An Experimental Study on Premature & Top-Down Cracking Mechnaisum on Flexible Pavement

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***Abstract* — this report examines the factors which are responsible for premature pavement cracks in flexible pavement. The investigation carried out included visual condition survey, excavation of test pits, coring of pavement samples and the examination asphalt mix design.**

I. INTRODUCTION

Top-down cracking (TDC) is a deterioration mechanism in flexible pavement that has been identified in temperate-climate countries. Climatic conditions, traffic, ageing, structure and construction quality are the main causes pointed out for the initiation and propagation of TDC. Longitudinal surface cracks are predominantly parallel to the asphalt concrete pavement centerline and located in the vicinity of the wheel paths. Unlike fatigue cracking at the bottom of the asphalt concrete (AC) layer, inspections of core samples show that longitudinal cracks form from the surface of the pavement and move downward.

Main Objective of this paper is to investigate the root cause of the Top-down cracking (TDC) cracking mechanism and to generate the site oriented remedial measure to control this kind of deterioration in flexible pavement

II. TERIMINOLOGY

- **IRC**- Indian Road Congress
- **MORT&H** – Ministry of Road, Transport and Highways
- **TDC**-Top-Down Cracks
- **BC / AC** – Bituminous Concrete / Asphalt Concrete
- **DBM** - Dense Bituminous Macadam
- **WMM** - Wet Mix Macadam
- **GSB** - Granular Sub-Base
- **CRMB** - Crumbed Rubber Modified Bitumen
- **VA**- Void in Mix
- **VMA**-Voids in Mineral Aggregate
- **VFB**-Voids Filled with Bitumen
- **PMB**-Polymer Modified Bitumen
- **MSA**-Millions of Standard Axle Loads

A. *Initial Signs of Pavement Distress:*

Initial signs of pavement distress in the form of hair-line cracks were observed on top of the trafficked DBM and BC layers. Cores were taken to examine the depths and the source of the cracks. After coring, it was observed that all the cracks formed from top to down of the layer and had penetrated for not more than 30 mm from the top of the layer. Observed initial signs of pavement distress is shown in figure below

B. *Pavement Investigation Method:*

The investigations carried out on the pavement to determine the causes of the distresses included the following

- Visual Condition Survey
- Coring of Samples
- Excavation of Test Pits
- Review of Pavement Mix Design
- Pavement Design review of the project as per IRC 37

C. *Visual Condition Survey:*

This is the most laborious and time consuming test of all, but very effective in identifying distresses which cannot be detected by machine. A visual inspection was carried out to record the various types of distresses and cracks which had appeared on the surface of the pavement. Measurements of cracks and visual condition survey is as shown in figure

As per our visual condition survey on pavement it has been founded that observed cracks are categorized into two stages.

- Stage 1-Hair cracks on DBM top & BC layer.
- Stage 2-Formation of top-down type cracks.

Until recently all cracked asphalt layers have been assumed to initiate from the bottom of the asphalt layers where the tensile strain is most severe and propagate to the top of the asphalt layer. This type of cracking is termed "bottom-up" cracking. Recently research and field results have shown that some cracking actually do initiate from the top of the pavement layer and propagate to the bottom. This is called "top down" cracking.

D. *Core Samples:*

A total of twenty four (24) cores (see below Figure) were taken, mostly from the distressed area of pavement and a few from non-distressed areas. Photographs of all the cores were taken. Cores taken from cracked areas showed that all the cracks are top - down cracks and had penetrated barely more than 10-20 mm from the top. Tests carried out on the cores included bitumen extraction, sieve analysis, determination of air voids, and relative compaction.

E. *Excavation of Test Pits:*

A ten number of test pits were dug in various locations were selected based on representative cracking type. The pits were dug through the whole pavement thickness, the pavement layer thicknesses, the bond between the pavement layers, presence of trapped moisture between the layers of the pavement, evidence of weak foundation up to subgrade are analyzed. In all ten pits were dug in the carriageway pavement.

