204	7.454	7.247

Location Offset Test

The location offset test was designed to deal with high compressive stress generated from the tire-marker impact scenario in which a tire hits the marker with offset rather than right in the middle. So, the test was evaluated against the second stage of the tire-marker impact simulation with tire loading of 31,100 N, tire speed of 31.3 m/s, contact offset of 51 mm and without contact angle. The simulated setup of the test is shown in Figure 45.

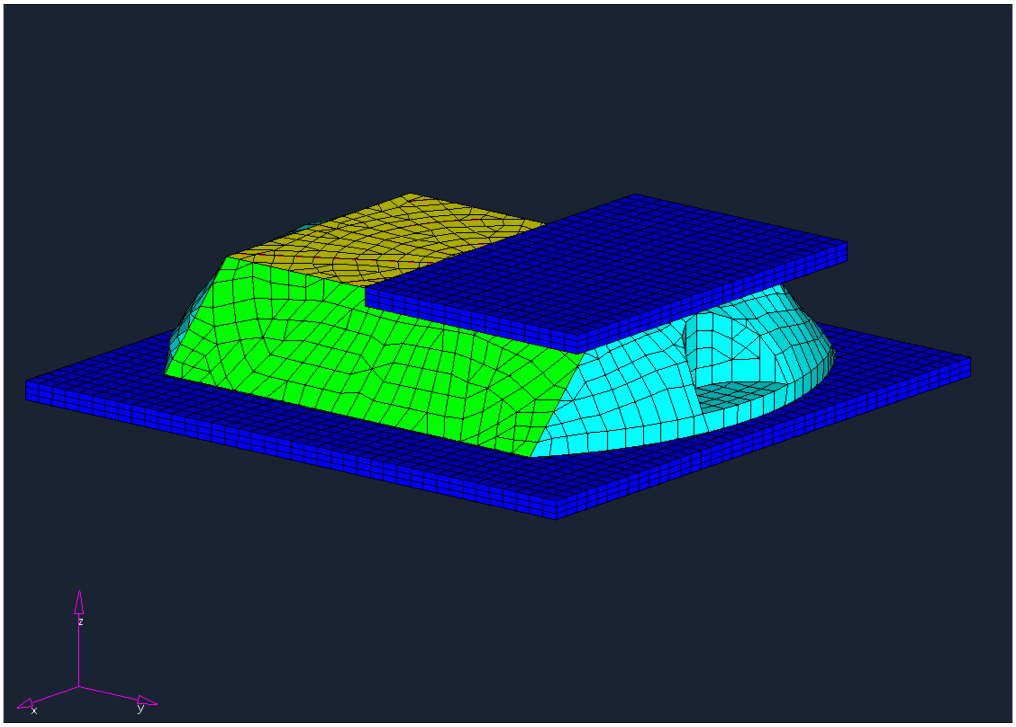


FIGURE 45 Simulated location offset test.

The test produces critical compressive stress at the same two top edges of the markers where maximum compressive stress is produced as a tire sits on top of the marker with offset, indicating it is a potentially good test for the designed purpose. The tensor plots of stress inside the markers during the test at a loading rate of 4.0 mm/min are shown in Figure 46.

