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# Analysis of Pavement Failure (Flexible Foundation): A Case Study of Bauchi-Kaduna

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## Abstract

This research investigates the causes of pavement failures shortly after a rehabilitation activity along Bauchi-Kaduna Road (Magama-Gumau-RahamaRoad.). One of the principal objectives of this research effort was to identify sources of Moisture and other conditions that led to the early rutting problems observed. Improper tack coat or failure, permeable dense-graded layers, inadequate drainage, and possibly insufficient Compaction of dense-graded material were the likely root causes of the observed moisture damage and consequential rutting problems. The other principal objective was to evaluate design, construction, and materials requirements -that will minimize the risk of such failures for future rehabilitation projects so that guidelines could be developed for this process.

**Keywords:** Pavement failures, Rehabilitation activity, Bauchi-Kaduna Road, Moisture sources, Early rutting

## INTRODUCTION

The project is on road work, a highway on a flexible pavement, and the site is located at the Magama-Gumau-Rahama of Bauchi state. It is a 56-kilometre road that links two states, Bauchi and Kaduna, and is the only alternative route to the country's northeastern part. The road was constructed as far back as 1982, with about 30 km of it with surface dressing and the remaining earthworks only. Due to the present economic and political situation, the government sees the need to open the road to better the lives of its people and promote economic activities within the region, apart from linking the two states together. The route comprises four layers: the subgrade, subbase, base course, and surface dressing. It has a lot of potholes, ruts, and slur due to a lack of maintenance and upgrades. The drainage system is that of the earth drain and has been washing away.

The project exhibited significant early distress that appeared to be associated with moisture damage. It was identified by personnel as a project warranting a detailed investigation. The following sections summarize the rehabilitation activity and the observed problems that occurred shortly after the rehabilitation activity. Rehabilitation Activity: Two inches (50 mm) The existing HMA surface was milled from both travel lanes and replaced with 2 inches (50 mm) of a 3/4 inches (19 mm) NMAS, dense-graded HMA. The entire surface was then overlaid with 2 inches (50 mm) of a 3/4 inches (19 mm) NMAS. It should be noted that including lime in the mixture was not a requirement specified in the contract documents.

Observed Problems: Within approximately six months of the rehabilitation activity, rutting to depths of 1 inch (25 nm) and greater began forming in isolated areas. Additional rutting continued to develop in remote regions after that. No determination of the distress's causes was made when the pain was first observed. The company has retained backup samples of the 3/4-inch (19 mm) NMAS and dense-graded HMA obtained during the production of the mixture.

### Problem Statement

In the last several years, several major interstates and smaller projects have exhibited pavement that appeared to be associated with moisture damage within months following rehabilitation activity. These projects were investigated to determine appropriate site investigation methods and testing to identify sources of moisture and other conditions that have led to premature failures and to evaluate design, construction, and material requirements that will minimize the risk of early losses related to moisture damage for future rehabilitation projects.

## Aim and Objectives

This research aimed to identify sources of moisture and other conditions that led to the rutting problem and to evaluate design, construction, and material requirements that will minimize the risk of such failures for future rehabilitation projects. More specifically, the objectives of this research effort are stated below:

1. Identify the potential cause(s) for the failure of the project.
2. Develop guidelines for pre-construction site investigations to identify the potential for moisture-related problems.
3. Develop guidelines for pavement structural design, construction techniques, and materials selection and testing when the potential for moisture-related problems exists.

## Significance of the Study

Implementing the guidelines developed through this project will likely have several potential benefits. These include, but are not limited to, the following:

Reduced risk of early failures due to moisture-related damage.

1. Improved guidelines for investigating projects during the pre-construction phase will help identify when the conditions contributing to moisture-related failures are present.
2. Improved pavement structural design techniques and elements can reduce the risk of moisture-related failures.
3. Improved construction and material specifications and testing can reduce the risk of moisture-related failures occurring.
4. Substantial savings in maintaining and rehabilitating pavements that would have failed due to moisture damage can be achieved by implementing measures to preclude the likelihood of moisture damage.

## Literature Review

### Nature Of A Pavement

Modern pavement consists of several elements that have various functions that contribute to its ability to remain safe, stable, and durable for some time and under the action of many vehicles. The pavement's surface is, of course, the part with the most traffic. The needs of traffic are that the surface should be sufficiently uniform to allow traffic to pass in comfort and safety and at reasonable speeds; that it should not be so slippery as to allow skits in wet weather; and that it should be sufficiently free draining to avoid intrusive spray or pools standing water in wet weather.

“Pavement generally has a higher initial cost than asphalt but lasts longer and has lower maintenance costs” (American Association of State Highway and Transportation Officials, 2020, p. 48). In some cases, however, design or construction errors or poorly selected materials have considerably reduced pavement life. Therefore, pavement experts must understand materials selection, mixture proportioning, design and detailing, drainage, construction techniques, and pavement performance. Understanding the theoretical framework underlying commonly used design procedures and the methods' applicability limits is essential.

The serviceability and longevity of rigid pavement construction depend on the rate of pavement deterioration, which is a function of factors such as material properties and climatic load characteristics. As the main reason behind damage and delaminating processes, cracks can be considered a tensile failure in concrete. Pavement cracks can occur at any location within the pavement where tensile stresses exceed the strength. Tensile stresses are induced in a rigid pavement due to the bending action of the concrete base under vehicular and climatic forces. The pavement response to these loads can be individually calculated and then superimposed to determine the total value of stresses or deflections, provided that the pavement materials exhibit clastic behavior while cut. Tent rigid pavement design procedures are well established, but questions remain about the assumptions' accuracy.

Smith et al. (2020) defined a highway pavement as a structure consisting of superimposed layers of processed materials above the natural soil subgrade, whose primary function is distributing the applied vehicle loads to the subgrade. The pavement structure should provide a surface of acceptable riding quality, adequate skid resistance, favorable light-reflecting characteristics, and low noise pollution. The ultimate aim is to ensure that the transmitted stresses due to wheel load are sufficiently reduced so that they will not exceed the bearing capacity of the subgrade. Two types of pavements are generally recognized as serving this purpose: flexible and rigid. This chapter provides an overview of pavement types, layers, their functions, and pavement failures. Improper design of pavements leads to their early failure, affecting their riding quality.

### Requirements of a pavement

An ideal pavement should meet the following requirements:

- Sufficient thickness to distribute the wheel load stresses to a safe value on the subgrade soil imposed upon it,
- Adequate coefficient of friction to prevent skids from being structurally strong enough to withstand all types of vehicle stresses.
- Smooth surface to provide comfort to road users even at high speed, produce most minor noise from moving vehicles.
- Dustproof cover so that traffic safety is not impaired by reducing visibility.
- Impervious surface, so that sub-grade soil is well protected and,
- Long design life with low maintenance costs.

### Types of Pavements

The pavements can be classified based on their structural performance into flexible and rigid pavements. In flexible pavements, wheel loads are transferred by grain-to-grain contact of the aggregate through the granular structure. The flexible pavement, having less flexural strength, acts like a flexible sheet (e.g., bituminous road). On the contrary, in rigid pavements, wheel loads are transferred to subgrade soil by the flexural strength of the pavement, and the pavement acts like a rigid plate (e.g., cement concrete oracles). In addition to these, composite pavements are also available. A thin layer of flexible pavement over rigid pavement is ideal, with the most desirable characteristics. However, such pavements are rarely used in new construction because of the high cost and complex analysis required.

### Flexible Pavements

Are those pavements that reflect the deformation of the subgrade and the subsequent layers to the surface flexible? Usually, asphalt is laid with no reinforcement or specialized fabric reinforcement that permits limited flow or repositioning of the roadbed underground.

a. The design of flexible pavement is based on the load-distributing characteristics of the component layers. The black top pavement, including water-gravel-bound macadam, falls into this category.
b. Flexible pavement, on the whole, has low or negligible adjustable strength in its structural action). The loose pavement layers transmit the vertical or compressive stresses to the lower layers by grain transfer through contact points of the granular structure.
c. The vertical compressive stress is maximum on the pavement surface directly under the wheel load and is equal to the contact pressure under the wheels. Due to the ability to distribute the tension over a large area in the shape of a truncated cone, the stresses decrease in the lower layer.
d. As such, the flexible pavement may be constructed in several layers, and the top layer has to be the most robust with the highest compressive stresses.
e. To be sustained by this layer, in addition to wear and tear, the lower layer has to take up only a lesser magnitude of stress as there is no direct wearing action due to traffic loads. Therefore, inferior material with a lower cast can be used in the lower layers.

Flexible pavements will transmit wheel load stresses to the lower layers by grain-to-grain transfer through the contact points in the granular structure (see Figure I).