The sizes of the pits were approximately 1m by 1m. The pits were carefully excavated layer by layer and logged. The layers were examined for thickness, bonding between each other, presence of water between the layers, and for the asphalt layers coating of the aggregates with bitumen, and for the granular layers the moisture content of the material.

Field Density Test of the Wet Mix Macadam as well as those of the Granular-Sub Base, sub grade was checked. GSB, WMM, Subgrade samples from the pits were collected for testing as per MORTH Cluase.900.

F. *Analysis of Results:*

According to several site survey and core sample investigation observed cracks are hair-line cracks and Top-Down (TDC) mechanism cracks. The few transverse cracks observed in the examination. From examination of the cores taken, it was found out that the cracks were 'top-down' cracks. The widths of the cracks were less than 2-5 mm. Field study results have shown that all cracking are actually initiated from the top of the pavement layer and propagate to the bottom. This is called "top-down" cracking.

Top-down cracks (TDC) are longitudinal and/or transverse cracks that initiate at the pavement surface and propagate downward and outward. Field investigation has shown that most longitudinal TDC are located in the vicinity of the wheel paths. TDC is categorized into three stages.

- The first stage consists of a single short longitudinal crack or cracks appearing just outside the wheel path.
- Over time, the second stage develops where the short longitudinal TDC grow longer and new sister cracks develop parallel to the original crack.
- Finally, the TDC evolve into the third stage where the parallel longitudinal TDC are connected via short transverse TDC.

G. *Several causes of Top-Down cracking Machnesium:*

- Load-induced stresses and strains.
- Thermal stresses.
- Quality / Hardening of the binder.
- Segregation in the Asphalt mix.

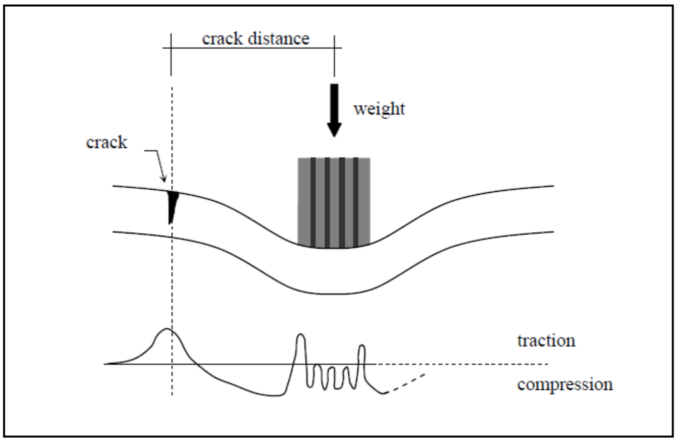
H. *Load-induced stresses and strain- In Brief:*

Load-induced stresses and strains are generated by high traffic level, high traffic loading. The load-induced shear strains at the edge of the wheels in the vertical plane are higher than the load-induced lateral tensile strains at the same location on the pavement surface.

Therefore, the shear strains on the vertical plane play an important role in TDC initiation and propagation. Tensile stresses away from the edges of the tire are the driving mechanisms are also responsible for the propagation of TDC.

The pavement layer stiffness with denser and thicker asphalt design and the location of the tire relative to TDC have significant impact on the magnitude of the load-induced tensile stresses away from the tire.

The magnitude of the shear strains on a vertical plane at the edge of the wheel path decreases rapidly with depth of cracks. Lesser thickness / incomplete loading of the Asphalt layer results in increasing the load-induced shear strains. Hence, lesser thickness / incomplete loading on Asphalt layers are more vulnerable to TDC. Load induced stress and strains and cracks initiating mechanism shown in figure.



With reference with IRC: 37-2001 Annexure-2 maximum single axle load equivalency factor is only up to 22.68 MT(i.e. 22680 Kg) as 55 times of standard single axle loading. Nevertheless the loading of the project stretch is incredibly increased on these grounds as unanticipated manner in incomplete pavement structure. High surface horizontal tensile stresses due to truck wide-based tires and high inflation pressures are cited as causing the highest tensile stresses over the pavement.

