

**Mississippi Department of Transportation** 

In Cooperation with the US Department of Transportation Federal Highway Administration

# A Synthesis Study of Noncontact Nondestructive Evaluation of Top-down Cracking in Asphalt Pavements

# FINAL REPORT UM-CAIT/2013-01

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#### Center for Advanced Infrastructure Technology The University of Mississippi Carrier 203B, University, MS 38677-1848, USA Voice: 662-915-5363 Fax: 662-915-5523 http://www.olemiss.edu/projects/cait/Index.html cait@olemiss.edu

**CAIT Project Director and PI:** Waheed Uddin, Ph.D., P.E.

Professor and Director CAIT

Department of Civil Engineering

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Illinois, and Mississippi. Pro	per and timely maintenan	ce of top-down	cracking is critic	cally important for
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without depending on cores.	An existing viable nonde	structive and no	oncontact techno	logy operating at
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#### ABSTRACT

The primary objective of this research study was to conduct an extensive literature review on top-down cracking evaluation studies, prepare a synthesis of findings, and recommend a follow up phase for a pilot study in Mississippi with a candidate technology. The top-down cracking appearing mostly in longitudinal wheel paths on asphalt highway pavements, was first reported in the 1970s in tropical countries, later reported in the 1980s in the UK, the Netherlands, France and South Africa, followed by field investigations in the late 1990s and 2000s in the United States, several European countries, and Japan. Since then the top-down cracking distress has been identified as the most important distress observed on asphalt highways in many states including Florida, Indiana, Michigan, Washington, Illinois, and Mississippi. Proper and timely maintenance of top-down cracking is critically important for thick asphalt pavements. Therefore, a procedure is needed to expedite field survey of top-down cracking without depending on cores. An existing viable nondestructive and noncontact technology operating at highway speed was not found in this study. Therefore, a problem statement for research need is prepared for a national study through NCHRP.

#### ACKNOWLEDGEMENTS

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This report is authored by Waheed Uddin, the Principal Investigator of State Study 255, with the assistance of doctoral student Zul Fahmi M. Jaafar and other CAIT research assistants.

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# **TABLE OF CONTENTS**

TITI	LE PAGE		
TEC	HNICAL	REPORT DOCUMENTATION PAGE	i
ABS	TRACT.		ii
ACK	NOWLE	EDGEMENTS	iii
DISC	CLAIME	R	iii
TAB	LE OF C	CONTENTS	iv
LIST	OF TAE	BLES	v
LIST	OF FIG	URES	v
1.	INTRO	DUCTION	1
	1.1	Problem Statement	1
	1.2	Background	1
	1.3	Objective	2
	1.4	Research Methodology	3
2.	LITERA	ATURE REVIEW AND SYNTHESIS	5
	2.1	Literature Search Process	5
	2.2	Personal Contacts	6
	2.3	Synthesis of Literature Review	6
	2.4	Summary	17
3.	CANDI	DATE NONCONTACT TECHNOLOGY FOR TDC SURVEYS	18
	3.1	Background on Remote Sensing Applications	18
	3.2	Nondestructive Technologies Used for TDC Evaluation	19
	3.3	Synthesis of GPR Studies	23
	3.4	Candidate Noncontact Technology for TDC Surveys	25
4.	SUMM	ARY, CONCLUSIONS AND RECOMMENDATIONS	27
	4.1	Summary	27
	4.2	Conclusions	27
	4.3	Recommendations	28
5.	REFER	ENCES	30
APP	ENDIX .	A: Tech Memo on Synthesis of Selected TDC References	<b>A-</b> 1

# LIST OF TABLES

Table 1.	Summary of key data sources based on selected references on TDC research	8
Table 2.	Candidate nondestructive test equipment for TDC evaluation on	
	asphalt pavements	24

# LIST OF FIGURES

# Page

Page

Figure 1.	Evidence of top-down cracking in a core extracted from an	
	asphalt highway pavement	1
Figure 2.	Stress and strains developed through the asphalt pavement layer subjected to	
	heavy load on the surface of an asphalt highway pavement	2
Figure 3.	Crack detection using cores (after [7])	4
Figure 4.	Chronological history of TDC distress knowledge base	7
Figure 5.	Cores exhibiting TDC, extracted from thick asphalt highway pavements	
	in Portugal, summer 2003 (Photos by Uddin at the University of Minho's	
	asphalt laboratory, courtesy of E. Freitas) 1	6
Figure 6.	Electromagnetic spectrum (after [38]) 1	18

# **1. INTRODUCTION**

## **1.1 Problem Statement**

The research study addresses surface cracking distress on asphalt highway pavements, which is a potential issue in Mississippi, other states, and many European countries. It is important to identify and quantify top-down cracking for implementing appropriate maintenance intervention policies. The top-down cracking phenomenon is the focus of this proposed study.

#### **1.2 Background**

Top-down cracking (TDC), generally observed in the wheel path of thick asphalt highway pavements, has been identified as an important surface pavement distress in many studies over the last decade. It starts from the surface and propagates downward, which is different from the well-known fatigue related bottom-up cracking. Figure 1 shows TDC to partial depth through a core. This core was extracted on SR 25 asphalt pavement in Leake County, a state highway in Mississippi [1].



Uncracked core from asphalt pavement



Top-down cracked core from the same asphalt pavement

# Figure 1. Evidence of top-down cracking in a core extracted from an asphalt highway pavement

Tensile strains and stresses induced by heavy truck traffic loads are the primary mechanisms for both types of cracking, as shown in Figure 2 [2]. A layered elastic analysis shows tensile strains develop at the outer edge of contact loading area, which may initiate TDC at the surface. Surface asphalt resistance to tensile strains and stresses is degraded due to added interaction of traffic loads with binder aging, temperature gradient, and segregation in the top part of the surface asphalt layer [3, 4, 5, 6].



# Figure 2. Stress and strains developed through the asphalt pavement layer subjected to heavy load on the surface of an asphalt highway pavement

Top-down cracking in asphalt pavement has been reported in Florida and other states including Michigan, Colorado, Louisiana, Wisconsin, Indiana, Ohio, Minnesota, Pennsylvania, Washington, and Mississippi. Proper, timely maintenance of top-down cracking is critically important for perpetual pavements. Therefore, a procedure is needed to expedite field surveys of top-down cracking during condition surveys of pavement assets at the network level without depending on cores.

#### 1.3 Objective

The primary objective of this research study is to conduct an extensive literature review on topdown cracking evaluation studies, prepare a synthesis of the findings, and recommend a follow up phase for a pilot study in Mississippi with a candidate technology. If a viable noncontact highway speed technology is not found, then a problem statement for research need will be prepared and submitted for a national study through NCHRP. The proposed research provides state-of-the art reviews, findings, and recommendations to address the issue of top-down cracking evaluation at highway speeds. A viable high-speed method, as a part of pavement condition survey, will help in enhancing pavement asset management. Appropriate maintenance and rehabilitation treatments for areas with top-down cracking may not be the same as those used for traditional fatigue-distressed asphalt highway pavement. This will affect overall maintenance cost and performance of highway pavements.

#### Detection of TDC in Field

The European Cooperation in Science and Technology (COST) Research Report 336 states a core-based approach to identify these crack types [7].

"Cores cut for the backcalculation process will also provide information about the type and condition of the asphalt layers and provide an indication of the adhesion between the layers. The cores are sometimes used for further material investigation. In cases where crack formation is visible at the pavement surface, additional cores will be cut on these cracks to determine if they are surface cracks or cracks over the full depth of the asphalt layer. Unfortunately, it is not possible to take cores specifically in places where crack formation has occurred solely at the bottom."

Figure 3, taken from the COST 336 Report, illustrates that by analyzing a line of cores extracted close together, attempts can be made to identify whether the cracks originated at the bottom or at the top of the asphalt layer.

#### **1.4 Research Methodology**

The following research methodology is followed to produce the required deliverables that address the top-down cracking problem:

- Comprehensive worldwide literature review of journal papers, reports, and online/internet sources on top-down cracking studies and use of field methods.
- Personal contacts by email and telephone to pavement researchers and organizations actively pursuing asphalt pavement performance and condition surveys.

- Review of nondestructive noncontact technologies used for pavement condition evaluation which are potential contenders for top-down cracking surveys at highway speed.
- Synthesis of all literature review and related information from personal contacts.
- Recommendations based on the state of knowledge related to top-down cracking survey methods and equipment.

It is important to identify and quantify top-down cracking for implementing appropriate maintenance intervention policies for thick asphalt highways including perpetual pavements.