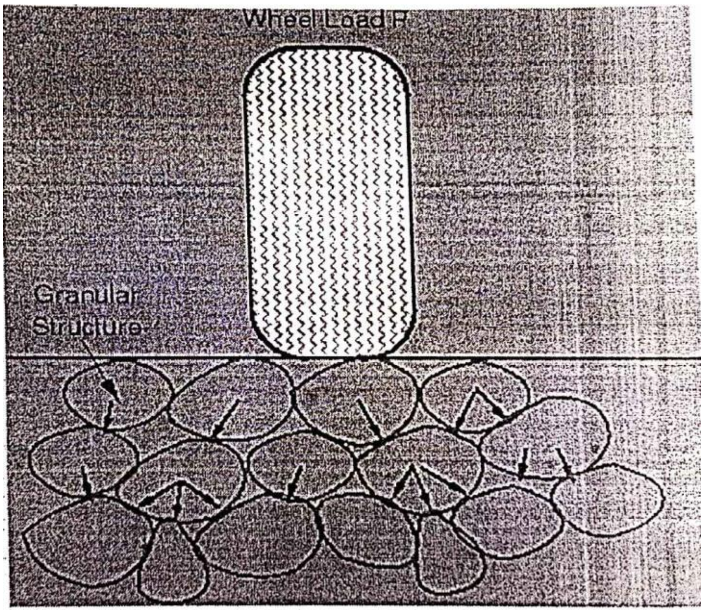

Figure 1: Load transfer in granular structure

### Deflection on flexible pavement

The wheel load acting on the pavement will be distributed over a broader area, and flexible pavements typically have many layers. Hence, the flexible pavement design uses the concept of a layered system. Based on this, the flexible pavement may be constructed in several layers, and the top layer has to be of the best quality to sustain maximum compressive stress and wear and tear. The lower layers will experience less stress, and low-quality material can be used. Flexible pavements are constructed using bituminous materials. These can be surface treatments (such as bituminous surface treatments generally found on low-volume roads) or asphalt concrete surface courses (commonly used on high-volume roads such as national highways). Flexible pavement layers reflect the deformation of the lower layers onto the surface layer (e.g., if there is any undulation in the subgrade, then it will be transferred to the surface layer). In the case of flexible pavement, the design is based on the overall performance of flexible pavement, and the stresses produced should be kept well below the allowable stresses of each pavement layer.

### Types of Flexible Pavements

The following types of construction have been used in flexible pavement:

i. Conventional layered flexible pavement,
ii. Total --depth asphalt pavement, and
iii. Contained rock asphalt mat (CRAM).

**Conventional flexible pavements:** These are layered systems with high-quality, expensive' materials placed at the top where stresses are high and low-quality, cheap materials are placed in the lower layers.

**Full-depth asphalt pavements** are constructed by placing bituminous layers directly on the soil subgrade. It is more suitable when there is high traffic and local materials are unavailable.

**Contained rock asphalt mats** are constructed by placing dense/open-graded aggregate layers in between two asphalt layers. Modified thick-graded asphalt concrete placed above the subgrade will significantly reduce the vertical compressive strain on the soil subgrade and protect it from surface water.

## Typical layers of a flexible pavement

base course, tack coat, binder course, prime coat, base Course, sub-base Course, compacted sub-grade, and natural sub-grade (Figure 2).

### Seal Coat:

Seal coat is a thin surface treatment used to waterproof the surface and to provide skid resistance.

### Tack Coat:

A tack coat is a very light application of asphalt, usually asphalt emulsion diluted with water. It provides. Proper bonding between two layers of binder course must be thin, uniform over the entire surface, and set very fast.

### Prime Coat:

A prime coat is an application of IOW viscous cutback bitumen to an absorbent surface like granular bases on which a binder layer is placed; it provides bonding between two layers. Unlike tack coat, prime coat penetrates the layer below, plugs the voids, and forms a water-tight surface.

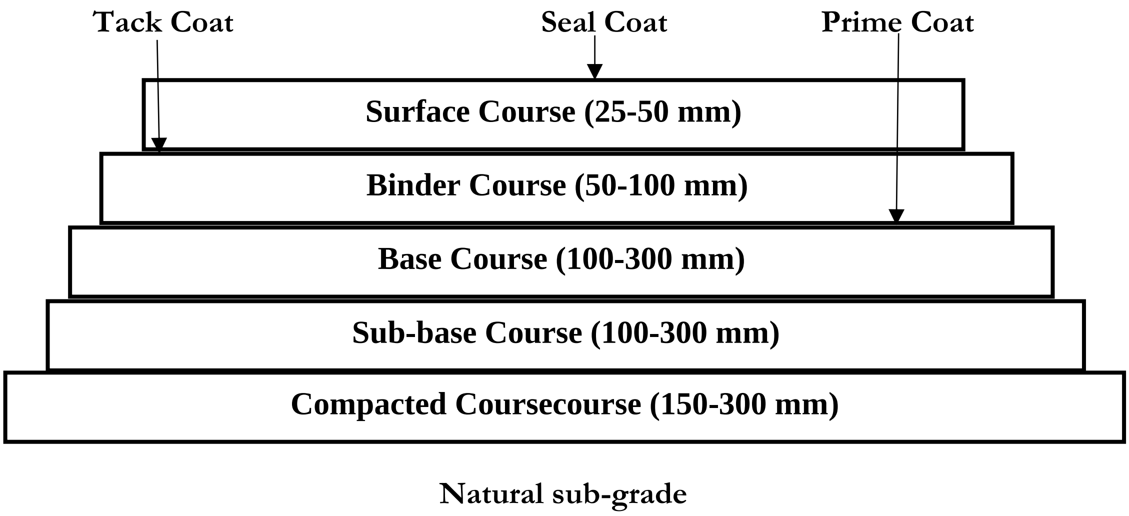

**Figure 2: Typical cross-section of a flexible pavement**

### Surface course

Surface course is the layer directly in contact with traffic loads and generally contains superior-quality materials. They are usually constructed with densely graded asphalt concrete (AC). The fictions and requirements of this layer are:

i. It provides characteristics such as friction, smoothness, drainage, etc. Also, it will prevent the entrance of excessive quantities of surface water into the underlying base, sub-base, and sub-grade.
ii. It must be tough to resist the distortion under traffic and provide a smooth and skid-resistant riding surface.
iii. It must be waterproof to protect the entire base and subgrade front from the weakening effect of water.

**Binder course**

This layer provides the bulk of the asphalt concrete structure. Its chief purpose is to distribute the load to the base course. The binder course generally consists of aggregates with less asphalt. It does not require quality as high as the surface course, so replacing a part of the surface course with the binder course results in a more economical design.

**Base course**

The base course is the material layer immediately beneath the surface of the binder course, providing additional load distribution and contributing to the sub-surface drainage. It may comprise crushed stone, slag, or other untreated or stabilized materials.

**Sub-Base Course**

The sub-base course is the layer of material beneath the base course, and its primary functions are to provide structural support, improve drainage, and reduce the intrusion of fines from the subgrade into the pavement structure. If the base course is open-ended, then so is the sub-base system. More penalties can serve as a filler between the subgrade and the base course. A sub-base course is only sometimes needed or used. For example, a pavement constructed over a high-quality, stiff subgrade may not need the additional features offered by a sub-base course. In such situations, the sub-base course may not be provided.

**Sub-grade**- The topsoil, or subgrade, is a layer of natural soil prepared to receive the stresses from the layers above. It is essential that the soil subgrade is not overstressed at any time. It compacted to the desirable density, near the optimum moisture content.

## Failure of flexible Pavements

The major causes of flexible pavement failures are fatigue, rutting, and thermal cracking. The fatigue cracking of flexible pavement is due to horizontal tensile strain at the bottom of the asphaltic concrete. Rutting occurs only on flexible pavements, as indicated by permanent deformation or rut depth along the wheel load path. Two design methods have been used to control rutting: one to limit the vertical compressive strain on the top of the subgrade and the other to limit rutting to a tolerable amount (12 mm normally). Thermal cracking includes both low-temperature cracking and thermal fatigue cracking.

## Identifying The Causes Of Pavement

The cause or causes of pavement failure can be established by interpreting the data collected during the surface condition survey and the additional testing. The causes of deterioration, combined with the extent of the failures, must be considered when selecting the most appropriate method of rehabilitation maintenance. Bituminous-surfaced toads will generally deteriorate either by rutting or by cracking. To help identify the cause of the deterioration. Rutting and cracking have been subdivided into six categories based on the nature of the failure. Its position and type of road construction. These are:

i. Rutting without shoving.
ii. Rutting with shoving.
iii. Heel path cracking-thin bituminous seal.
iv. Non-wheel path cracking- asphalt surfacing.
v. Non-wheel path cracking — thin bituminous seal.