I. *Thermal stresses:*

It has been recognised the effect of temperature is important in asphalt pavement, such as high temperature rutting and low temperature cracking, etc. This damage may not only impact the external appearance of pavement, but also accelerate the deterioration of pavement structure. Thermal cracking of asphalt pavement mainly occurs in variation weather, when asphalt mixture exhibits apparent brittleness which is similar with elastic material, thus it rational to analyse it based on elastic theory, but the variation of temperature still has an influence on materials characteristics of asphalt. Thermal stresses are results of the contraction of the asphalt layer due to variable pavement temperatures and the restraining force caused by the friction between the Asphalt and base layers and causes difference in temperature on bottom and top of the asphalt layer.

Thermal stress based on the contraction force in the asphalt, which is a function of the properties of the asphalt binder, temperature and the cooling rate. Note that the thermal coefficient of contraction and expansion of the asphalt is not a constant value and it varies with the temperature of the mix. The value of the coefficient of thermal contraction of asphalt mixtures at any temperature can be obtained the properties of the asphalt binder and aggregate and their volumetric relationship as shown in equation below.

$$\alpha_{MIX} = \frac{V_{MA} \times B_{AC} + V_{AGG} \times B_{AGG}}{3 \times V_{TOTAL}}$$

Where:

α MIX = linear coefficient of thermal contraction of the asphalt mixture (1/oC)

VMA = percent volume of voids in the mineral aggregate

B_{AC} = volumetric coefficient of thermal contraction of the asphalt in the solid state (1/oC)

V_{AGG} = volumetric coefficient of the aggregate

B_{AGG} = volumetric coefficient of thermal contraction of the aggregate (1/oC)

V_{TOTAL} = 100 percent

Temperature and the properties of the asphalt mix affect the magnitude of the thermal stress induced in the pavements. Thermal and load induced stresses as possible causes of TDC in flexible pavements, low temperatures and fast cooling rates could result in high thermal stress. Further, the high thermal stresses combined with load-induced stresses can result in TDC initiation in flexible pavements.

J. *Quality / Hardening of the binder:*

In tropical environments, on low penetration binder severe bitumen hardening occurs at the surface of asphalt courses. This results in the formation of a brittle skin that is prone to early top-down cracking. The occurrence of such cracking is not strongly related to the usual structural strength parameters. This hardening of binder in asphalt mixtures is one of the key components of TDC mechanism. Higher thermal stress induced by low penetration binder cases high stiffness on upper portion of dense and thicker asphalt layer.

As the change in the Indian standard specification for bitumen the adopted binder in throughout the project is viscosity grade VG-30 .Test results by in-house laboratory and third party agency implies the VG-30 has the penetration values ranging between 50-60 mm this is acceptable by IS 73-2006. On the other hand to the reference of IRC 37-2001, the penetration grade bitumen 60/70 is adopted for the pavement design. The entire characteristic properties of penetration grade binder 60/70 and Viscosity grade binder VG-30 is not matching.

K. *Segregation in Asphalt mix:*

Segregation refers to the separation of coarse and fine aggregates in an asphalt mix. The mechanism of segregation is based on the motion of aggregates. Segregation of the asphalt mixtures in pavements may lead to premature distress, such as stripping, raveling, rutting, and longitudinal and fatigue cracking. These distresses are usually caused by the decreased tensile strength or durability of the mix. Segregation may occur during stock piling and handling, hot mix asphalt production, truck loading and unloading, transportation and/or lay down operations. The amount of segregation that occurs may be exacerbated by such factors as aggregate type and mixture design. Due to our proper mix design and enhanced material properties the segregation is not identified in entire project stretch.

L. *Pavement Design Review of The Project:*

Pavement Structural design should involve carrying out some kind of structural analysis using material characteristics of pavement layers. But IRC 37-2001 design specifies the pavement layers only by their nomenclature, like BC, DBM or WMM but not tagging with their material properties.

On estimating of pavement design, more than 150,000,000 of standard axle will pass over the road in less than 6 years. It means that in case of all structural layers are completed this road should start to cracking in less than 5 years.