Figure 3. Crack detection using cores (after [7])

## 2. LITERATURE REVIEW AND SYNTHESIS

#### 2.1 Literature Search Process

An exhaustive search was undertaken to access all possible research papers and reports related to laboratory and field studies on top-down cracking conducted in the United States, Canada, European countries (the UK, the Netherlands, France, Portugal, Spain, and Italy), and Japan. The following sources were used in literature search and personal contacts were made with researchers and nondestructive test equipment manufacturers:

- Internet searches (Google, Google Scholar, Scribd).
- Online library sources: Transportation Research Board (TRB) library, online integrated Transportation Research Information Database (TRID) that combines over 900,000 records worldwide from TRB's Transportation Research Information Services (TRIS) and the OECD's Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database.
- TRB publications, including the Transportation Research Record (TRR), Transportation Research Circulars, web documents, and reports and syntheses prepared for the National Cooperative Highway Research Program, the Strategic Highway Research Program (SHRP), and SHRP2.
- U.S. Department of Transportation (DOT): Federal Highway Administration (FHWA).
- Long-Term Pavement Performance (LTPP) and Datapave links from FHWA and TRB.
- State DOTs and other state highway agencies and their publications.
- University Transportation Centers (UTCs) and related graduate dissertations.
- European Union (EU) initiatives including relevant COST transportation research reports.
- Research reports of UK's Transportation Research Laboratory and the Japanese Construction Ministry/Public Works Research Institute.
- Proceedings of international asphalt pavement conferences and journal papers.

In performing the literature review, contacts and/or web access were made with the research agencies in the U.S. and abroad (UK, Portugal, France, Spain, and Japan), industry groups, pavement websites, and international conferences on asphalt/bituminous pavements.

Additionally, graduate student staff assisted in Web searches using the common internet search engine Google.

#### **2.2 Personal Contacts**

Personal contacts were made with acoustics/lasers researchers of the National Center for Physical Acoustics (NCPA) at the University of Mississippi to identify any prior application developed for the Army and the Department of Defense (DoD) using remote sensing laser and acoustic technologies for identifying anomalies below pavement surface. None of these technologies appear to remotely map cracking depth in the asphalt layer.

As the Chief Editor of the *International Journal of Pavements (IJP)*, the author has maintained the personal contacts with lead pavement researchers, noncontact pavement evaluation equipment manufacturers, and industry professionals in the U.S. and 16 other countries including UK, Portugal, Greece, Japan, China, Malaysia, New Zealand, and Brazil. Other personal contacts of the author with the Pavement Specialist group of universities in Portugal, Holland, and UK were pursued. Their inputs were solicited. E-mail communications and telephone interviews were used to obtain additional information as needed on the current TDC research and evaluation practices.

During 2011, the author attended the 5<sup>th</sup> International Conference on Bituminous Materials and Pavements (ICONFBMP) in Thessaloniki, Greece, in June (attendees from 36 countries). In summer of 2012, the author participated in the 7<sup>th</sup> international pavement conference on Maintenance and Rehabilitation of Pavements and Technological Control (MAIREPAV7) in New Zealand. Both trips were made at no cost to the project. This provided excellent opportunities to explore and discuss on-going research in top-down asphalt cracking evaluation technologies. The author is also a member of the experts from the U.S. who were in the team led by "Roma Tre" University in Italy that was awarded COST Action TU1208 project on applications of ground penetrating radar in civil engineering (http://www.gpradar.eu/).

#### 2.3 Synthesis of Literature Review

#### Overview of TDC Research until 2000s

Hundreds of papers, reports, and web documents were scanned and reviewed for direct relevance to the study objectives. Selected references [3-36] from 1980s through, 1990s, 2000s, and 2011-

2013 were studied in detail. Figure 4 shows a chronological history of top-down cracking research worldwide. A summary of key topics studied in some of these references [3-47] is provided in Table 1. A structured summary of selected references is included in the Appendix that includes: abstract, objectives, research methodology, summary of work accomplished, and key results.

Years	Continents	Countries	Source of Reports
1970s	Africa	Kenya (Tropical Climate)	[3] TRL/ Rolt (2000)
1980s	Europe	United Kingdom (UK)	[3] TRL/ Rolt (2000)
	Europe	France	[8] Dauzats and Linder (1982)
	Europe	The Netherlands	[12] Gerritsen et al. (1987)
	Africa	South Africa	[10] Hugo et al. (1982)
		·····	
1987-1989	North America	USA SHRP: Long-Term Paveme	ent Performance (LTPP) Study Started
		(No TDC reported or considered	d in experiment design and condition data plans)
1990s	Asia	Japan	[4] Matsuno and Nishizawa (1992)
	North America	USA - California	[16] Craus et al. (1994)
	North America	USA - Florida	[5] Myers et al. (1998)
	Furope	Portugal	[19] Freitas et al. (2003)
20005	North America	USA - Washington State	[6] Uhlmever et al (2000)
	North America	USA – Michigan	[18] Svasdisant et al. (2000)
	North America	USA - Indiana	[25] Pellinen et al. (2004)
	North America	USA - Colorado	[27] Hermelink et al. (2008)
	Asia	Japan	[14] Taniguche et al. (2009)
2010-	N		
2010s	North America	USA SHRP – LTPP and SHRP 2 over 1,000 in-service pavement	<b>Studies on-going</b> (No TDC reported for sections in USA and Canada, Sep 2013)
		·····	
2012-2013	North America	USA - Mississippi	MDOT SS255 Project

# Figure 4. Chronological history of TDC distress knowledge base

Figure 4 shows that unlike Europe, TDC was not on the radar screen of pavement researchers and highway agencies in the United States until the late 1990s. Two international conferences on

the structural design of asphalt pavements (1982 in the Netherlands and 1987 in the United States at Ann Arbor, Michigan) included papers reporting TDC investigations during the 1980s, which were presented by researchers from the UK, the Netherlands, France, and South Africa. The author attended the 1987 conference and was extensively involved in field studies of pavement performance from the mid 1980's to 1989, performed investigations of early failures, and examined numerous asphalt pavement cores from Oklahoma, Texas, Arizona, and later in Mississippi throughout most of the 1990s. No core was observed with any evidence of TDC. Generally, cores were not extracted from areas of visible surface cracks.

Table 1. Summary of key data sources based on selected references on TDC research

						2	,			
No.	Ref	Year	Title	State/ Country	Publisher/Source	NDT	Lab	Field	Case Study	*
1	[3]	2000	Top-Down Cracking: Myth or Reality	UK	TRL	No	Yes	No	Yes	No
2	[4]	1992	Mechanism of Longitudinal Surface Cracking in Asphalt Pavement	Japan	7th International Conference on Asphalt Pavements, University of Nottingham	Yes	Yes	Yes	Yes	Yes
3	[5]	1998	Mechanisms of Surface- Initiated Longitudinal Wheel Path Cracks in High-Type Bituminous Pavements	United States	Paper, Journal of the Association of Asphalt Paving Technologists, Florida	Yes	Yes	Yes	Yes	Yes
4	[6]	2000	Top-down Cracking in Washington State Asphalt Concrete Wearing Course	United States	TRR 1730 Paper Washington State	Yes	Yes	Yes	Yes	Yes
5	[8]	1982	A Method for The Evaluation of The Structural Condition of Pavements with Thick Bituminous Road Bases	France	Fifth International Conference on The Structural Design of Asphalt Pavements, The Netherlands	Yes	Yes	Yes	Yes	Yes
6	[9]	1982	Aspects of the interpretation and evaluation of falling weight deflection measurements	The Netherlan ds	Fifth International Conference on The Structural Design of Asphalt Pavements, The Netherlands	Yes	Yes	Yes	Yes	Yes
7	[10]	1982	Four Asphalt Pavement Case Studies Using a Mechanistic Approach	South Africa	Fifth International Conference on The Structural Design of Asphalt Pavements, The Netherlands	Yes	Yes	Yes	Yes	Yes
8	[14]	2009	Three-Dimension Diagnosis of Pavement Damage Using CT Scanner	Japan	Public Work Research Institute and Hokkaido University	Yes	Yes	Yes	Yes	Yes
9	[17]	2001	Propagation Mechanisms for Surface-Initiated Longitudinal Wheel Path Cracks	United States	Sponsor: Florida Department of Transportation (FDOT) and FHWA	No	Yes	No	No	Yes