An extensive literature review was undertaken for forensic investigations of failure requirements and construction practices to minimize the risk of moisture-related damage in HMA pavements.

## Moisture Damage in Hot Mix Asphalt Pavements

In a general sense, moisture damage in hot mix asphalt pavements can be defined as a loss of strength and durability due to the effects of moisture (Little & Jones, 2003; Chen et al., 2021): loss of cohesion (strength) of the asphalt film, failure of the adhesion (bond) between the aggregate and asphalt, and degradation of the aggregate particles subjected to freezing (Chen et al., 2021). Moisture damage is commonly manifested in the form of stripping as a result of detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scour (Kandhal & Rickards, 2001; Hossain et al., 2020; Hassan et al., 2022). Table 2.1 summarizes the numerous factors that affect the susceptibility of HMA mixtures to moisture damage (Stuart, 1990; Hicks, 1991; Al-Qadi et al., 2015; Imran et al., 2018).

Moisture damage generally starts at the bottom of an asphalt base layer or the interface of two layers (Khosla et al., 1999; Kim et al., 2020). Eventually, localized potholes are formed, or the pavement ravels or ruts. With hardened binders, localized fatigue cracking (longitudinal cracking that. progresses to alligator cracking) may occur, resulting in a weakened pavement structure. Subsequent water intrusion into these localized water-damaged areas, coupled with traffic loading, further degrades the structural integrity of the pavement layer and possibly the underlying layers, which, if not repaired, can lead to substantial localized failure of the pavement structure (Scholz, 1995; Rahman & Hossain, 2021). Surface raveling or a loss of surface aggregate can also occur with chip seals. Occasionally, binder from within the pavement will migrate to the pavement surface, resulting in flushing or bleeding (Stuart, 1990; Perez & Celauro, 2018).

## Pre-Re-Construction Site Investigations

The principal goal of a pre-construction investigation is to determine the mechanism(s) related to observed pavement distress and the events that may have led to the problems. Such an investigation should find what caused the distress and rule out unrelated mechanisms (Crampton, 2001; Zhang & Wang, 2019). The essential tasks involved in a pre-construction investigation are shown in Table 1.

**Table 1: Factors Influencing Moisture Damage**

| Major Factors | Description |
|---|---|
| Aggregate properties | • Composition (degree of pH acidity, surface chemistry, type of minerals, source of Aggregate).<br>• Physical characteristics (angularity, surface roughness, surface area, gradation, gradation, porosity and permeability).<br>• Dust and clay coatings.<br>• Moisture content.<br>• Resistance to degradation. |
| Asphalt binder properties | • Grade od stiffness |

| | |
|---|---|
| | • Chemical composition<br>• Crude source and refining process. |
| HMA Mixture Characteristics | • Air void level and Compaction<br>• Types of HMA (dense-graded, gap-graded, open-graded). |
| Environmental factors | • Temperature<br>• Freeze-thaw cycles<br>• Moisture vapour<br>• Dampness<br>• Pavement age<br>• Microorganisms<br>• The presence of ions in the water |
| Traffic | • Percent of trucks<br>• Gross vehicle weight of trucks<br>• Truck tire pressure |
| Construction of HMA Pavements | • Compaction<br>• Drainage<br>• Weather<br>• Segregation<br>• Contractor experience |
| Design of HMA pavements | • Air void content<br>• Subsurface drainage<br>• HMA mix selection<br>• Designer experience<br>• Designer site visit |

**Site visit and condition survey**

The principal goal of the initial site visit and condition survey is to inspect the section investigation to obtain information about what is present in the pavement. It should include the type, severity, and extent of each distress, and these should be drawn on a plan map (or straight-line chart) of the pavement section, preferably with others such as drainage systems, structures and culverts, and surrounding topography and hydrology. Once the disturbances have been identified, the potential locations and methods for field investigations and sampling can be determined. The onsite analysis also supports the investigative team in developing alternate rehabilitation strategies by considering the existing local conditions and restrictions that will influence the final decision (Victorine, 1997).

### Field testing

The principal objective of a field investigation is to determine the in-situ properties of pavement layers, which may differ from the expected (designed) properties. Scullion (2001) identifies two broad categories of field investigation methods: nondestructive and destructive testing. Nondestructive testing is used to examine a pavement without impairing' its future usefulness. Nondestructive methods include condition surveys, falling weight deflectometer (FWD) surveys, ground penetrating radar (GPR) surveys, portable seismic pavement analyzer (PSPA) surveys, and automated road analyzer (ARAN) surveys. Destructive testing involves destroying part or all of the pavement section, necessitating repair of the affected pavement. Coring, dynamic cone penetration (DCP) testing, and trenching are examples of destructive testing used for pavement investigations.

### Laboratory testing

Samples to be tested in the laboratory should be obtained during field investigations. For evaluating moisture-damaged pavements, Kandhal (1994) recommends getting at least seven 4-inch (100 mm) diameter cores from random locations within two 500-foot sections, with one representing a typical "distressed area" and the other representing a relatively "good area." Kandhal emphasizes using C02, or compressed air rather than water, to cool the core barrel so that moisture content tests can be performed on the cores. If dry coring cannot be accomplished, Kandhal recommends obtaining samples using a jackhammer. Irrespective of the type of sample, it is recommended that it be sealed in airtight containers for transport to the laboratory.

**Table 2: Field Investigation Methods to Evaluate Water Damage (Scullion, 2001)**

| Pavement Distress | Evaluation Method |
|---|---|
| Rutting (probable outcome of stripping) | • Condition survey, extent and severity of the problem<br>• Drainage<br>• GPR survey (Moisture in base, stripping in HMA, layer thickness).<br>• FWD survey (layer moduli)<br>• DCP survey (strength profile in base and subgrade).<br>• Samples (from rutted and non-rutted areas, cores and bag samples).<br>• Trenching (trench to identify problem layer). |

| | |
|---|---|
| Alligator cracking (probable outcome of stripping). | • Condition survey, extent and severity of the problem<br>• Drainage<br>• GPR survey (Moisture in base, stripping in HMA, layer thickness, layer bonding)<br>• FWD survey (layer moduli)<br>• DCP survey (strength profile in base and subgrade<br>• Samples (from areas with and without cracks, cores and bag samples)<br>• Bonding between layers (observation from coring slab removal, seismic pavement analyzer test (SPA) test). |
| Longitudinal cracking (probable outcome of stripping). | • Condition survey, extent and severity of the problem<br>• Drainage<br>• Undisturbed samples of fill and subgrade foundation soils<br>• Geometric factors: lane, paved or unpaved shoulder, side slopes<br>• Other: the presence of trees close to the pavement edge |
| Raveling (probable outcome of stripping) | • Condition survey, extent and severity of the problem<br>• HMA cores for laboratory evaluation |

In a case history study of premature failures of asphalt overlays (three in the US and one in Australia), Kandhal and Richards (2001) found that saturation of the pavement and asphalt layers was the root cause of the stripping problems. They determined that forensic investigations should include assessing the moisture conditions in failed areas and areas without failure. Kandhal (1994) recommends determining the in-situ moisture conditions of the asphalt layers by weighing the cores before and after air-drying them. Once the moisture conditions are determined, he recommends sawing the cores so that additional testing can be performed on individual layers of lifts, including bulk specific gravity, indirect tensile strength, and a visual assessment of stripping performed on the split specimens.

Scullion (2001) compiled a list of recommended tests based on the observed distress. Table 3 summarizes some laboratory evaluation methods suggested in the literature to investigate distress due to moisture damage.

**Table 3: Lab Evaluation methods to investigate pavement distress**

| | | |
|---|---|---|
| Rutting (probable outcome of stripping | • HMA properties | • Hveem stability, water susceptibility, condition<br>• Asphalt content, asphalt penetration, air void content<br>• Aggregate properties (gradation, absorption, shape, surface texture)<br>• Wheel tracker performance (Asphalt Pavement<br>• Analyzer, Hamburg Wheel Tracker<br>• Repeated load test |
| | • Base, subbase, subgrade | • Gradation, field moisture content<br>• Tri-axial classification and tube suction test (moisture susceptibility) |
| Alligator cracking (probable outcome of stripping) | • HMA properties | • Moisture susceptibility<br>• Asphalt content, asphalt penetration, air void content<br>• Aggregate properties (gradation, absorption, shape, surface texture) |
| | • Base subbase, subgrade | • Gradation, field moisture content<br>• Tri-axial classification and tube suction test (moisture susceptibility) |
| Longitudinal cracking (probable outcome of stripping) | • HMA properties (segregation of HMA near crack) | • |
| Raveling (probable outcome of stripping) | • HMA properties<br>• Air voids | • Asphalt content<br>• Asphalt properties (penetration, viscosity)<br>• Aggregate properties (gradation, absorption, surface, texture, mineralogy)<br>• Moisture susceptibility |

### Data analysis

This step involves reviewing all evidence relating to the project to determine the most reasonable explanation for the failure. Some of the questions that should be asked to compare the data obtained from the field to form evidence on the probable causes of failure are (Crampton, 2001):

What did the industry standard call for?