The designed road recognizes three modes of failure as below

- Excessive compressive strain on subgrade resulting in permanent deformation of pavement surface
- Large tensile strains at bottom of bituminous layer causing cracking of bituminous layer
- Permanent deformation within the bituminous layer.

The 3rd Mode of failure, Permanent deformation in asphalt mix, not considered in IRC Pavement Design. Currently, no pavement design method is capable of predicting or analyzing top-down cracking potential although efforts are being made to include such model in the new mechanistic-based IRC -37 and AASHTO and etc. design procedure.

M. *Traffic Estimation, Analysing Method, Assumptions and Criteria:*

Design has been carried out using Analytic method for Flexible Pavement Design. EVERSTRESS software has been used to calculate the stresses and strains. Possible number of standard axle passing over the road is determined as per Indian Standard. In conclusion, results of modelling have been valuated to find out the proper road structure and Layer thicknesses. Available Traffic data for the year of 2005 is used to determine the possible amount of traffic for designing.

Three Layered system of analytic method has been implemented to calculate the stresses and strains. Assumptions to modelling the system are completely as per IRC-37-2001. Criteria for calculation of allowed number of Standard axle passing is considered as per IRC37. Work quality is assumed to be satisfying Indian Standards completely and the results of modelling for various cases are presented in Table.

CBR value	Road Structure		
	Case1	Case ll	Case lll
6%	162,534,205	56,795,613	11,864,975
8%	219,851,124	81,173,631	19,277,809

Case1	BC=5cm, DBM=16cm, WMM=25cm, SUBBASE=20cm
Case1l	BC=0cm, DBM=16cm, WMM=25cm, SUBBASE=20cm
Case1ll	BC=0cm, DBM=8cm, WMM=25cm, SUBBASE=20cm

As it is shown in Table the allowed number of standard axle for case 3(BC=0, DBM=8cm) is about 11 million, which is very near to the passing number of same in 4 months on our road. Therefore the fracture of DBM 1 layer is absolutely due to heavy traffic and is not having anything to do with quality of work. Traffic estimation for 6 years, is more than 150,000,000 of standard axle will pass over the road in less than 6 years. It means that in case of all structural layers are completed this road should start to cracking in less than 5 years.

N. *Integrated mix design – pavement structural design:*

The fatigue life of a bituminous layer can be increased by increasing the bitumen content. But, voids in mineral aggregates (VMA) being fixed for a given aggregate gradation, increase in bitumen content will result in less air voids, which is undesirable for a mix. High tensile stresses are amplified by heavy stiffened DBM layer in the thicker pavement design and induce thermal strain over the pavement. Therefore DBM as a bituminous surface on the WMM shall not be laid. The flexible BM layer should be provided between WMM and DBM layers to avoid crack occurrence. Further, a thin layer of BC (say 50 mm) on the DBM surface should be provided. This has been the slipup in the pavement design as per IRC 37-2001 in providing the flexible layer (BM) in thicker asphalt design rather than the denser mix.

It shows the serious necessity of reducing the load on the road by modifying design or widening the road more than the current situation. Hence it is strongly recommended to review the general design of road structure and include the parameter of TDC; Top-Down Cracking.

The Asphalt Mix Designs are in accordance with the contract Specifications and did not contribute to the distresses manifested on the surface of the pavement. However to avoid future cracking potential caused by mix design it will be advisable to try 'Refusal Density Design' as recommended in the British Transport Research Laboratory (TRL)'s Overseas Road Notes 19 and 31 , although this method of design is not included in MORTH design. Refusal Density design is an extension of Marshall Mix Design and it ensures that after secondary compaction due many years of trafficking, there is still enough air voids of 3% by TRL Overseas Road Note 19 to prevent plastic flow and rutting.

Design the asphalt mix to be the resistance of both cracking and plastic rutting is diffcult by the specified grading requriment. Thus, there is a need to deviate from the specified gradation in order to come up with non-standard gradations, which possibly can give rise to better fatigue lives, yet without compromising with volumetric and strength requirement. For such type of asphalt mix is arrivied by the following requriment adopted as designal creterial and excuted at site in the same manner.