NDT=Nondestructive testing \* Numerical Analysis

10	[18]	2003	Mechanistic Analysis of Top- Down Cracks in Asphalt Pavements	United States	TRB Paper Sponsor: Michigan MDOT	Yes	Yes	Yes	Yes	Yes
11	[19]	2003	Assessment of Top-Down Cracking Causes in Asphalt Pavements	Portugal	University of Minho and University of Coimbra	No	Yes	No	No	No
12	[20]	2005	Effect of Construction Quality, Temperature, and Rutting on Initiation of Top- Down Cracking	Portugal	University of Minho and University of Coimbra	No	Yes	No	No	Yes
13	[21]	2002	Mechanistic Analysis of Top- Down Cracks in Asphalt Pavements	United States	Sponsor: Michigan Department of Transportation (MDOT)	Yes	Yes	Yes	Yes	Yes
14	[22]	2003	Micro-Mechanic Study on Top-down Cracking	United States	Louisiana State University	No	Yes	Yes	No	Yes
15	[23]	2006	Evaluation and Mitigation of Asphalt Pavement Top-Down Cracking	China and Colombia	Annual Conference, Transportation Association of Canada Charlottetown, Prince Edward Island	No	No	Yes	Yes	No
16	[24]	2008	Analysis of Shear Stress in Asphalt Pavements Under Actual Measured Tire- Pavement Contact Pressure	Japan	6th ICPT, Sapporo	No	Yes	No	No	Yes
17	[25]	2004	Evaluation of Surface (Top- down) Longitudinal Wheel Path Cracking	United States	Sponsor: Indiana Department of Transportation	Yes	Yes	Yes	Yes	Yes
18	[26]	2004	A Model for Top-Down Reflection Cracking in Composite Pavements	UK	TRL	No	Yes	Yes	Yes	Yes
19	[27]	2008	Top-Down Cracking in Asphalt Pavement: Causes, Effects, and Cures	United States	Sponsor: Colorado Department of Transportation	No	Yes	No	Yes	No
20	[30]	2008	Analysis of Top-Down Cracking Behavior of Asphalt Pavements	India	Indian Institute of Technology, Kharagpur	No	Yes	Yes	No	Yes
21	[31]	2010	Multi-Domain Hybrid Boundary Node Method for Evaluating Top-Down Crack in Asphalt Pavements	China	Huazhong University of Science and Technology, Wuhan	No	Yes	No	No	Yes
22	[33]	2003	Effects of Segregation on the Initiation and Propagation of Top-Down Cracks	United States	TRB Paper Michigan DOT	No	Yes	Yes	Yes	No
23	[34]	2013	Achieving Sustainability Without Compromising Long – Term Pavement Performance for Road Infrastructure Assets	United States	2013 IJPC, Sao Paulo, University of Mississippi	No	Yes	No	No	No
24	[40]	2006	MDOT: Ground Penetrating Radar Study – Phase 1: Technology Review and Evaluation	United States	Final Report: FHWA- MS-DOT-RD-06-182	Yes	Yes	Yes	Yes	Yes
25	[43]	2005	Evaluation of Top-Down Cracks in Asphalt Pavements by Using a Self-Calibrating Ultrasonic Technique.	United States	University of Minnesota	Yes	Yes	Yes	No	No

26	[44]	2010	A Study of GPR Vertical Crack Responses in Pavement Using Field Data and Numerical Modelling	Italy	Institute of Electrical and Electronics Engineers (IEEE), Lecce	Yes	Yes	Yes	No	Yes
27	[45]	2013	Development of High-Speed Ultra Wideband Ground- Penetrating Radar for Rebar Detection	United States	Sponsors: U.S. DOT and NIST	Yes	Yes	No	No	Yes
28	[47]	2013	SHRP2: Nondestructive Testing to Identify Delamination Between HMA Layers	United States	TRB Report	Yes	Yes	Yes	Yes	Yes

#### Historical Overview of Early TDC Research Studies Outside the United States

According to Rolt [3] top-down cracking on asphalt pavements was discovered in the late 1970s in UK's Transportation Research Laboratory (TRL) research, as summarized here. Initially, the severity of this phenomenon was ignored by most of the engineers, who did not even discuss this type of distress and claimed that it happened in countries with tropical climates only. The TRL engineers had initiated possible solutions to prevent this cracking problem. From 1973 to 1977, the first asphalt performance study was carried out on eight different sites with varying climatic conditions. The original objective was to produce a design specification for more durable asphalt overlays between 30 and 170 mm thick in tropical environments. The performance monitoring of the asphalt layer was carried out, focusing on the severity of asphalt rutting, cracking and deflection. An extensive number of cores were cut to study crack pattern in detail. The early findings showed that some cracks started from the top and propagated downwards. Other cracks occurred from the bottom and spread upward. The critical radial stresses were experienced at the lower side of asphalt layer. It was noted that the width of those cracks that started at the top decreased with depth until it was very thin and almost impossible to view. The crack could possibly propagate to the full depth after a longer performance period. The properties of recovered bitumen were assessed periodically, and it was found that rapid age hardening occurred on most of the experimental sections. The viscosity of recovered bitumen reduced as the layer depth increased. This report highlighted that the hardened asphalt is the key component in cracking mechanism. Nonetheless, about 25% of the study area surveyed showed no cracks throughout eight years of study period.

The second study by TRL was conducted during 1978-1983 involving in-service sections and laboratory investigations. The objective was to provide a better understanding between asphalt

material properties and bitumen aging. To investigate the aging, asphalt slab were manufactured in a laboratory and exposed to the field environment for 24 months. The slabs were fabricated with a variety of mix compositions and variables. Some blocks were coated with a surface dressing to reduce aging rate on the top of the asphalt mix. After certain periods of exposure, the blocks were tested using a gamma-ray scanner to measure the density of the blocks as a function of depth. The results from the mathematical model relating age and mix variables showed that after 24 months, bitumen viscosity in the top 3 mm section increased by a factor range of 200 -500. The increased viscosity was strongly related to the degree of aging in the mix. The air voids, bitumen, and filler content affected the viscosity by factor between 1 and 3 based on the variables studied. The final findings proved that under hot tropical conditions, regardless of the bitumen grades, the aging will happen as the duration increases. In countries with pavement temperatures 8°C lower, hardening was approximately 33% of the warmer climate [3].

Similarly, TDC deterioration in the 1980s was also reported on highways in France, the Netherlands, and South Africa at the Fifth and Sixth International Conferences on the Structural Design of Asphalt Pavements [8, 9, 10, 11, 12]. A recent presentation by Rolt [13] reviews the latest progress associated with longer life pavement research in the UK and steps taken to address TDC initiation and propagation mechanisms.

A detailed field investigation and numerical study of TDC in 1992 conducted in Japan was reported during the 7<sup>th</sup> international conference on asphalt pavements held in the UK [4]:

- Surface-initiated cracking of the asphalt wearing course in the longitudinal direction was commonly observed within 5 years after construction, but it did not extend in shaded areas under overpasses.
- Second, structural response analysis results showed that very high tensile strains occur at the edge of truck tires at or near the surface of the asphalt wearing course.
- These high strains occur when the upper portion of the asphalt layer shows a lower stiffness due to high surface temperatures.
- A prominent effect of thermal gradient in the top asphalt wearing course is a contributing factor for degradation of surface asphalt layer, making it more susceptible to TDC initiation.

Further, the recent field studies and laboratory investigations used a computed tomography (CT) scanner for multiple X-ray images in Japan [14]. The of numerical analysis results indicated that a higher level of tensile strain at a depth below the pavement surface is calculated in the asphalt, which can lead to cracking initiated from within the asphalt layer and propagating to the surface. The lead author, Taniguchi of Japan's Public Works Research Institute, states in an email to the author on September 28, 2013:

"This paper concluded that longitudinal cracking occurred from not the surface or bottom but within pavement. Standard specifications for Pavements (JSCE, 2007) indicate that design for top-down cracking is the same design as the design for fatigue cracking. Sealing is used as an emergency measure, and milling and overlay is used as a drastic measure in the site."

#### No Reports of TDC During SHRP-LTPP Studies

The Strategic Highway Research Program started in 1987 in the United States. Over 1,000 pavement sections with majority on asphalt highways were selected for the LTPP studies. The author served as the lead materials engineer with the LTPP technical assistance team during 1987-89. No TDC distress was discussed during the LTPP planning meetings, pavement section selection, initial inventory and condition database creation, and later on during the 20 years of monitoring phase all over the United States. TDC was not considered at the time of finalizing the experiment design and selecting in-service highway pavement sections in early years of the LTPP project. The occurrence of TDC was not reported anywhere in the United States to the best of available knowledge.

The author had been a key member of FHWA-ASCE team from the mid-1990s to mid-2000s that developed the annual Datapave contest for university graduate students. Several graduate students, advised by the author, from the University of Mississippi explored the LTPP-Datapave database for their research papers. No TDC data was found in the LTPP database. It would have been beneficial if some sections in selected states would have been cored for diagnostic evaluation before some of these pavements had overlays or milling and inlays due to excessive surface distresses. During the current study, the author and his graduate students explored the online LTPP database in the summer of 2013 for the southern region and found no TDC data.

Email communications with the FHWA's LTPP contact person revealed that no TDC data is present in the current LTPP database.

#### TDC Studies in the United States and Other Countries

In the United States, top-down cracking was discovered in the late 1990s [5, 6, 15, 16]. During the 2000s, a lot of research closely related to American Association of State Highway and Transportation Officials (AASHTO) pavement design had been carried out in several states including California [16], Florida [5, 17], Washington [6], Michigan [18, 21], Indiana [25], Colorado [27], and Illinois [28]. Top-down cracking has been assumed to start from the top of the surface by most researchers in Europe and the US [3, 5-15]. However, Japanese investigators reported that TDC occurred somewhere from the middle of the asphalt layer [4, 14]. Wang, et al., [22] reported similar findings in Louisiana and stated that a mix sensitive to rutting will probably also be sensitive to TDC.