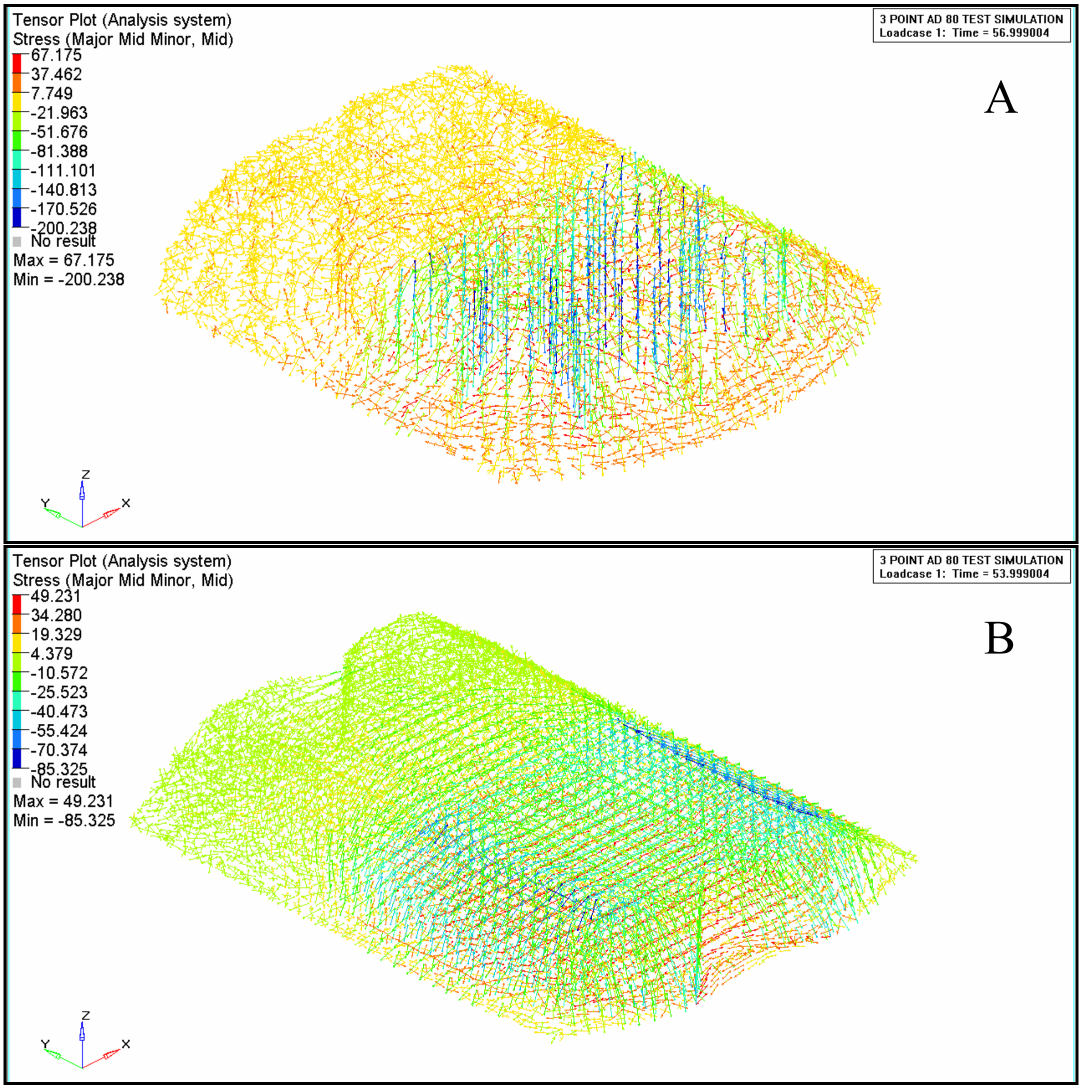


FIGURE 46 Stress tensor plots for RRPM A and B in location offset test.

The magnitudes of the critical compressive and tensile stress commensurate with the loading rates of the test as well as those from the designated tire-marker impact simulation are presented in Table 11. Only compressive stress was evaluated to determine the appropriate loading rate. The results demonstrate that the loading rates of 4.0 and 5.0 mm/min should be used in the location offset test to examine the performance of RRPMs on flexible and rigid pavement, respectively.

TABLE 11 Evaluation of Location Offset Test in Different Loading Rates

Laboratory Test		Location Offset Test			Tire-Marker Impact	
Loading Rate (mm/min)		3.0	4.0	5.0	Flexible	Rigid
Compressive Stress (Mpa)	RRPM Type A	117.917	200.238	223.765	186.384	222.884
	RRPM Type B	68.302	85.325	88.149	75.82	86.464
Tensile Stress (Mpa)	RRPM Type A	29.104	37.462	40.562	33.959	26.249
	RRPM Type B	15.277	23.858	28.677	10.262	10.595