What did the design documents call for?

What was constructed?

What changed after construction?

However, even after all testing and analyses are completed, uncertainties remain. In that case, through a combination of previous experience and engineering principles, the most likely cause of the problem must be determined (Victorine, 1997).

### Summary report

Reports should include: Items such as the project history and background, a description of pavement structure, and a description of material types. A detailed description of the pavement condition, the types of distress involved, and the failure modes should also be included. Environmental conditions, soil conditions, traffic history data, and projections must be included. A summary of the evaluation and testing strategies used for the investigation and the findings of these tests should also be presented. Finally, a prioritized overview of possible corrective strategies and their associated costs should be included (Victorine, 1997).

### Design Practices

The design and construction of HMA overlays are the most widely used methods for rehabilitating HMA pavements in the United States. They provide a relatively fast, cost-effective means of correcting existing surface deficiencies, restoring user satisfaction, and (depending on the thickness) adding structural load-carrying capacity (Sebaaly et al., 2020; NHI and FHWA, 2019). Some of the most essential steps to be considered while designing an HMA overlay include (Sebaaly et al. 2020):

l. Identify the complete history of the pavement" deflection;

2. Identify the traffic requirement;

3. Survey the conditions of the project;

4. Conduct nondestructive testing;

5. Conduct overlay design analysis; and

6. Evaluate alternatives and make final recommendations.

The first four steps 'Were covered previously in Sections 1.2.1 and 1.2.3. the following paragraphs provide an overview of the critical considerations found in the literature for designing HMA overlays, including:

- Cold milling depth,
- Drainage design, and
- HMA mix-design

## Materials Requirements

Proper material selection and testing are critical to obtaining a desirable HMA mix that resists moisture damage in the pavement. Before production in the hot-mix plant, component materials are often tested to ensure they have the same physical properties desired in the mix design (Russell et al., 2001). The literature reviewed ten documents on the best practices in material selection and testing reported from previous studies.

## Aggregate Selection and Testing

Aggregates comprise approximately 92% to 96% of the volume of HMA (depending on the mix type). Hence, aggregate properties are fundamental to the performance of flexible pavements. Pavement distress, such as rutting, stripping, surface disintegration, and lack of adequate surface frictional resistance, can be directly attributed to improper aggregate selection and use (Kandhal et al., 1997). Some of the properties and characteristics of aggregates that have been reported in the literature that contributed to moisture damage include (Khosla et al., 1999; Birgisson et al., 1990; Parker, 1989; Kandhal, 1994):

- Degradation of Aggregate.
- High moisture contents in the mineral aggregates before mixing with the asphalt binder.
- Excessive dust coating on the Aggregate can prevent thorough coating of asphalt binder

- on the Aggregate.
- Siliceous. aggregates, which often have slick, smooth areas, may give rise to stripping, while roughness may help to promote bonding.
- Interlocking properties of the aggregate particles, which include individual crystal faces, porosity, angularity, absorption, and surface coating, are also believed to improve the bond strength in an asphalt mixture.
- Aggregates that impart a low pH value to water.

Aggregates must pass a stringent series of mechanical, chemical, and physical tests to demonstrate that they will perform satisfactorily and meet or exceed specifications. A study by Kandhal (1997) reported the variety used by the various state highway agencies in the US. The author listed the aggregate tests for I-IMA as follows:

- Particle Shape and Surface Texture (coarse Aggregate).
- Particle Shape and Surface Texture (Fine Aggregate).
- Porosity or Absorption.
- Cleanliness and Deleterious Material.
- Toughness and Abrasion Resistance.
- Durability and Soundness.
- Expansive Characteristics.
- Polishing and frictional Characteristics.

Kandhal et al. (1998). conducted a study to determine the best test method for aggregates to study the presence of detrimental plastic fines in the fine aggregate, which may induce stripping in HMA mixtures. The study concluded that AASHTO TP57 (methylene blue lest) is the best test for fine aggregate in determining the propensity for stripping in HMA.

## Asphalt Binder Selection and Testing

The most essential characteristic of asphalt related to stripping resistance is the viscosity of the asphalt binder. Several studies have documented that high-viscosity asphalt cement resists displacement by water better than asphalt cement with low density (Hicks, 1991). Most states in the US utilize the Super Pave performance-grade specification (AASHTO MP l), which stipulates a variety of tests for binder selection.

## METHODS

### Field Investigations

Field investigations included personnel interviews, initial site visits, records reviews, obtaining pavement cores, excavating trenches, and conducting ground-penetrating radar surveys. This section provides details regarding each of these activities.

### Personnel Interviews

Personnel were interviewed to obtain their thoughts on pavement distress's possible cause or causes on the investigated projects.

### Initial Site Visits

In conjunction with the personnel interviews, initial site visits were made visually. Examine the pavement conditions of the five projects being investigated. Appendix D summarizes the observations made during these visits. Some of the information the investigators collected during the initial site visits included:

- Visual pavements surface.
- Photographs of existing pavement conditions.
- Visual assessment. And photographs of the topography and geographic features near the project.

A windshield survey conducted a visual examination of the pavement surface. A detailed distress survey was not a feasible method for the following reasons:

- Heavy traffic volume on the pavement sections under study and a lane closure would have flowed considerably.
- The distresses were located in numerous isolated locations. A detailed condition survey at each site would have merely provided similar information to what was observed at the intermittent locations.

The investigators from the front passenger car seat performed the windshield survey, driving at the speed limit but frequently at a slower speed on the shoulders along the distressed locations. Frequent stops were made near locations where severe distress was witnessed. Drainage features at and near these locations were inspected to determine if improper drainage contributed to the distress. In addition, several photographs of the distressed pavements were taken at these locations.

## Records Review

Review of records is an essential process in the investigation of pavement failure. It helps to identify any deficiencies in the design and construction of the pavement or any other factors that might have influenced the failure. A detailed records review was conducted with the help of the Construction section to obtain the following information:

- Pavement design information.
- Existing pavement structure immediately before rehabilitation.
- Geotechnical and bridge design information related to soil, Aggregate, and Moisture conditions on the project.
- Topography and geographic features in the vicinity of the project.

Environmental conditions immediately before, during, and immediately after rehabilitation.

- HMA aggregates source test results.
- HMA mix design information.
- HMA production test results.
- Type of milling equipment used to remove existing HMA, depth of cut per pass, and per cent of total depth of existing HMA removed.
- Whether or not traffic was allowed on the milled surface and, if so, for how long?
- Pre- and post-construction pavement performance is derived from the pavement management system database and observations made by the maintenance personnel.
- Maintenance activities performed before and following rehabilitation.
- Forensic evaluation information already obtained by personnel.

## Field Sampling and Testing

Field sampling and testing consisted of cutting cores from the pavements, excavating trenches along three of the projects, and conducting ground penetrating radar (G PR) surveys along four of the projects. GPR surveys were conducted in the outside travel lanes in the southbound and northbound directions. Data were collected along both wheel tracks, between the wheel tracks, and along the fog line and analyzed to determine the differential thickness of the pavement layers (i.e., the difference in thickness of pavement layers within the wheel tracks relative to the thickness of the layers between the wheel tracks) as well as to determine the Activity Index (a measure of radar reflection amplitude relative to the average reflection amplitude over a given length of pavement and normalized to unity). The final report provided by the subcontractor (Appendix K) provides details of the GPR surveys and data analyses. This section summarizes the observations made during field sampling of the projects and a summary of results obtained from the GPR surveys. The following tests were conducted at the Payment Evaluation Unit (PEU) laboratory.