Uhlmeyer, et al. [6], in a study for the Washington State Department of Transportation, discovered that thick asphalt concrete was also susceptible to top-down cracking. The authors concluded that top-down cracking would randomly stretch, especially for asphalt layers with thicknesses surpassing 160 to 180 mm. The observed performance years before the TDC occurred varies from 1 to 5 years (Japan), 3 to 5 years (France), 5 to 10 years (Florida) and up to 10 years for the UK. Uhlmeyer, et al. [6] noted that top-down cracking occurred typically 3 to 8 years following construction of pavement sections that satisfy structural requirements and were designed for acceptable equivalent single-axle loads.

The Michigan Department of Transportation published a report in 2003 based on their sponsored comprehensive TDC evaluation project [18, 21]. Based on laboratory tests, cores, and mechanistic analysis, the authors concluded that the TDC was caused by tensile stresses and strains induced at the top of the pavement structure. The interactions of traffic load, temperature, and hardening of asphalt binder caused shrinkage and stiffness variations between the asphalt surface, leveling, and base courses [21].

A study, sponsored by the Indiana DOT, evaluated three surface cracked pavements during 2002 and 2003 [25]. The depth of the crack was approximately 20 mm from the surface based on visual observations. A three dimensional (3D) X-ray tomography (CAT scanning) was

performed on cracked cores to evaluate the path and mechanism of crack propagation in the pavement. The results of the crack depth from the imaging analysis were compared with the visual observations. Further 3D imaging analysis was conducted at the FHWA's Turner Fairbank Highway Research Center (TFHRC) with the Simulation, Imaging and Mechanics of Asphalt Pavement (SIMAP) program. The image analysis results indicated that the crack on the top of the core did not penetrate deeper than the surface layer, which agreed with the visual observations. The authors' conclusions included the following key findings [25]:

- Most TDCs were located just outside the wheel path and progressed in three stages.
- TDCs were caused by high surface tensile stresses induced by traffic loads and were enhanced by temperature, aging of the asphalt binder, construction material quality, temperature gradient, and compaction effort.
- The magnitude of the surface tensile stress increases as:
  - The ratio between the asphalt surface course to the asphalt base course moduli increases
  - $\circ$  The base layer modulus increased in stabilized or rubblized bases
  - The thickness of the asphalt layer increased in pavements with high base layer modulus
  - The thickness of the AC layer decreased in pavements with conventional aggregate bases.
- The aging of the asphalt binder caused a reduction in the tensile strength and strain at the failure point of the asphalt mix.

In a follow-up study the Michigan researchers reported segregation of asphalt mix as another contributing factor to TDC distress [33].

Other countries where extensive TDC failures have occurred include Portugal [19, 20], India [30], China [31], and Malaysia as observed by the authors of the 2013 International Journal of Pavements Conference (IJPC) paper [34]. Many European countries have reported this asphalt pavement distress, and it is listed as the most significant distress, in the recent European study of climate change impacts on asphalt road pavements in regions north of the Alps [35].

#### Importance of TDC Consideration in Pavement Design and Construction Process

Top-down cracking on thick (4 inch or more) asphalt/bituminous layers may become a critical failure mechanism. This means that stresses and strains at the pavement surface (top of the bound asphalt layers) may cause cracking in the pavement layer that begins at the top of the surface layer. This cracking is distinct from traditionally recognized bottom-up fatigue cracking and environmentally induced cracking caused by climatic factors. Most existing asphalt pavement design methods consider conventional bottom-up fatigue cracks, which initiate at the bottom of the asphalt layer and propagate upwards. Thickness design methods generally do not consider top-down cracking initiation and growth.

Project 1-42 of the National Highway Cooperative Research Program (NCHRP) investigated mechanisms and performance prediction models of top-down cracking [36] based on hot mix asphalt material parameters for integration with the Mechanistic-Empirical Pavement Design Guide (MEPDG).

Another factor that may have contributed in accelerated binder aging and consequently the TDC distress is the introduction of recycled asphalt pavement (RAP). This will accelerate binder aging in the surface layer leading to accelerated deterioration of asphalt pavements on heavily trafficked roads as it uses aged binder in the mix. Since the adaptation of Superpave asphalt material specifications by most US highway agencies in the 1990s, the effective asphalt binder content has been reduced already in hot mix asphalt (HMA) compared to the asphalt contents designed using the traditional Marshall method. RAP has been implemented in asphalt highway paving projects since around that time. Generally, RAP is specified in the amounts of 10% (e.g., Mississippi DOT) to 20% (Washington state DOT) of design asphalt content, and even more if the contractor does the mix design and shows the right binder blend to meet Superpave performance tests [37].

The intention of using RAP from sustainability considerations has been good because there is less demand for raw materials. However, possible adverse impacts of mixing of aged binder on long-term pavement performance have not been thoroughly studied. What if the TDC and other surface distresses are caused by a reduction in asphalt binder content in the top layer and faster binder aging due to the mixing of aged binder from the RAP? Is the use of RAP leading to

accelerated deterioration of asphalt pavements on heavily trafficked roads? These issues must be given due consideration in pavement material research programs [34].

The Washington State DOT (WSDOT) reportedly feels that the vast majority of asphalt cracking on their highway network is top-down [37]. Many other states including Mississippi [1] are considering TDC as a significant distress on asphalt highways that needs to be evaluated during periodic condition surveys as a part of their asset management system.

# Need for Remote Sensing TDC Survey at Highway Speed

In most pavement studies, top-down cracking was first identified through visual distress surveys and visual observation of cores. Such was the case in the 2003 highway pavement research study in Portugal by University of Minho researchers [19], who cored through cracks and discovered top-down cracks that had propagated downward partially into the asphalt layer. The author observed this phenomenon for the first time at a tour of Minho's asphalt pavement research facility (Figure 5) during the 2003 MAIREPAV3 international pavement conference [19].



# Figure 5. Cores exhibiting TDC, extracted from thick asphalt highway pavements in Portugal, summer 2003 (Photos by Uddin at the University of Minho's asphalt laboratory, courtesy of E. Freitas)

A noncontact distress survey technology using a mobile platform and traveling at highway speed is needed for identifying and measuring extent/severity of the top-down cracking for networklevel condition survey of asphalt highways.

#### 2.4 Summary

In the recent 25 years, there has been an alarming increase of pavement distress related to topdown cracking in the longitudinal wheel path of asphalt pavements. Currently, TDC is a major asphalt pavement distress in Florida, Washington, Colorado, Michigan, and other states, as well as in many countries abroad. It has been a topic of frequent and continuing discussion between researchers worldwide, mostly focused on the roles of binder aging, segregation, thermal gradient within the surface asphalt layer in creating this distress. The cracking distress is further accelerated because of wheel loads and contact stresses. TDC identification in the field and consideration in pavement design methods are problematic compared to fatigue cracking that is assumed to initiate from the bottom of pavement system. Maintenance and rehabilitation programming for pavement asset management at the network-level can benefit tremendously if TDC evaluation is feasible as a part of network-level condition surveys.

## 3. CANDIDATE NONCONTACT TECHNOLOGY FOR TDC SURVEYS

#### 3.1 Background on Remote Sensing Applications

Remote sensing technologies used for nondestructive evaluation of pavement integrity can be classified in three broad groups based on the inherent energy source:

- Electromagnetic (EM) waves utilizing optical and thermal properties of test materials
- Acoustic methods based on sound waves and acoustic properties of test materials
- Stress waves based on mechanical energy source and stress wave propagation theory

The last two groups generally require contacts with the pavement surface. The EM methods include both passive sensors and active sensors [38]. The operating principles of these methods and their applications for pavement were reviewed, as well as several conference proceedings were scanned specifically for noncontact nondestructive detection of top-down cracking on asphalt pavements [38-56].

#### EM Methods

Figure 6 shows the electromagnetic spectrum [38]. The shorter wavelength on the left of UV band includes X-ray that has been used in pavement core investigations. The author has seen a recent medical use of UV sensors for highlighting veins in a patient's arm. Both UV and X-ray are active sensors because these EM waves are generated and the response from the test medium is measured and interpreted. Photos and imagery are passive sensors which measure reflections in the visible band.



about 10 nm for the extreme ultraviolet.

Figure 6. Electromagnetic spectrum (after [38])

Laser sensors are active sensors which emit light in near infrared (IR) band and are used for 3D terrain mapping [38]. EM waves in infrared (IR) band (1- 300  $\mu$ m wavelength), and waves in the radar band (0.3 – 1.0 million  $\mu$ m wavelength or 1 -3 GHz frequency) are useful for assessing surface and subsurface pavement deterioration.