Laboratory Test Summary

Based on the evaluation of the four laboratory tests, the researcher believes that each of them is capable of replicating the tire-marker impact in certain perspectives, but none of them is able to replicate the tire-marker impact comprehensively. Therefore, these tests should be used together to test the performance of RRPMs in the field. Specifically, ASTM compression test is good at replicating the second stage of the tire-marker impact in terms of compressive stress. ASTM longitudinal flexural test is capable of replicating all three stages of the impact in terms of tensile stress. Offset test is able to replicate the distribution of both compressive and tensile stress inside the markers at the first and third stage of the impact. Location offset test replicates the critical compressive stress produced at the second stage of the impact with contact offset. On the other hand, ASTM compression test, offset test and location offset test are suitable to RRPMs on both types of pavement, while ASTM longitudinal flexural test is more appropriate for RRPMs on flexible pavement than on rigid pavement as it generates tensile stress in the pattern that is more like what is produced inside the markers during the impact on flexible pavement. Furthermore, the loading rates for some laboratory tests can be differentiated for RRPMs on rigid and flexible pavement. The summary of these laboratory tests is shown in Table 12.

TABLE 12 Laboratory Test Summary

Laboratory Tests		Tire-Marker Impact					
		Stage 1		Stage 2		Stage 3	
		Rigid	Flexible	Rigid	Flexible	Rigid	Flexible
Loading Rates (mm/min)	ASTM Compression	N/A	N/A	4.0	3.0	N/A	N/A
	ASTM Flexural	2.5	2.5	2.5	2.5	2.5	2.5
	Offset	4.0	4.0	N/A	N/A	4.0	4.0
	Location Offset	N/A	N/A	5.0	4.0	N/A	N/A

SUMMARY AND FUTURE WORK

The researcher conducted a comprehensive study of tire-marker impact by investigating the impact on flexible pavement and comparing it with that on rigid pavement using the finite element computational tools. First, the critical locations and magnitudes of the stress inside the markers during the tire-marker impact on flexible pavement were identified. The researcher then analyzed the effect of various external factors on the Von Mises stress inside the markers during the impact on flexible pavement. This work along with the previous research on the tire-marker impact on rigid pavement established the basis for a thorough evaluation of the laboratory tests and pointed out some critical aspects a good test should take into consideration. Furthermore, the researcher compared the tire-marker impact on the two types of pavement in terms of the patterns and magnitudes of the stress inside the markers during the impact. Based on the comparison and field observation, the researcher was able to evaluate the individual laboratory tests more specifically and distinguish the laboratory testing procedures and standards designed for RRPMs to be installed on rigid and flexible pavement, i.e. the suitability and the specific loading rate of a laboratory test.

In addition, the researcher conducted two separate studies of RRPMs which are not related to developing laboratory tests. First, the marker-pavement interface forces on both types of pavement were studied to demonstrate the relationship between the shear forces generated on rigid and flexible pavement. In addition, the researcher examined the effects of marker profile on the Von Mises stress inside the markers during the tire-marker impact on rigid pavement.

The next part summarizes the findings from these studies, the limitations of this research, and the future work to extend and improve this research.

FINDINGS

The major findings from the study of tire-marker impact on flexible pavement are the following:

- The critical Von Mises stress is produced at the top edges of the markers, which is identical to what was found on rigid pavement, but the magnitude of the critical Von Mises stress on rigid pavement is about 10 percent larger than that on flexible pavement for all the three stages of impact;
- When the tire is about to ascend or descend the markers, tensile stress is produced all over the other side of the markers and is especially intense from the mid-bottom of the markers, while compressive stress is generated at the top of the lens and especially intense at the top edges of the markers where the tire contacts the markers. When the tire sits on top of the markers, the critical compressive stress is seen at the non-lens side of the top surface as well as the top edges of the markers, while tensile stress is found throughout the markers and especially significant from the mid-bottom of the markers. In terms of the magnitude, compressive stress is predominant;
- The critical locations of compressive stress are at the top edges of the markers, identical to what was found for markers on rigid pavement, but the magnitude of the critical compressive stress on rigid pavement is approximately 11 percent larger than that on flexible pavement for all the three stages of impact. Furthermore, the patterns of the critical tensile stress are different for RRPM A between the two types of pavement in spite of a similar general distribution. The magnitude of the critical tensile stress at the third stage of impact is larger on flexible pavement than on rigid pavement, and such difference is significant for RRPM A;

- Tire loading and contact location have consistent effects on the stress inside the markers during the impact on flexible pavement. However, tire speed and contact angle do not have consistent effects on the stress for both types of markers. This conclusion is in agreement with what was previously reached on rigid pavement, demonstrating that loading rate and contact location should be taken into consideration when developing a laboratory test.