**Soil/Stone Base**

a. Moisture Content
b. Particle Size Analysis
c. Atterberg Limits
d. Compacting
e. Moisture Density Relation
f. California Bearing Ratio (CBR)

**Asphalt Concrete**

a. Cove Thickness Measurement
b. Bulk Density
c. Marshall Test
d. Maximum Specific Gravity-Rice Method
e. Extraction-Pan Samples

## RESULTS AND DISCUSSION

### Analysis of Data

**TABLE 4: Summary of Relevant Sections of FMWH Specification Requirement**

| CLOSE | SPECIFICATION | REMARK |
|---|---|---|
| 6201 | Materials suitable for concrete<br>Wearing<br>Binder<br>Optimum Bit. Content 5-8% 4.5-6.5<br>Marshall Stability 350kgmin 350kgmin<br>Marshall flow 2-4mm 2-6mm<br>Void in total mix 3-5% 3-8% | |

| | | |
|---|---|---|
| 6251(3)<br>6252(11) | Materials suitable for stone base<br>% Passing Sieve 200: Non-Plastic<br>Or LL≤ 30%<br>Or PI ≤ 6%<br>Continuously graded Aggregate falling into Grating Envelope A-E% passing sieve 2000 ≤ one-third passing sieve 36 | Wet process |
| 6201 | Marshall is suitable for sub-base<br>%passing sieve 200≤ 35%<br>Liquid Limit (LL) ≤ 35%<br>Plasticity Index (PI) ≤ 12%<br>CBR (24 Hrs Soaking) ≤ 30%<br>Relative Compaction ≤ 100% of WASC | Type I sub base if % passing sieve 200 is more significant than 35%, there is no need for further Tests and material rejected. |
| 6201 | Materials suitable for subgrade/fill<br>% passing sieve 200 ≤. 35%<br>Liquid Limit (LL) ≤ 50<br>Plasticity Index (PI) ≤ 30% | Specification is silent on CBR |

### Asphaltic Concrete (Wearing Course)

From the analysis above, most specification requirements, such as stability, flow, bitumen content and aggregate grading, were met. An increase in the void contents above the specification requirement of the section may be due to the adoption of the lower limit of the bitumen content in the production of asphaltic concrete.

**Table 5: Summary of asphaltic concrete test result for wearing Course**

| S/N | Location | Thickness | BDG | MSD | %Void | Mar.Stab | Mar. flow | BitCont, | Remark |
|---|---|---|---|---|---|---|---|---|---|
| 1. | 8+300 | 38 | 2.36 | 2.51 | 5.5 | 778 | 4 | 5.3 | Sound |
| 2. | 8+600 | 39 | 2.45 | 2.53 | 56.3 | 832 | 5 | 5.5 | Sound |
| 3. | 8+900 | 42 | 2.34 | 2.47 | 5.3 | 621 | 4 | 5.7 | Sound |
| 4. | 9+200 | 37 | 2.44 | 2.51 | 5.1 | 742 | 3 | 5.1 | Sound |
| 5. | 9+500 | 40 | 2.36 | 2.52 | 5.8 | 681 | 3 | 4.9 | Sound |
| 6. | 9+800 | 41 | 2.52 | 2.52 | 6.1 | 589 | 4 | 5.2 | Sound |