- To avoid the plastic cracking Refusal VA shall be 3% on the 448 blows of marshal compaction.
- To avoid the premature cracking VFB should be 65% in 112 marshal compaction.
- To avoid the premature cracking VMA should be 18% and above in 112 marshal compaction.

Minimum and Maxmum effective asphalt content will be derived from following formulae:

1. Minimum EAC= $\frac{65\times(VMA)\times(Gb)}{100\times(Gmb)}$

Where VFB ≥ 65% = $100 \times \frac{(Pbe \times Gmb)}{(VMA) \times (Gb)}$

2. Maximum EAC=$(VMA - loss\ VA - 3) \times \frac{Gb}{Gmb}$

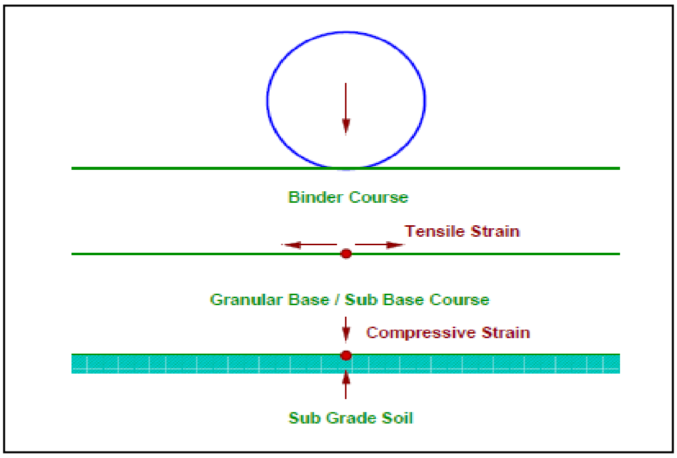
Where Refusal VA ≥3% =$(VMA - Vol.of\ Bitumen - Loss\ of\ VMA\ in\ 448\ refusal)$

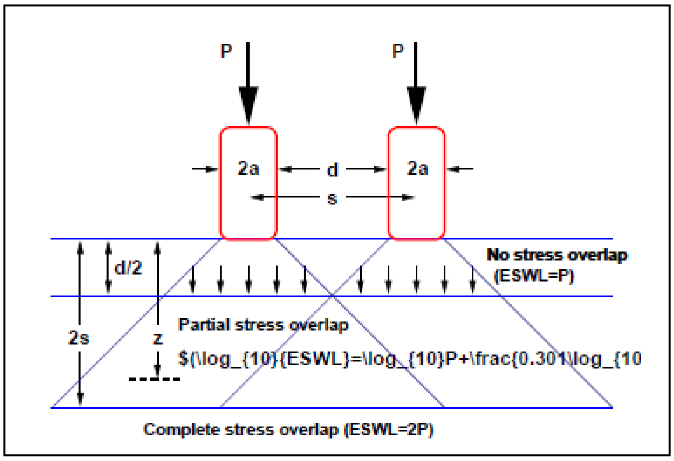
O. *Eccentric Loading:*

IRC: 37-2001, recommended Road design shall be consider number repetitions of standard axle load (Msa). If the axle loads is not a standard one, then it must be converted to an equivalent axle load by number of repetitions of given axle load and its equivalent axle load factors is calculated for design. According to that number of maximum standard axle moving per day on the particular stretch with standard axle is converted into load equivalency value and adopted for design for completed pavement structure.

The unpredicted additional load intensity with almost double times more than equivalency load factor to the standard axle loading calculated as per design is applied to our project stretch even though the pavement structure is incomplete this is the frontrunners for high inflation eccentric loadings. This consistent loading pattern induces tensile strain at the bottom of the bituminous layer beyond extendable rate and bituminous surfacing of pavements displays flexural fatigue cracking.