#### Acoustic Methods

The acoustic method, based on sound waves, includes ultrasound sensor technology. These methods are discussed in detail by Uddin, et al. [38], but only limited work has been reported in literature related to TDC evaluation [43, 49]. The acoustic response is affected by aggregate, chip seal, and moisture on asphalt pavements.

#### Stress Wave Methods

The stress wave method uses a small mechanical impact on pavement surface, and the stress wave response is measured by seismic sensors placed on the test surface. These methods include impact echo (IE) methods, spectral-analysis-of-surface wave (SASW) tests, and rolling dynamic deflectometer equipment [38, 47, 51, 52, 53]. The data interpretation is the key in stress wave methods because the sensor data are analyzed using inverse procedure based on stress wave propagation theory. The wave theory assumes an elastic media with no discontinuity such as cracks. For the objective of this study these methods suffer from the "contact" limitation because an excitation mechanical force is needed and sensors are in contact with the pavement surface.

#### **3.2 Nondestructive Technologies Used for TDC Evaluation**

Recent studies have used X-ray and CT scan technology for laboratory evaluation of cores extracted from cracked pavement including top-down cracks [25]. These methods are not feasible for network-level condition surveys because of radiation related safety regulation.

Top-down cracking has been a subject of intensive laboratory research using acoustic methods in the United States [43] and in Spain [49]. The ultrasonic test method at the Minnesota Road Research Project test facility used high-frequency (greater than 20,000 Hz) piezoelectric transducer sound wave generator to characterize the properties of materials or detect their defects [43]. The researchers in Spain [49] used an ultrasonic low-frequency short-pulse device with dry point contact transducers without the need for any special surface preparation. This is a nondestructive, inexpensive and easy-to-implement technology. The laboratory tests indicated successful measurement of the depth and extent of top-down cracking by means of ultrasonic techniques using different bituminous mixtures, pavement thicknesses and crack depths [49].

However, at the current state of practice both acoustic and stress wave technologies are not suitable for TDC survey applications at highway speeds.

Laser mapping of the pavement surface has evolved as a well-established condition survey technology where laser sensors scan the pavement surface and provide accurate 3D pavement surface maps. However, its use to measure surface cracks is still in the research phases [54, 55] and it has been reported to measure only cracks wider than 2mm [54]. A recent enquiry with the Florida DOT pavement evaluation engineer [56] indicates that this top-down cracking problem is an extensive research topic. Noncontact laser technology has been utilized by the Florida DOT in efforts to provide on site evaluation of top-down cracking, but was not successful [56]. A recent contact with pavement researchers in France [57] did not find any highway-speed equipment developed for measuring cracking depth in the asphalt layer or any related research in progress.

#### Principles of GPR Testing for Pavement Evaluation

A ground penetrating radar (GPR) survey is most frequently conducted by recording EM wave reflection profiles. A lower operating frequency of 1 GHz penetrates deeper than a higher frequency of 2 or 3 GHz. For network-level pavement applications at highway speed, air-coupled horn antennas are mounted on a holding bracket attached with the front bumper of the survey vehicle. The elevated antenna off the ground also reduces antenna-ground and antenna-target interactions, which result in lesser antenna clutter. The various components of a GPR system have been studied by the author including Mississippi DOT's SS110 project [39] and SS182 project [40]. The following excerpt is from Reference 40.

"A typical GPR system consists of the following components.

- Antenna (Transmitter/Isolator/Receiver)
- Data acquisition /Signal processor computer and software
- Scanned image display
- Data interpretation software

• Data processing software integration with DMI, GPS, and video or digital image (typically required with air-coupled antenna/GPR systems for pavement applications)

The function of the transmitter is to generate a known waveform. The name "short pulse radar" is derived from the fact that the transmitted waveform of such a system is actually a very narrow pulse, which typically might last on the order of one-billionth of a second. Such a short pulse is necessary to improve the ability of the radar to distinguish smaller objects and features under the ground. During the transmit cycle, the isolator provides a direct path from the transmitter to the antenna. The antenna serves two functions. First, it provides a smooth electromagnetic transition from the transmitter to the ground. The second function of the antenna is to direct the radiated electromagnetic energy into the ground in a desirable pattern. The antenna is designed so that the great majority of the radiated energy is directed into the ground and very little is radiated in other directions.

The electromagnetic wave transmitted by the antenna travels in the radiated direction until it strikes a discontinuity in the electromagnetic properties of the media. A portion of the wave passes through the discontinuity and a portion is scattered or reflected in other directions away from the discontinuity. Such a discontinuity is almost always associated with a material change in the media. The first such discontinuity is associated with the air-ground interface. At this interface, a portion of the incident wave is scattered back away from the ground and a portion propagates into the ground. Next, the wave traveling within the ground strikes the next discontinuity (pavement-base interface or pavement void area). Again, a portion of the incident energy is reflected away from the discontinuity, with the remainder continuing in the downward direction. The portion of the wave reflected by the discontinuity (void under pavement) forms the basis for target detection and assessment.

The GPR antenna can be mono-static (the same antenna transmits and receives) or bi-static that contains two antennas, one transmitting and one receiving antenna. Most commercial antennas used for non-invasive GPR applications on highway pavement are bi-static. The receiving antenna collects the electromagnetic energy in the return reflection, or echo, and delivers it to system receiver and sampler. The receiver captures weak target signals and amplifies them for subsequent processing. The receiver typically gates, filters, mixes, and samples the incoming signals to shift the incoming waveform to a desired frequency band and to reduce the signal contamination produced by electrical noise and reflections (called "clutter") from objects that are not of interest to the radar operator. Of the two primary signal contaminants, noise and clutter, clutter is the more severe in typical ground-penetration applications and is the principal limitation of the radar system's ability to detect faint target echoes caused by moisture or temperature effects.

Following signal reception, the output of the receiver is then passed to the signal processor which extracts the desired information from the received signal. The final radar system component in the field is the display, which presents the information contained in the radar return signal in an appropriate format for interpretation by the operator. Detailed radar scanned data interpretation is performed in the office using a stand-alone data interpretation software for structural assessment of pavements and to determine layer thickness and other desired properties."

The EM waves in the frequency range of 1-3 GHz (used currently in most commercial GPR equipment) can penetrate asphalt layers. It is a proven noncontact nondestructive method for asphalt layer thickness assessment at highway speed [40]. Thermal imaging by IR sensors is particularly useful if combined with a GPR survey. Both of these survey results at highway speed were conducted on US Highway 78 pavement in Marshall County, Mississippi, and their scan data interpretation confirmed the surface cracks and voids beneath the concrete pavement [39].

# 3.3 Synthesis of GPR Studies

## NCHRP Studies

The following NCHRP reports evaluated GPR technology for pavement thickness, debonding distress, stripping and other problems below the pavement surface:

- NCHRP Synthesis 255 published in 1998 [41]
- NCHRP Synthesis 357 published in 2006 [42]
- NCHRP Report 747 published in 2013 [48]

The first two reports were reviewed in depth in the earlier Mississippi DOT SS182 study report. NCHRP report 747 is a guide for forensic investigations of highway pavements and provides good review of GPR applications. Unfortunately, there is no case study of TDC evaluation using GPR in these reports.

A recent SHRP2 study evaluated several nondestructive devices at the National Center for Asphalt Technology (NCAT) pavement test track [47]. This report presents the findings of the first two phases SHRP2 Renewal Project R06D, using GPR, IE, and SASW nondestructive testing equipment to identify delamination between HMA layers. The devices provided quality results and shorter test duration, and covered a longer test section. The devices were able to measure changes in pavement response, but none of the technologies are capable of identifying partial bond or no bond due to inadequate tack coat during construction. The report states that GPR can identify variations in the pavement, isolate the depth of a discontinuity in the pavement, and provide a relative degree of severity. The report recommends that enhanced data analysis software development is needed for network-level application tool for detecting delamination in HMA pavements [47]. These studies support that the GPR technology is a viable nondestructive test equipment that is capable of testing at full lane width and operating at moderate highway speed.

# Annual TRB Meeting Papers

The following TRB paper DVDs from the 2011, 2012, 2013 annual meetings were scanned for any TRB paper or presentation on GPR applications for TDC evaluation.

- 90th TRB Annual Meeting, Jan 23-27, 2011: Five nondestructive testing related papers were identified, but none of the papers discussed GPR technology to evaluate cracking distress.
- 91st TRB Annual Meeting, Jan 22-26, 2012: Six related papers were found, but none of the papers discussed GPR technology to evaluate cracking distress.
- 92nd TRB Annual Meeting, Jan 13-17, 2013: Twelve related papers were found. Only two papers discussed GPR technology to evaluate cracking distress. One paper from Australia described 3D laser technology for crack mapping on the pavement surface.