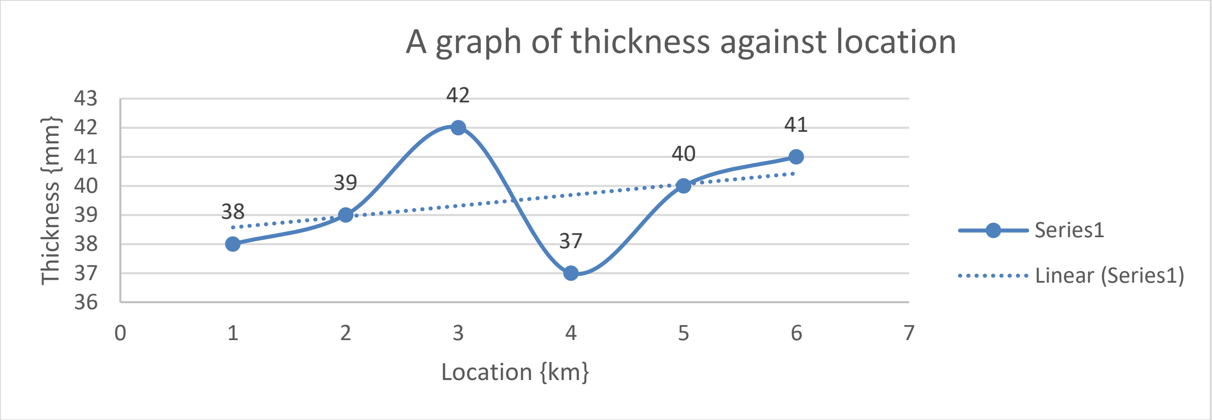

Figure 3: A Graph of thickness against location

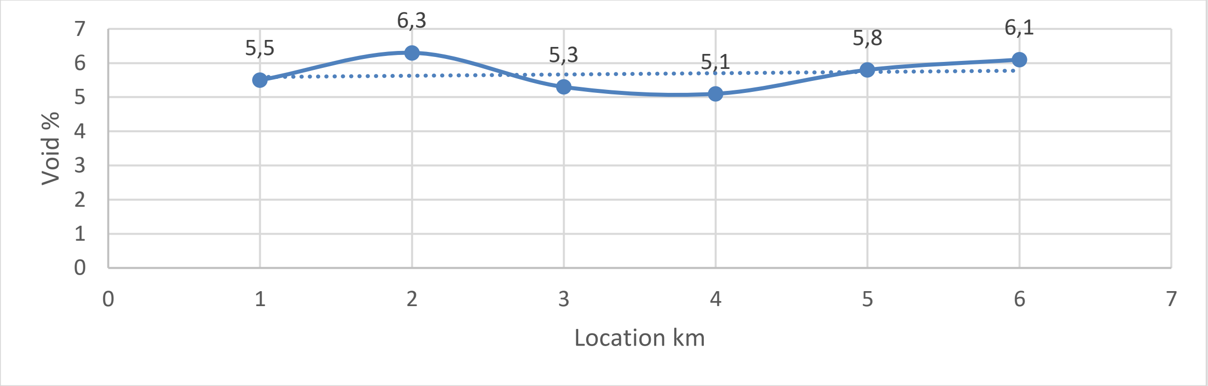

Figure 4: A graph of percentage void against location

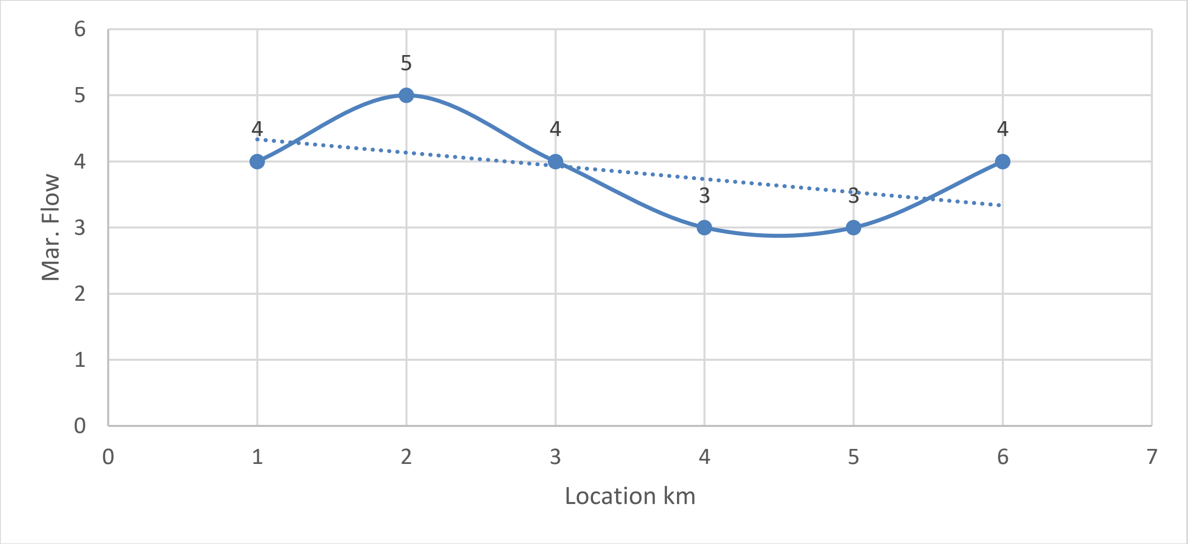

Figure 5: Graph of Mar. Flow against location

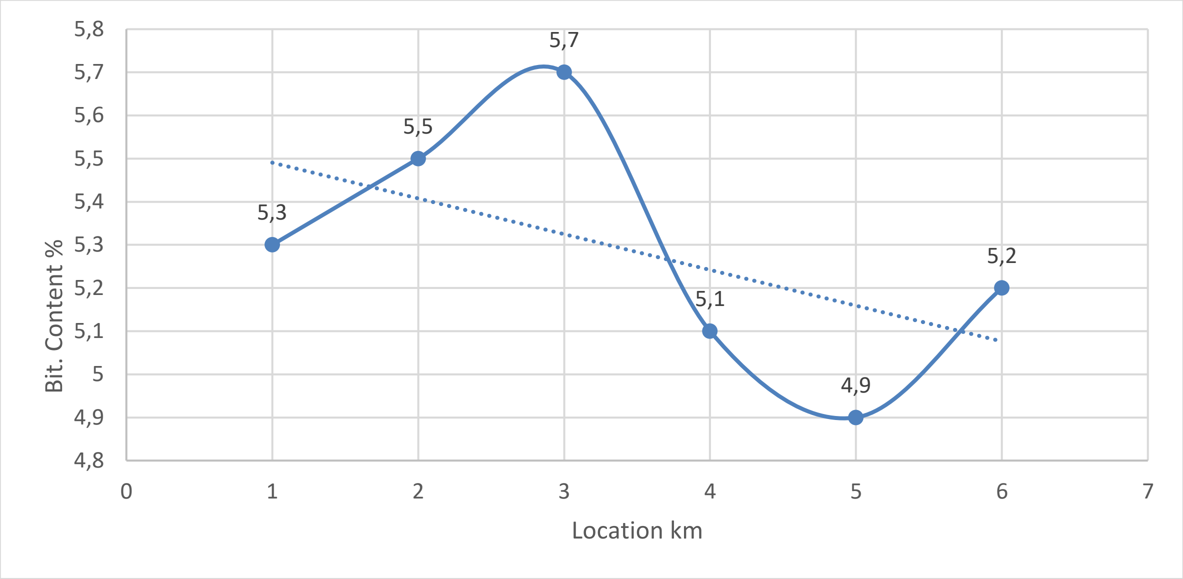

**Figure 6: A graph of Bit. Content against location**

## Asphaltic Concrete (Binder course)

The above analysis met the most significant requirements: void content, stability flow, and bitumen content. Observed that because enough filters were generally used, voids content was kept within specification requirements, although the aggregate grading was slightly out of the upper limit in a few locations.

**Table 6: Summary of asphaltic concrete test results for binder course**

| S/N | Location | Thickness | BDG | MSD | %Void | Mar.Stab | Mar. flow | BitCont, | Remark |
|---|---|---|---|---|---|---|---|---|---|
| 1. | 8+300 | 64 | 2.443 | 2.54 | 3.8 | 596 | 6 | 4.4 | FAILED SECT |
| 2. | 8+600 | 66 | 2.525 | 2.438 | 3.6 | 708 | 5 | 5.2 | FAILED SECT |
| 3. | 8+900 | 77 | 2.449 | 2.526 | 6.8 | 636 | 6 | 4.8 | FAILED SECT |
| 4. | 9+200 | 59 | 2.433 | 2.525 | 3.3 | 532 | 5 | 5.2 | SOUND SECT STIRLING |
| 5. | 9+500 | 63 | 2.392 | 2.531 | 5.5 | 441 | 5 | 4.6 | FAILED SECT |
| 6. | 9+800 | 68 | 2.321 | 2.57 | 9.7 | 650 | 6 | 4.4 | FAILED SECT |

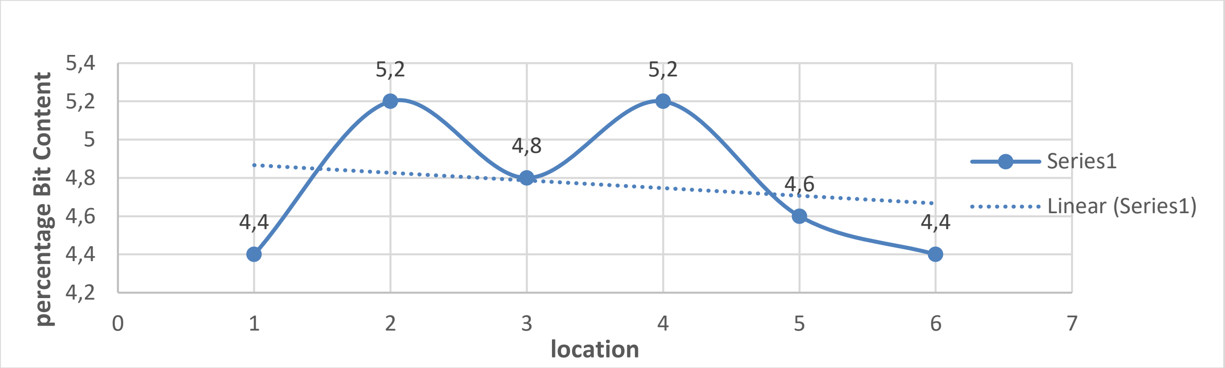

**Figure 7: A graph of percentage bit content against location**

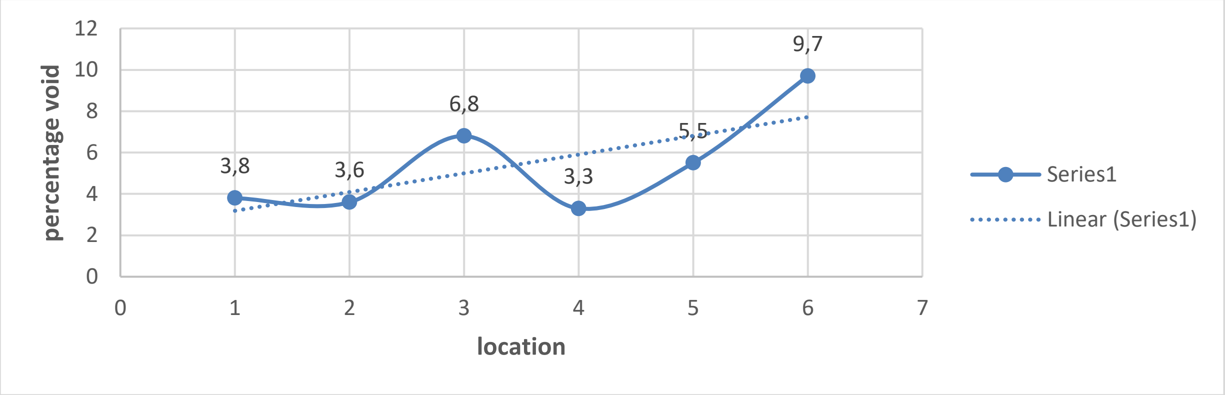

**Figure 8: A graph of percentage void against location**

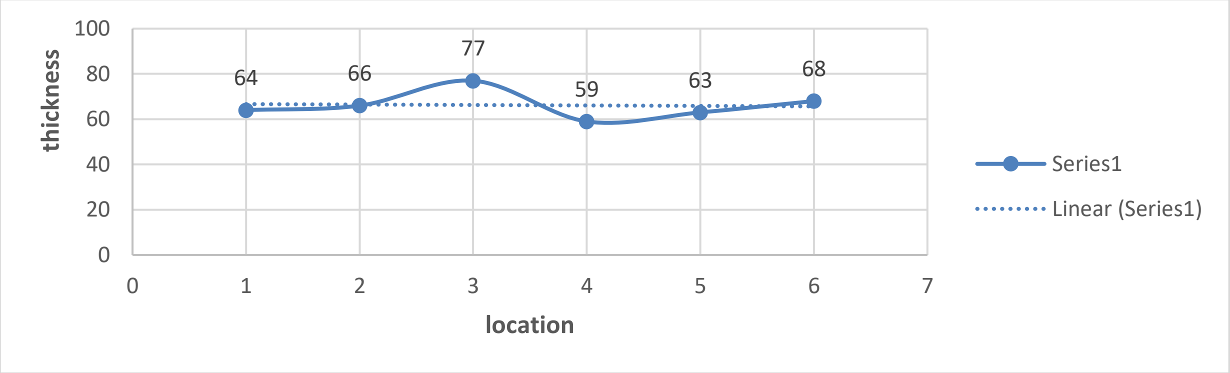

**Figure 9: A of thickness against location**

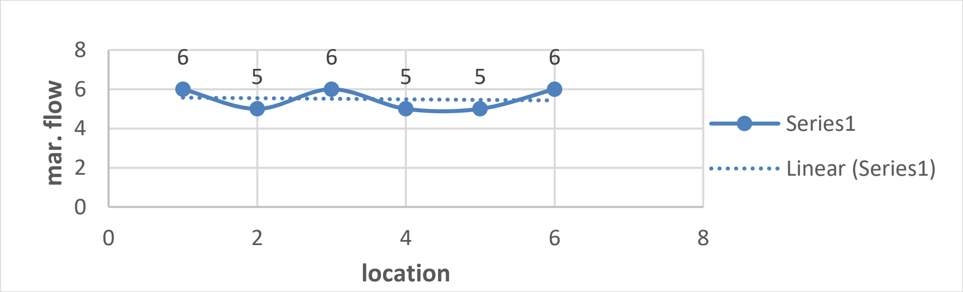

**Figure 10: A graph of Mar. flow against location**

## Stone Base

From the above analysis, the specification requirement on percentage passing BS sieve 200 is equal to 1/3 % of the percentage passing BS sieve No. 36 was met. The stone base in a sound section is generally plastic, which is mainly required. Also, the aggregate grading was within the specification envelope—in 50% of the sample collected. Adequate thickness requirement was met, and Compaction was achieved; therefore, it is reasonable to state that a generally suitable crushed stone base was used in the sound sections of the carriageway.