This flexural fatigue cracking results from the horizontal strains at the pavement surface due to high wheel loads. When calculating horizontal strains at the pavement surface, the tire-pavement contact stress is assumed to be equal to the tire inflation pressure and to be uniformly distributed over a circular contact area. However, in high traffic intensity loads the tire-pavement contact stress is non-uniformly distributed in a noncircular area. Typical loading pattern on the roads explained in figures

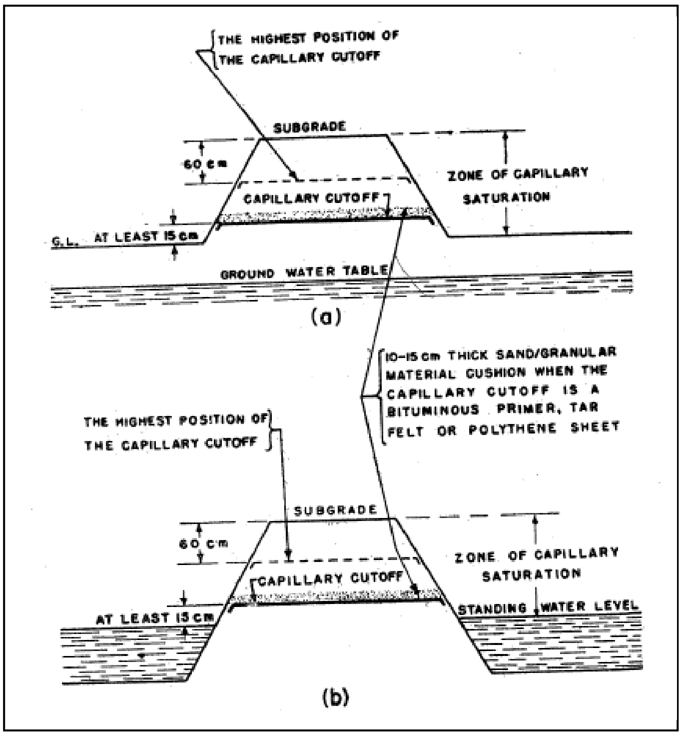




P. *Drainage Measures for capillary cut-off :*

Drainage measures are especially important when the road is built over the cutting or built on low permeability soils or situated in heavy rainfall precipitation area. On reference to the IRC 37:2001 clause 5 to provide the suitable means of capillary cut off on water logged area and difference of 0.6-1.0m on the heavy rainfall areas are mandatory. For these condition IRC: 37 suggested that 100-150 mm of open graded crushed stone layer to ensure the drainage. But those of above mention parameter are not considering in project design as per IRC 37 & IRC 34.

Maximum lengths of the project road from Km.153+000 to Km.205+000 are rehabilitees over the existing subgrade, where places having low embankment's & widening work done directly on Sub-grade top of existing road of the project stretch and 80% of observed cracks are positioned on this location. The entire project stretch are lies on the heavy water logged area and meeting the high rainfall intensity because the moisture damage on the pavement and capillary action beneath the pavement leads the pavement distress on grand potential of traffic volume.



Q. *Recommendations & Remedial Actions:*

1) *Temporary remedial action for Crack Sealing /filling:*
The pavement surface shall be thoroughly cleaned of all dirt, water, and oil to the satisfaction of the engineer. Cracks 3 mm wide or greater shall be cleaned and filled with suitable bituminous material in accordance with MORTH table 500-47.

a) *Methodology for Crack Sealing:*

- Total asphalt layer having cracks should be cleaned with the high-pressure air compressor.
- That layer has been dried thoroughly by suitable means available at site.
- Tack coat (emulsion, bitumen grade VG-10 or elastomeric bitumen rubber membrane) shall be sprayed excessively on the top of the layer.
- PTR Roller has been rolled over it for the uniform filling of the seal closing of the cracked layer.
- The 6mm down mineral shall be sprayed on the top of the layer & PTR roller should been rolled over it.