Table 2 lists several nondestructive test equipment used in the SHRP2 study and by other agencies.

# Table 2. Candidate nondestructive test equipment for TDC evaluation on asphalt pavements

Manufacturer (Country)	Model and Specs	Operation/Speed	Source / User	
GSSI (USA)	3-GHz horn antenna	Attached to vehicle	SHRP2	
GSSI (USA)	2.6-GHz ground-coupled antenna	Attached to vehicle	SHRP2	
MALA AB (Sweden)	1.3-GHz ground-coupled antenna array (MIRA)	Manually operated, walking speed	SHRP2	
MALA AB (Sweden)	2.3-GHz ground-coupled antenna	Manually operated, walking speed	SHRP2	
3D-Radar (USA, Norway)	150-MHz to 3-GHz, B3231	Attached to vehicle	SHRP2	
Mechanical wave device from Geomedia (USA)	Portable Seismic Pavement Analyzer (PSPA)	Manually operated	SHRP2	
Mechanical wave device from Oslon Instruments, Inc. (USA)	Scanning impact echo (IE) and spectral analysis of surface waves (SASW)	Attached to vehicle	SHRP2	
IR camera from Infrared Camera, Ins. (USA)	Model: 7,320, Resolution of 320No240 piNoels and 30Hz frame rate	Can be mounted on vehicle	SHRP2, Wisconsin DOT, Illinois DOT, Washington DOT	
IR camera from Infrasense, manufactured by FLIR (Worldwide)	Model: A40M, Resolution of 320No240 piNoels and maNoimum 60Hz frame rate, wide-angle lens	Attached to mounting platform on top of vehicle, about 13 ft above pavement surface	SHRP2, Wisconsin DOT, Illinois DOT Washington DOT,	

# COST Action TU1028 Project on GPR Applications

The most important fact of the viability of GPR for TDC evaluation is the data processing and interpretation. A major research effort in EU is underway through the COST Action TU1028 project on GPR applications for enhancing data processing and analysis to benefit the end use. The author is an invited member among the experts from the United States who participated in the team led by "Roma Tre" University in Italy that was awarded the COST project on GPR applications in civil engineering (http://www.gpradar.eu/).

After a lengthy review 20 papers on GPR's use for cracking analysis were found among all the papers included in the Proceedings of First Action TU1028's General Meeting held in Rome, 22<sup>nd</sup>-24<sup>th</sup> July, 2013 [50].

# 3.4 Candidate Noncontact Technology for TDC Surveys

A noncontact distress survey technology at highway speed for identifying and measuring extent/severity of the top-down cracking conditions is not well established at this time. No highway-speed remote sensing technology is available in practice that can scan pavement surface and map crack propagation through the asphalt layer thickness. No such effort is underway actively as indicated by the proposer's recent e-mail contacts in the U.S. and Europe.

The following evaluation criteria should be considered for developing equipment specifications for the purpose of network-level TDC surveys:

- 1. Equipment Robustness and Durability (with respect to effectively detecting and mapping crack depth)
- 2. Field Data Collection and Processing (highway speed operation, calibration and accuracy/precision)
- 3. Operating Restrictions (daytime or nighttime, seasonal)
- 4. Field and Office Data Processing (level of education and training required)
- 5. Data Quality and Usefulness (reliability of data interpretation and network summary)
- 6. Cost of Equipment and Annual Maintenance

# Impact of Top-down cracking evaluation on MDOT transportation facilities and services:

Mississippi DOT's highway evaluation program depends on noncontact equipment for surface

distress evaluation and longitudinal roughness measurement, operated at highway speeds, for surveying the highway network 100% once in 2-year cycles. Maintenance and rehabilitation treatments for areas with top-down cracking are not the same as those used for fatigue-distressed asphalt highway pavement. Time and cost savings to the Department will be significant in implementing MEPDG calibrations and designing better performing maintenance and rehabilitation strategies, especially in the case of thick asphalt and perpetual pavements. Therefore, it is important to evaluate top-down cracking as a part of highway speed pavement condition surveys to preserve highways and safety of highway users [58]. However, an understanding and equipment operating at highway speed for noncontact nondestructive evaluation of this distress type on asphalt pavement have not yet been established.

#### 4. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

#### 4.1 Summary

The surface cracking distress on asphalt highway pavements, known as top-down cracking appearing mostly in longitudinal wheel paths, was first reported in the 1970s in the UK based on investigations in tropical countries. Later, this cracking distress was discovered on asphalt roads in the UK, the Netherlands, France, and South Africa in the 1980s. Attention was paid only in the late 1990s in the United States when this surface cracking distress in asphalt pavements was first investigated. The top-down cracking has been identified as the most prevalent cracking distress on asphalt pavements in the 2000s, as shown by numerous field studies conducted in the United States, Europe, and Japan.

Asphalt mix segregation, binder aging, dry mixes, and climatological effects contribute in creating this distress. The cracking distress is further accelerated because of wheel loads and contact stresses. However, an understanding and equipment for nondestructive evaluation at highway speed of this distress type have not yet been established. TDC identification in the field and consideration in pavement design methods are problematic compared to fatigue cracking that is assumed to initiate from the bottom of pavement system. It is important to identify and quantify top-down cracking for implementing appropriate maintenance treatments and considering mechanistic-empirical pavement thickness design procedures.

#### 4.2 Conclusions

- The top-down cracking phenomenon on asphalt highway pavements has been identified as an important issue in Mississippi, other states, and many European countries for identification in field condition surveys for pavement performance studies.
- Since late 1990s there has been an alarming increase of top-down cracking distress identified on asphalt highways in many states including Florida, Indiana, Michigan, Washington, Illinois, Colorado, Louisiana, Wisconsin, Ohio, Minnesota, Pennsylvania and Mississippi. Some researchers have hypothesized that this cracking distress may initiate from within the asphalt layer and propagate to the top based on extensive laboratory and numerical studies.

- The Washington State DOT reportedly feels that the vast majority of asphalt cracking on their highway network is top-down.
- Proper and timely maintenance of top-down cracking is critically important for perpetual pavements. Therefore a procedure is needed to expedite field survey of top-down cracking without depending on cores.
- Time and cost savings will be significant in implementing MEPDG calibrations and designing better performing MR&R strategies. Therefore, it is important to evaluate top-down cracking as a part of highway speed pavement condition surveys to preserve highways and safety of highway users.
- Noncontact distress survey technologies at highway speed for identifying and measuring extent/severity of the top-down cracking conditions are not well established at this time.

# 4.3 Recommendations

The most promising nondestructive noncontact technology operating at highway speed is the ground penetrating radar. The data interpretation must yield top-down cracking presence on the surface and penetration depth in asphalt pavements. Unfortunately, at this stage of knowledge a follow up phase is not recommended for a pilot study in Mississippi with a candidate technology. Because a viable noncontact highway speed technology is not found; therefore, a problem statement for research need will be prepared and submitted for a national study through NCHRP.

There are several positive impacts of implementing study recommendations to MDOT transportation facilities or services. These include:

- (1) A viable high-speed method to evaluate top-down cracking will enhance periodic pavement condition survey as a part of pavement asset management.
- (2) The asphalt pavement performance models will improve for pavement sections exhibiting top-down cracking by developing survivor rate data for these pavement types and identifying mix and construction problems.
- (3) Pavement asset management will improve by selecting appropriate maintenance and rehabilitation treatments for areas showing top-down cracks, which may not be the same as those used for fatigue-distressed asphalt highway pavements. This will affect overall maintenance cost and performance of highway pavements.

(4) The noncontact evaluation of top-down cracking distress at highway speeds will result in enhanced preservation of asphalt highways and safety of highway users.

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# APPENDIX

# Tech Memo on Synthesis of Selected TDC References

# **Technical Memorandum**

To: Mississippi DOT SS255 Project File

From: W. Uddin and Project Staff

Subject: Synthesis of Selected Top-Down Cracking References

### **Reference Number:** [3]

Commentary: Author is among the earliest researchers to study TDC starting 1970s.

#### **Reference:**

Rolt, J. Top-Down Cracking: Myth or Reality. Department for International Development (DFID), TRL Limited, Crowthore Berkshire, GR45 6AU, United Kingdom, 2000, pp. 1-17.

**References Cited: 5 Study Sponsor:** TRL / UK Government

Abstract: None

#### **Objectives:**

This study was carried out to identify the most probable causes of TDC. Author also offered recommendations to prevent TDC.

#### **Methodology:**

Case study: Yes, Laboratory test: Yes, Field test: Yes, NDT: No, Numerical Analysis: No

The first asphalt performance study was carried out to produce a better design guide for countries in tropical environments. The analysis focused on performance monitoring which aimed to study mechanisms involved in the top-down crack formation. The degree of rutting and cracking on the road surface and deflections, were among the factors assessed. The second asphalt performance study was designed to develop a more firm understanding on the correlation between the aged binder and mix properties. At this stage, 32 test sections were identified to evaluate binder aging.