**Table 7: Summary of soil test result for stone-base Course**

| S/N | Location | Thickness | INSITU TEST | | LAB TEST | | ATTERBERT | | | | ASHTON CLASS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | NMC | DENS | NMC | OMC | #36 | #200 | LL | PL | |
| 1. | 8+300 | 150 | 3.3 | 2.213 | 2.17 | 4.4 | 6 | 0.1 | 28 | 12 | A-2-6(0) |
| 2. | 8+600 | 160 | 5.9 | 2.224 | 2.188 | 5.8 | 11 | 0.13 | 37 | 13 | A-2-6(0) |
| 3. | 8+900 | 170 | 5.9 | 2.286 | 2.165 | 5.8 | 5 | 0.1 | 33 | 13 | A-2-6(0) |
| 4. | 9+200 | 140 | 8.4 | 2.125 | 2.16 | 6.6 | 11 | 0.2 | 34 | 10 | A-2-4(0) |
| 5. | 9+500 | 140 | 3.1 | 2.16 | 2.16 | 6.7 | 13 | 0.4 | 27 | 13 | A-2-4(0) |
| 6. | 9+800 | 165 | 6.9 | 2.03 | 2.15 | 7.4 | 11 | 0.3 | 28 | 9 | A-2-4(0) |

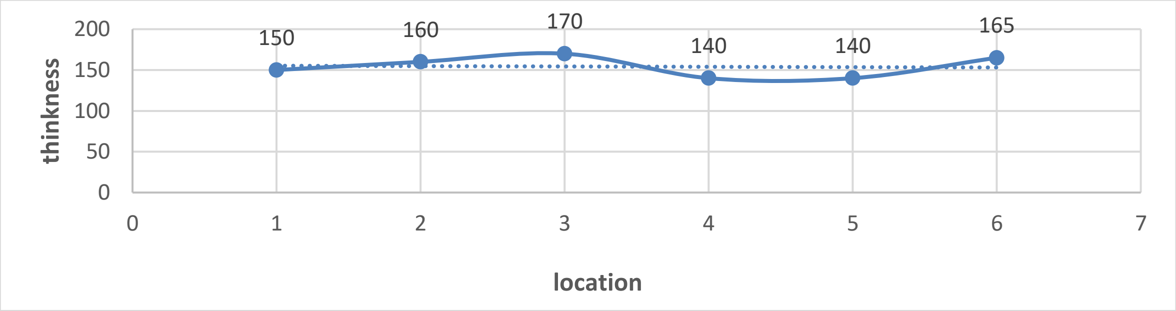

Figure 11: A graph of thickness against location

## Lateritic Sub-Grade Soils

From the analysis, the soils encountered in the sub—base have high Equid limit and plasticity index values. They are also too nuanced, with more than 35% passing BS sieve No. 200 in All the samples. The soils encountered here are A — 6 and A — 7 6 AASHTO classification materials susceptible to high (extreme) volume changes, resulting in early crack development. They also lose much strength in water, resulting in shear failure. It is shown in Soaking met average, while Compaction was achieved onsite.

It is reasonable to state that, like in the failed section, it is unsuitable in the base of the sound Section. They are also mainly clayey materials, and it is observed that failure did not occur in these sound sections because the natural contents are below the optimum moisture contents even during the rainy season.

**Table 8: Summary of soil test result for sub-base Course**

| S/N | Location | Thickness | INSITU TEST | | LAB TEST | | | ATTERBERT | | | | ASHTON CLASS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | NMC | DENS | MD | OMC | CBR | #36 | #200 | LL | PL | |
| 1. | 8+300 | 150 | 15.3 | 1.71 | 1.78 | 7.7 | 10 | 56 | 43 | 43 | 28 | A-7-5(2) |
| 2. | 8+700 | 140 | 12.2 | 1.92 | 1.96 | 4.8 | 11 | 43 | 29 | 55 | 40 | A-7-7(2) |
| 3. | 9+200 | 150 | 9.9 | 1.92 | 1.83 | 5.1 | 15 | 63 | 44 | 33 | 26 | A-6(3) |
| 4. | 9+800 | 140 | 9.8 | 1.93 | 1.91 | 5.3 | 20 | 55 | 38 | 38 | 32 | A-6(1) |
| 5. | 10+500 | 140 | 7.6 | 1.86 | 1.86 | 6.2 | 20 | 53 | 42 | 38 | 31 | A-6-2(3) |
| 6. | 11+800 | 160 | 9.5 | 1.81 | 1.84 | 7 | 10 | 68 | 57 | 28 | 36 | A-7(3) |
| 7. | 12+100 | 135 | 6.9 | 2.05 | 2.08 | 5.6 | 15 | 89 | 67 | 40 | 31 | A-6(3) |
| 8. | 12+400 | 200 | 10.2 | 1.97 | 1.83 | 5.4 | 10 | 47 | 37 | 37 | 23 | A-6(3) |

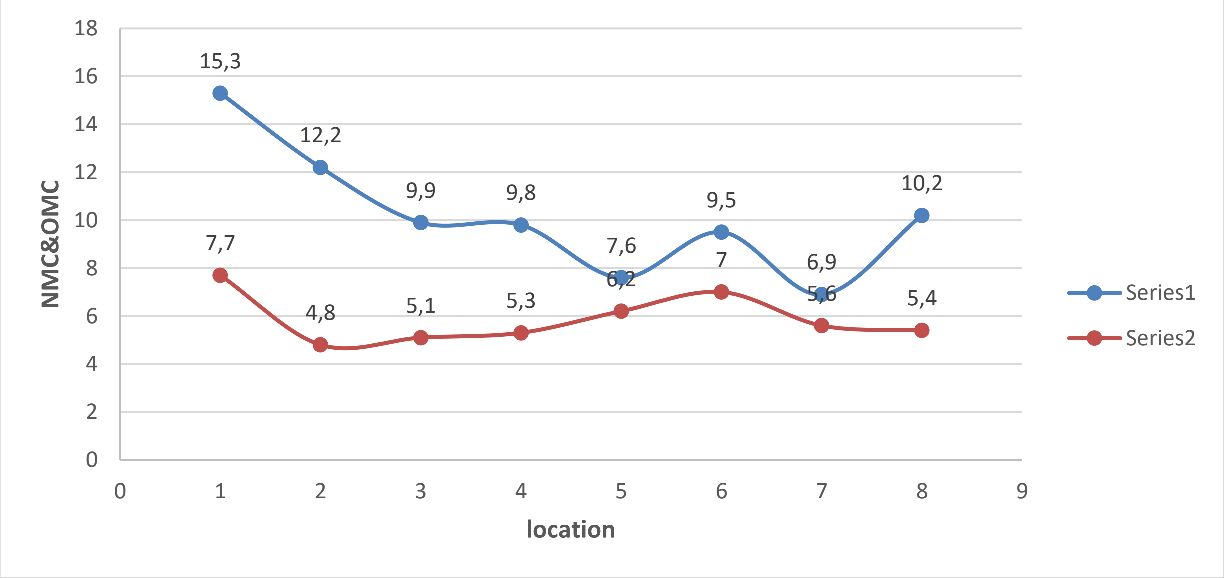

**Figure 12: A graph of NMC & OMC against the location**

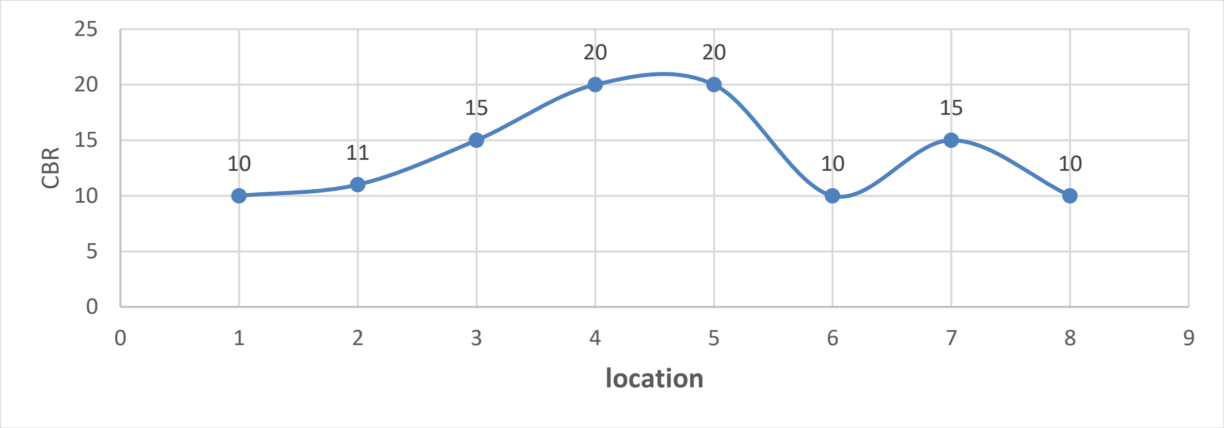

**Figure 13: A graph of CBR against location**

### Lateritic Subgrade Soils (Upper Layers)

From the analyses, the subgrade soils encountered have acceptable levels of liquid plasticity index and subgrade in most locations. However, their particulars are too fine as the proportion passing BS Sieve No 200 was higher than in all the tested samples. They are mainly clayey soil of A-2-7, A-6, A-7-6, and AASHTO classification groups, which also undergo swelling and shrinkage characteristics upon variation in moisture contents.