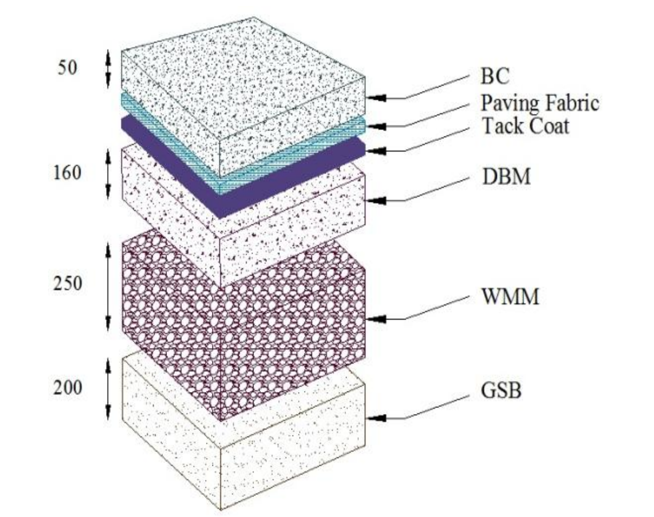
2) *Permanent Remedial Action*

a) *Case 1: On Completed DBM & BC Layers:*
Remedial actions should be done on DBM top and BC layer as per MORTH clause 522 Crack Prevention Courses.

b) Case ll: On Completed DBM Layers

Flexibility and tensile strength of the BC layer with polymer modified bitumen (PMB) is adquete to bare this kind of traffic overloading with moisture damage, reflective cracks from the existing asphalt layer is conceivable after execution of BC layers.

To avoid this kind of reflective cracking on BC and to elevating the flexibility and tensile strength of asphalt layer crack retarding layer geosynthetics as per MORTH clause 703 is layed as the interlayer between DBM top and BC layer are prescribed. Perspective cross section of the geosynthatics with asphalt layer is shown in below mention figure.



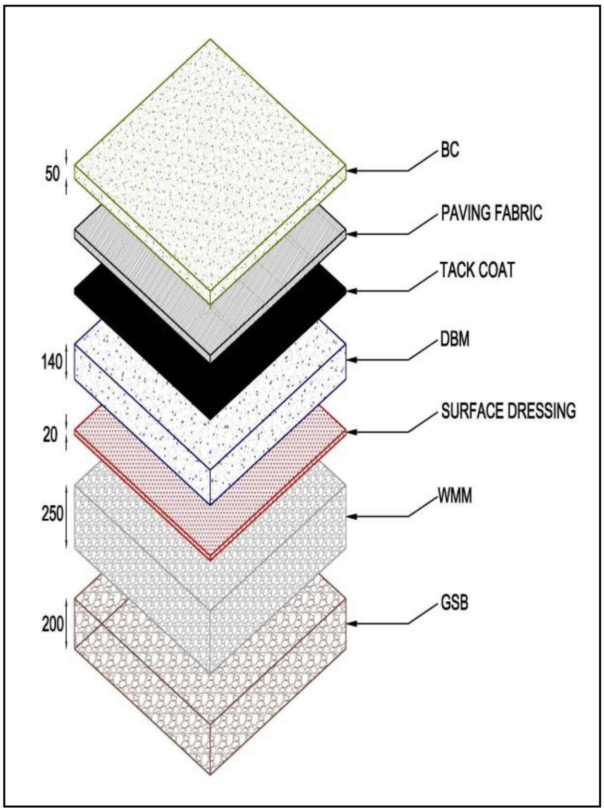
Abstract methodology for construction of BC with geosynthatics is as follows:

- Total asphalt layer having cracks sealed should be cleaned with the high-pressure air compressor.
- That layer has been dried thoroughly by suitable means available site.
- That asphalt layer should be free from water and other organic materials.
- Tack coat shall be sprayed on the top of the layer.
- Approved geosynthatics should layed over it.