#### **Summary:**

This report states that top-down cracking was discovered in the late 1970's. Initially, the severity of this phenomenon was ignored by most engineers who claimed that it happened in countries with tropical climates only. However, continuous observation of top-down cracking in France and Holland, countries with more temperate climates, found that there was considerable evidence of top-down cracking occurrences in these countries too. The engineers at TRL had initiated possible solutions to prevent top-down cracking problem.

From 1973 to 1977, the first asphalt performance study was carried out on eight different sites with varying climatic conditions. The original objective was to produce a design

Date: September 10, 2013

Revised: December 24, 2013

**Year:** 2000



specification for more durable asphalt overlays between 30 and 170 mm thick in tropical environments. It was overlaid on different road types, and was evaluated by deflection tests and traffic levels. The performance monitoring of the asphalt layer was carried out, focusing on the severity of asphalt rutting, cracking and deflection. An extensive number of cores were cut to study crack pattern in detail.

The early findings showed that the cracks started from the top surface and propagated downwards. Similar deterioration was also reported in France, Netherland, and South Africa. Common fatigue cracks occurred from the bottom and spread upward. The critical radial stresses were experienced at the lower side of asphalt layer. However, the width of the crack decreased with depth and it almost invisible. The crack could possibly propagate down to the full depth after a longer performance period. The properties of recovered bitumen were assessed periodically and it was found that rapid age hardening occurred on most of the experimental sections. The viscosity of the recovered bitumen reduced as the layer depth increased. This report highlighted that the hardened asphalt is the key component in top-down cracking mechanism. Nonetheless, about 25% of the study area surveyed was without any cracks throughout eight years of the study period.

The second asphalt performance study (1978-1983) was carried out to provide a better understanding between asphalt material properties and bitumen aging. To investigate the aging, asphalt slabs were manufactured in a laboratory and exposed to the field environment for 24 months. The slabs were fabricated with a variety of mix compositions and variables. Some blocks were coated with a surface dressing to reduce aging rate on the top of the asphalt mix. After certain periods of exposure, the blocks were tested using a gamma-ray scanner to measure the density of the blocks as a function of depth. The samples were cut horizontally about 3 mm thick. The effects of age and mix variables were quantified using multiple regression techniques. The results from the mathematical model showed that after 24 months, bitumen viscosity in the top 3 mm section increased by a factor range of 200 - 500. The increased viscosity as strongly related to the aged mix. The air voids, bitumen content, and filler content affected the viscosity by a factor between 1 and 3 based on the variables studied. The bitumen with surface dressing was also hardened, but at a lower rate compared to the unsealed blocks. The final findings proved that under hot tropical conditions, regardless of the bitumen grades, the aging will happen as the performance duration increases.

#### **Key Results:**

Thirty-two full scale test sections were constructed to investigate how to reduce aging. The variables studied included: asphalt thickness, bitumen content, and effect of pre-coated chippings at different altitudes and environments. The results of the full scale trials showed that overlay thickness between 120 and 240 mm and deflection measurements indicated little structural damage. The mixes with excess bitumen showed deformation. It was discovered that the cracks can be seen on the unsealed asphalt surfaces within 2 years, compare to sealed asphalt surfaces. To conclude, the aging effect on real road was less compared to "exposure blocks". In addition, severe asphalt hardening occurred with poor quality materials and traditional construction methods. The hardening has strong correlation with the ambient temperature. In countries where pavement temperature was 8°C lower, the hardening was approximately 33% of the warmer climates.

NDT methods used: No

Field: Sample coring, Yes Lab: Apparatus fabrication, Yes Sample preparation and coring: Yes Analysis: Yes

#### **Reference Number:** [6]

Year: 2000

**Commentary:** Recommended by Dr. David Luhr, State Pavement Management Engineer, Washington State DOT, November 2012.

#### **Reference:**

Uhlmeyer, J.S., K. Willoughby, L.M. Pierce, and J.P. Mahoney. Top-down Cracking in Washington State Asphalt Concrete Wearing Course. In *Transportation Research Record: Journal of Transportation Research Board, No. 1730*, TRB, National Research Council, Washington, DC, 2000, pp. 110-116.

#### **References Cited:** 12

Study Sponsor: Washington State Department of Transportation

#### Abstract:

For years, pavement engineers within the Washington State Department of Transportation (WSDOT) have observed that longitudinal and fatigue (multiple-interconnected) cracks in their thicker asphalt concrete (AC) pavements appeared to crack from the top of the wearing course downward. Often, the cracks stop at the interface between the wearing course and the underlying bituminous layers (a depth of about 50 mm). Studies done elsewhere in the United States and internationally have reported similar results. The results of extensive coring that WSDOT routinely collects in its pavement rehabilitation process were compared in a study. WSDOT normally cores AC pavements to determine thickness for use in mechanistic-empirical design. In addition to coring for AC thickness, specific information noting surface-initiated (top-down) cracking to partial crack depth or full-depth cracking was noted. WSDOT observed top-down cracking generally started within 3 to 8 years of paving for pavement sections that were structurally adequate for design equivalent single-axle loads.

Objectives: To study top-down cracking distress on asphalt highways using core and traffic data.

#### Methodology:

Case study: Yes, Laboratory test: Yes, Field test: Yes, NDT: Yes (FWD), Numerical Analysis: Yes

The analyses were carried out based on cored samples which were taken from different project sections to determine pavement thickness for use in mechanistic design and asphalt pavement evaluation. The samples were cored at 1 km increments, but this distance relies on the uniformity of observed distress and pavement thickness. The core locations were decided on the summary of falling weight deflectometer (FWD) data and coring were done at or near FWD drop locations. In this project, a sum of 143 cores that ranges between 40 to 280 mm were taken for top-down and full depth cracking evaluations. Out of the total, 33 of the cores have top-down crack with

crack width 3 to 4 mm at the top and closed with depth. The average depth for top-down cracked sections was 47 mm.

#### **Summary:**

A study on top-down cracking in asphalt concrete wearing was reported by Uhlmeyer, et al. (2000) in work done for the Washington State Department of Transportation. They discovered that thick asphalt concrete was also susceptible to top-down cracking, while the thinner sections cracked in full depth. The pavement layers with top-down cracks had an average thickness of 161 mm and 107 mm for full depth cracks. These cracks were referred to longitudinal and fatigue cracks with multiple interconnected lines propagated downward. Based on asphalt concrete core samples, originally taken to determine asphalt thickness for mechanistic-empirical design, it was observed that the cracks usually stopped at the interface between the wearing course and the underlying bituminous layers (50mm below surface).

Uhlmeyer, et al. (2000) noted that top-down cracking occurred typically 3 to 8 years following construction for pavement sections that satisfy structural requirement and were designed for acceptable equivalent single-axle loads. They concluded that top-down cracking was randomly stretched especially for asphalt layer with thickness surpassing 160 to 180 mm. The observed performance years before the top-down cracking occurred varied from 1 to 5 years (Japan), 3 to 5 years (France), 5 to 10 years (Florida), and up to 10 years for United Kingdom. The researchers also pointed out that the top-down cracking was exaggerated by a combination of truck tires (near or at tire edges) and thermal stresses. Truck tires were claimed to be the primary cause of top-down cracking and thermal related cracking was in part due to binder aging.

Uhlmeyer, et al. (2000) also related top-down cracks with traffic equivalent single axle load (ESAL). Based on the average number of ESALs during coring process, it is concluded that the top-down cracks required about 81,000 ESALs per mm of crack depth. The calculation was made based on the assumption that a crack growth progressed linearly, which is unlikely. They also discovered that asphalt pavement with top-down cracks also have stripping problems at the surface. The suggested rehabilitation option is dependent on the distress types. It can be rotomilled and the top layer of the wearing course can be replaced or overlaid. Full-depth cracked roadways may require removal and replacement of the asphalt layer.

#### **Key Results:**

Authors concluded that TDCs happened on structurally adequate pavements which were designed with good ESALs assumption. TDC are usually longitudinal cracks that appear near wheel paths and occur between 3 and 8 years. A full-depth crack occurred within 1 to 4 years. Surface initiated cracking located in or near wheel paths, usually on pavement thicker than 160 mm.

NDT methods used: Yes, (FWD) Case study: Yes Field: Yes Analysis: Yes

#### **Reference Number:** [8]

**Year:** 1982

**Commentary:** This paper is from the Proceedings of Fifth International Conference on The Structural Design of Asphalt Pavements, The Delft University of Technology, The Netherlands.

**Reference:** Dauzats, M. and Linder, R. A Method for The Evaluation of The Structural Condition of Pavements with Thick Bituminous Road Bases, *Proceedings*, Fifth International Conference on The Structural Design of Asphalt Pavements, The Delft University of Technology, The Netherlands, August 23 –August 26, 1982, Volume 1, pp. 387-409.