The study of interface forces and marker profile demonstrates the following:

- Both the shear and perpendicular interface forces generated from the tire-marker impact are larger on rigid pavement than on flexible pavement, indicating RRPMs on rigid pavement are more likely to be removed by traffic than those on flexible pavement if the same bitumen adhesive is used. This conclusion is validated in the field deck study by Zhang et al.
- The increase of marker height and lens slope will result in more critical stress inside the markers during the tire-marker impact while the variation of marker scale in the directions of marker length and width does not have consistent effect on the stress inside the markers.

The evaluation of ASTM and additionally developed laboratory tests reveals the following conclusions:

- ASTM compression test is good at replicating the second stage of the tire-marker impact in terms of compressive stress. ASTM longitudinal flexural test is capable of replicating all three stages of the impact in terms of tensile stress. Offset test is able to replicate the first and third stage of the impact in terms of both compressive and tensile stress. Location offset test replicates the critical compressive stress produced at the second stage of the impact with contact offset;

- ASTM compression test, offset test and location offset test are suitable to RRPMs on both types of pavement, while ASTM longitudinal flexural test is necessary for both but more critical to RRPMs on flexible pavement than on rigid pavement;
- Each of the four tests is capable of replicating the tire-marker impact in certain perspectives, but none of them is able to replicate the tire-marker impact comprehensively. So, these tests should be used together to test the performance of RRPMs.

LIMITATIONS

The limitations of this research include the following:

- The material properties for the RRPMs may not be perfectly accurate as they were not able to be obtained from an appropriate laboratory testing procedure directly. The values of material properties used in the models were calibrated ones from initial values from the manufacturer and online database, and the calibration always involves inaccuracy of some degree.
- The researcher modeled the flexible pavement using elastic material with a limited range of material properties, i.e. Modulus, Mass Density and Poisson Ratio. The elastic-plastic characteristics of the asphalt materials were not investigated. Besides, the Modulus values used for the pavement layers are common values, and were not calibrated in this research. All of these might cause inaccuracy in the results;
- The effect of repetitive impact can not be reflected in the current tire-marker impact model. In fact, repetitive impact may lead to marker fatigue failure;

- The current tire-marker impact model does not include adhesive material between marker and pavement surface, which might affect the conclusion that RRPMs on rigid pavement will have more severe retention problem than on flexible pavement, as different adhesive material is typically used on the two types of pavement;
- The marker profile was varied in scale, so the researcher was not able to study the marker height, length and lens slope separately, nor was he able to find out their individual effect on the stress inside the markers;
- The elastomeric pads were not modeled in the setup of the laboratory tests simulated in this research, and ASTM laboratory testing standards actually consist of elastomeric pads.

FUTURE WORK

The future work of this research can be carried out toward these areas:

- It is necessary to calibrate the RRPM model based on the material properties obtained from an appropriate laboratory testing procedure;
- The surface layer of the flexible pavement can be modeled with elastic-plastic material, which is more representative regarding the characteristics of the surface pavement;
- It would be meaningful to model repetitive impact in the current tire-marker impact model, as RRPM fatigue is an issue worth some research efforts;
- The effect of tire pressure on the stress inside markers was not studied in this research, and it is another external factor that might affect the tire-marker impact;
- It would be interesting to model a car tire in the tire-marker impact model so

that the extent of the impact on the markers can be compared between truck tire and car tire;

- More laboratory testing procedures should be developed and evaluated based on the tire-marker impact analysis from this research as well as the future work based on this one.

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