- Tack coat shall be spread over the geosynthatics.
- Wearing course mix has been paved as per MORTH & PQP manual and compacted over the geosynthatics.

c) Case lll: New Constructing DBM layer:

- To enhance the flexibility and to decrease the moisture induced damage of Asphalt layer following construction and design practices are prescribed. Perspective cross section for construction of new asphalt layer is shown in figure.
- Providing of 20mm thick surface dressing layer over WMM layer and traffic is allowed for few days before laying of DBM layer is advised and this layer shall act as a transmission layer and prevents the water entrance from the top of asphalt.
- DBM mix design and crust thickness are adjusted to achieve more flexibility as 80mm DBM 1st layer and 60mm top layer. DBM blending altered to achieve the maximum voids after secondary compaction. Instead of VG-30, using CRMB-55 in DBM layer is advisable to provide higher elastic recovery and enriches the flexibility with reduced moisture damage on base asphalt layer.
- Use of Geosynthatics as interlayer between DBM top & BC is prescribed. It ensures the distribution of tensile stress over larger area and act as the water retarding layer.
- Use of Polymer modified bitumen (PMB) in Wearing Course (BC) Layer is advised. Where PMB having the higher elastic recovery and greater sustain for moisture induced damage than CRMB in our tropical climates with heavy intensity of traffic volume with moisture damage factor.



R. CONCLUSION:

Based on the field and laboratory investigations, following conclusions were drawn:

Entire cracks observed in the project stretch are top-down cracks and Surface distress mechanisms of top-down cracks are entirely different from the bottom-up cracks. Traffic Load-induced stresses and strains, Quality of Binder & binder hardening, Environmental Conditions, Eccentric Loading are the probable causes of top-down cracking. In the case of bottom-up cracks the failure occurs due to Improper bond in below layer, clay in granular layers, excessive fines in asphalt mix, reduction in binder content, inconsistent temperature of asphalt mix and binder.

High surface horizontal tensile stresses due to truck wide-based tires and high inflation pressures are cited as causing the highest tensile stresses over the pavement. Moisture damage on top of asphalt layer is able to reduce about 30% of tensile strength. A reduction in strength accompanied by moisture damage makes the pavement prone to 'top-down' cracking. With increase in traffic volume and passage of time as well as infiltration of moisture, raveled areas can increase in size and depth TDC. This resulting the fatigue flexural distress on pavement in TDC mechanism.

On this high weather variation thermal stresses induced and results on contraction of the asphalt layer leads to variable pavement temperatures and the restraining force caused by the friction between the Asphalt and base layers and causes difference in temperature on bottom and top of the asphalt layer.

Higher thermal stress induced by low penetration binder cases high stiffness on upper portion of dense and thicker asphalt layer. To reduce the thermal stress on the surface of the asphalt layer the softer binder with penetration grade 80-100 or VG-30 with 60-70 mm penetration values are advisable in this tropical climate condition. This can able to prolong the fatigue life of asphalt layer and reduce the premature binder hardening.To enchancing the tensile strength and ensuring flexiblity of asphalt layer rubber modified binder are advised for DBM top layer.

Segregation of the asphalt mixtures in pavements may lead to premature distress, such as stripping, raveling, rutting, and longitudinal and fatigue cracking.

Refusal Density in mix design is an extension of Marshall paving design method and it ensures that secondary compaction due to trafficking which is not consider in MORTH specfication.Hence to avoid premature cracking asphalt design includs refusal density is recommended with allowable VA in maximum compaction should not less than 3% and VMA 16% in standard compaction.

The nature of DBM layer surface is non-viscous and hence stiffer and more brittle it elevated tension stress on the tire edges and cause top down cracking in 160mm thicker pavement design. so there is necessity to come up with open graded or gap graded mix such as BM without complying volumetric parameters for first layer to increase the pavement flexibility.

Currently no pavement design method prescribed by IRC -37, AASHTO or any other standards is capable of predicting or analyzing tensile stress on top surface of asphalt, top-down cracking potential and also not tagging with the material properties. New pavement design integrating with site material properties and present distressing mechanism should be adopted.

Unpredicted additional load intensity with almost double times more than equivalency load factor to the standard axle loading calculated as per design is applied to our project stretch even though the pavement structure is incomplete this is the frontrunners for high inflation eccentric loadings. In high traffic intensity loads the tire-pavement contact stress is non-uniformly distributed in a noncircular area.

The entire project stretch are lies on the heavy water logged area and meeting the high rainfall intensity because the moisture damage on the pavement and capillary action beneath the pavement leads the pavement distress on grand potential of traffic volume. Hence proper means of capillary cut-off is advisable.

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