It can be inferred that soil of the same characteristics was encountered in the sound and failed sections, but failure did not occur in sound areas because they were dry even under the rains due to good drainage and the use of suitable stone base.

### Latheritic Subgrade Soil (Lower Layers)

From the analysis. The upper sub-grade layer, generally materials finer than 35% of BS Sieie: 200•, was encountered in many lower sub-grade layers. They are mainly salty soils. The general grounds characteristics here are the same as in the failed sections.

**Table 9: Summary of soil test result for sub-grade Course**

| **S / N** | **Location** | **Thick ness** | **INSITU TEST** | | **LAB TEST** | | | **ATTERBERT** | | | | **ASHTON CLASS** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **NMC** | **DENS** | **MD** | **OMC** | **CBR** | **#36** | **#200** | **LL** | **PL** | |
| 1. | 8+300 | 150 | 13.4 | 1.42 | 1.62 | 20.8 | 5 | 72 | 59 | 47 | 24 | A-7-6(10) |
| 2. | 8+700 | 140 | 13.6 | 1.98 | 1.89 | 10.7 | 10 | 83 | 58 | 46 | 32 | A-7-6(14) |
| 3. | 9+200 | 150 | 13.6 | 1.74 | 1.74 | 12.5 | 7 | 63 | 49 | 49 | 27 | A-7-5(6) |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4. | 9+800 | 130 | 9.1 | 1.93 | 1.83 | 13.2 | 6 | 46 | 33 | 37 | 16 | A-2-6(0) |
| 5. | 10+100 | 120 | 19.1 | 1.67 | 1.86 | 14.2 | 5 | 73 | 59 | 51 | 32 | A-7-6(16) |
| 6. | 1+300LHS | 140 | 18.2 | 1.77 | 1.88 | 14 | 5 | 54 | 38 | 55 | 28 | A-7-6(4) |
| 7. | 6+200 | 135 | 19.4 | 1.72 | 1.73 | 13.7 | 4 | 67 | 47 | 46 | 14 | A-6(3) |
| 8. | 4+590 | 130 | 14.5 | 1.71 | 1.76 | 15.5 | 8 | 63 | 47 | 52 | 52 | A-7-5(7) |

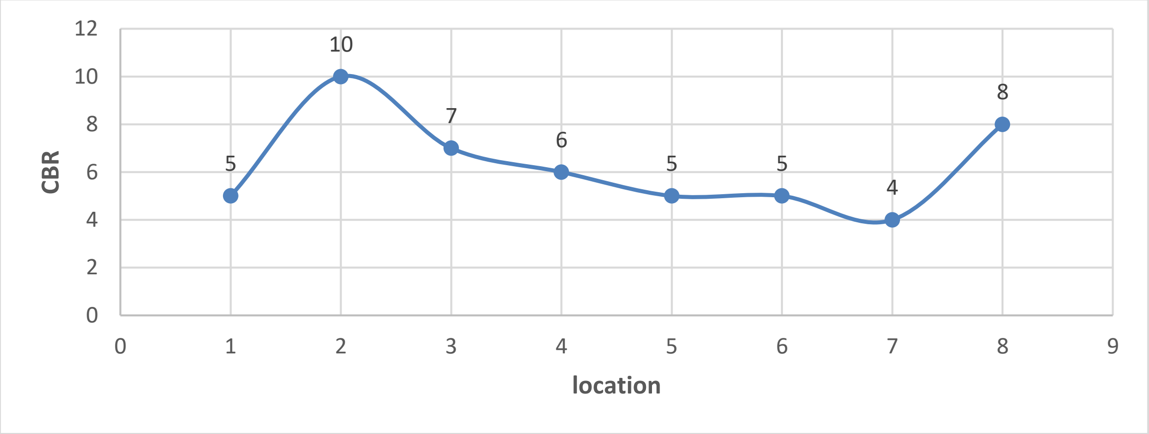

**Figure 14: A graph of CBR against location**

## Investigation The Pavement Drainage

It is pertinent at this point to investigate the possibility of structure entry. In the highway under study, running water, stagnant water or observed close to the pavement in most of the locations during visual were. It shows that water was near the pavement on almost the entire highway. It is, therefore, reasonable to conclude that, bearing in mind the characteristics of materials encountered here, failure of the sections under study may be because the pavement structure at cut and fill sections are made up of primarily clayey, micaceous sub-grade and sub-base of grave clay with high plasticity indices that are susceptible to high volume changes, entry of water resulted in loss of much bearing capacity. In this state, if axle loads from commercial vehicles are applied to these sections, rapid subsidence results. Thus, pavement distress in the form of rutting with cracks, depression or base shear begins to manifest on the wheel path of the slow lane on which commercial vehicles ply. Good drainage is provided at sound sections but is lacking in the failed areas, perhaps due to hasty project completion. Therefore, it is reasonable and logical to conclude that the sound areas did not fall because surface water was not allowed to percolate into the pavement structure with similar soil characteristics to fail sections.

## CONCLUSION

From visual inspection, it is seen that reasonable effort was made at drainage. Test results on the lateritic soils used in (the sub-base revealed that unsuitable were used, and the grounds have high liquid limit and plasticity index values. They are also too fine as more than 35% passed IIS Sieve No. 200 in most locations. Such materials are susceptible to high volume changes upon introducing or withdrawing water, resulting in early crack development. They also lose much strength in the presence of water, resulting in shear failure.

It is shown in the low CDR values obtained in all the samples tested after 24 hours of Soaking.

Based on the findings from this study, the following conclusions appear warranted:

Moisture can weaken asphalt cement, and the bond between the asphalt cement and the aggregate surface through several mechanisms, summarized herein, causing a reduction in strength and stiffness of HMA mixtures.

Moisture can enter pavements by means of:

a) Capillary action.

b) Infiltration from the surface.

c) Seepage from surrounding areas.

Moisture can occupy pavements as liquid water or moisture vapor above the capillary fringe. A literature review revealed that the best defense against moisture-induced damage in HMA pavement structures is to provide sufficient drainage to prevent the accumulation and prolonged storage of water in the structure.

Site visits were highly informative concerning verifying information obtained during the maintenance personnel interviews and record reviews, determining current pavement conditions, and scouting potential locations for further evaluations, such as coring and trenching activities.

Findings from laboratory investigations generally supported those from the field investigations. Results of air void analyses of the pavement layers correlated reasonably well with observations made from the trenches in those layers with relatively high air void.

## Recommendation

It's recommended that open earth drainages should be provided at all locations, and subsoil drainage should be provided in another area where there is an imminent failure. The guidelines contained herein are recommended to be integrated into the Pavement Guide (2007). In addition, given that water was found to be seeping through existing, dense-graded I-MA layers, the Engineer should investigate the efficacy of installing surface drains within the existing, milled surface (similar in concept to wearing course surface drains) spaced at regular intervals along a project to provide transverse drainage paths for water that tends to flow longitudinally through the pavement.

Given the findings documented herein regarding water seepage between paving layers, ODOT personnel should pay particular attention to ensuring that the surface to receive an overlay is properly milled (cold planed), adequately cleaned and that the tack coat is correctly applied. Implementation of this latter recommendation should include a review of the specifications for milling, cleaning the surface and laying the tack coat to ensure that these are adequate and that these activities are performed to specification through inspection activities.

The guidelines for materials selection and testing techniques contained in the Section Were Developed to assist materials engineers in selecting materials for HMA mixtures that reduce the risk of moisture-related problems in rehabilitated HMA pavements that incorporate the materials. Although personnel currently implement the spirit of the guidelines presented herein, the use of the methylene blue (AASHTO TP 57) test should be investigated as a potential replacement for the sand equivalent (AASHTO T 176) test due to the ability of the methylene blue test in identifying fine aggregates that have the for causing stripping in HMA pavements. s

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