#### **References Cited:** 24

Study Sponsor: The French Road and Bridge Laboratories

### Abstract:

The first disorders found in the bituminous pavements built in France since 1979 have led to accelerated development of a method for the analysis and follow-up of this type of pavement. After a summary statement of the behavior of bituminous pavements, based on 1400 km, this document describes a method based in part on the general principles of organization common to all stabilized structures and in part on specific tests; the originality of the method lies in the interpretation of these tests. Following a short description of the means of investigation, a large part of this document is devoted to analysis of the mechanical performance of the pavement based on such standard tests as deflection, the product r x d, and recent tests like the ovalization test, the value of which is that it measures elastic strains in the pavement. Tests of materials taken in situ, in particular the direct tensile test serve to determine the moduli of the materials and the characteristics at failure, and, via correlations, the allowable fatigue strain at  $10^6$  cycles. The method makes use of calculation of the probability of failure of the pavement based on the probabilistic hypothesis of the appearance of structural deterioration according to the dispersion of thicknesses, the nature of the material, and the fatigue law of the material. This method, used in the follow-up maintenance of pavements, helps to judge the structural quality of the pavement and provides the information needed in deciding what maintenance work should be done, or in some cases for overlay design.

**Objectives:** To study the material properties of road sections in France and their performance.

# Methodology:

Case study: Yes, Laboratory test: Yes, Field test: Yes, NDT: No, Numerical Analysis: No

The methodologies are described in the paper.

#### **Summary:**

The French Road and Bridge Laboratories has carried out extensive research to study the material properties of road sections in France and its performance. The authors have described the technique to construct road bases, namely "grave-bitume", which is a well-codified material, characterized essentially by the quality of the aggregate. The road section built using these techniques were exposed to an extreme hot weather in 1976, an intermediate temperature during cold climate, damp weather during winter, and traffic aggravated deterioration on the wearing courses. The problems related to road distresses have led researchers to development a new method to analyze flexible pavement road in order to find causes of the distresses. The authors

have studied the visible behavior of thick flexible pavements (10 cm or more) built on "gravebitume" road base.

### **Key Results**:

The observations on 1,400 km flexible pavement road have revealed longitudinal, random, and transverse cracks caused by heavy trucks. The higher number of heavy trucks increased all type of cracks at most of the sections. As the pavement ages increased, the percentages of sections having less than 10 meter of longitudinal cracks decreased, at higher rate after 3 or more years. Other detailed laboratory test results and analyses were reported in the paper.

NDT methods used: No Field: Yes Lab: Yes Sample preparation: Yes Analysis: Yes

# **Reference Number:** [14]

Year: 2009

**Commentary:** Dr. Uddin attended the conference too and contacted the senior author later about TDC evaluation.

### **Reference:**

Taniguchi, S., I. Nishizaki., and A. Moriyoshi. Three Dimension Diagnosis of Pavement Damage using CT Scanner. *Proceedings, MAIREPAVE6 Conference*, Torino, Italy, 2009, pp. 1-10.

### **References Cited:** 15 **Study Sponsor:** Not available

# Abstract:

Pavement quality is currently evaluated by examining the surface deformation and deflection, either visually, or by an automated pavement surface measuring device. However, these methods evaluate only the pavement surface or estimate the quality of each layer. In this study, the authors developed a technique for three-dimensionally diagnosing the causes and degrees of pavement damage. A 3-D crack analysis of each sample was conducted using an X-ray CT scanner (CT) and a 3-D void analysis program. 3-D images of in situ specimens showed that longitudinal cracking occurred not from the surface or bottom, but from within the pavement. The technique can thus be used to directly identify the 3-D pavement damage of each layer; and it can easily and precisely diagnosis the position and level of damage in asphalt concrete pavement.

# **Objectives:** None

# Methodology:

Case study: Yes, Laboratory test: Yes (3D Void scanner and CT Scanner), Field test: Yes, NDT: Yes (FWD), Numerical Analysis: Yes

The 3-D analysis was performed on cored specimens taken from a 5-year in-service expressway, that covered outer wheel path (OWP) and between wheel path (BWP) segments. The specimens were taken from two sections of the same expressway, 10 km apart, and had different mix properties. The asphalt layer was exposed to cold weather and approximately 2,500 vehicles travel per day. The visual inspection revealed no rutting or cracks on specimens from one section, while the other section had top-down cracks and slight rutting.

#### **Summary:**

A study on three-dimensional diagnosis of pavement damage using a CT scanner was reported by Taniguchi et. al (2009). The authors developed a technique to evaluate the cause and degree of damages within asphalt pavement. Most of the analyses carried out by other researchers are based on evaluation of pavement surfaces (one or two dimensional) and the quality of each layer is based on the estimation. Their observations and analyses are based on the CT scanner and a 3-D void analysis program. The authors claimed that the 3-D scanner precisely and directly diagnose damages within the pavement structure. Although elastic modulus of each layer can be estimated by FWD, the degree of damages itself is not evaluated by the elastic modulus values.

#### **Key Results:**

The asphalt slab for specimens from the section that had cracks and rutting was scanned to observe the cracking distribution from top, longitudinal, and transverse sides. The 3-D images of in situ specimens showed that the longitudinal, or top-down cracks, propagated from the middle of pavement layer. In addition, the 3-D images in the binder course and asphalt treated base under BWP at both sections displayed extensive cracking. The study revealed that the cracks also happened at non-wheel path.

NDT methods used: Yes, FWD Field: Sample coring, Yes Lab: Yes, Apparatus fabrication: No Analysis: Yes

# **Reference Number:** [17]

Year: 2001 tate of Florida by the

**Commentary:** TDC field investigation was carried out in the U.S. state of Florida by the researchers from the University of Florida.

#### **Reference:**

Myers, L.A., R. Roque, and B. Birgisson. Propagation Mechanisms for Surface-Initiated Longitudinal Wheelpath Cracks. In *Transportation Research Record: Journal of Transportation Research Board, No. 1778*, TRB, National Research Council, Washington, D.C., 2001, pp. 113-122.

#### **References Cited:** 16

Study Sponsor: Florida Department of Transportation (FDOT) and FHWA

#### Abstract:

Field observations of cores and the trench sections extracted from the asphalt concrete highway pavements exhibited propagation of surface-initiated longitudinal wheelpath cracks.

The initiation of these cracks was explained by the high-contact stresses induced under radial truck tires; however, the mechanisms for the surface crack propagation have not yet been explained. A combination of finite element modeling and fracture mechanics were selected for the physical representation and analysis of a pavement with a surface crack. An approach was developed to simulate a cracked pavement and predict the pavement's response in the vicinity of the crack and throughout the depth of the asphalt layer. Analysis of pavement's response indicated that the mechanism for crack propagation was primarily tensile. The shear stresses were not significant to control crack growth, regardless of the load position. Effects of shear pavement structure and load spectra (magnitude and position) were evaluated in a comprehensive parametric study of the cracked pavement. Load positioning had the most effect on the crack propagation, along with asphalt and base layer stiffness. The direction of crack growth was computed and changed with increased crack lengths. Therefore, identification of a tensile failure mechanism for crack propagation was accomplished, along with a demonstration of the importance of defining the load spectra and inspection of the change in the direction of crack growth. Most important, the defined mechanism offered an explanation for crack propagation and confirmed observations of crack growth in the field.

# **Objectives:**

The primary objective of this study was to identify the failure mechanisms for the development and propagation of longitudinal wheelpath cracks that initiate at the surface of bituminous pavements. Authors identified critical conditions that contribute to the propagation mechanism of surface-initiated longitudinal wheel path cracking. More specifically, the aim was to identify how cracks propagate beyond the initial 10–20 mm and to determine the predominant driving force (tension, shear, or a combination of the two) for failure. However, micro-cracks analyses were not considered in this study.

Other goals of this study include the following:

- To demonstrate the necessity for modeling and analyzing cracked pavement for the determination of top-down cracking propagation. Modeling and analyzing an asphalt concrete pavement with the physical presence of a flaw would capture the stress redistributions that occur at the crack tip that result in the critical condition for top-down crack propagation.
- To demonstrate the importance of defining load spectra is critical for predicting the cracking failure mechanism.
- To investigate how stress states within the asphalt concrete pavement influence the direction of crack propagation.

#### Methodology:

Case study: No, Laboratory test: Yes, Field test: No, NDT: No, Finite Element Analysis (ABAQUS): Yes

Initially, evaluation of TDC on flexible pavement site was observed from cored samples and trench sections extracted from the longitudinal wheelpath cracks. On the road surfaces, the wheelpath experienced the highest stress induced by radial truck tire pressure. Cores and trench sections showed surface cracks that propagated downwards. Authors reported that longitudinal surface cracks were induced by high vertical and lateral stresses in the wheel path. Authors also highlighted some characteristics and limitations of the analysis in the research. Different analytical methods were taken into consideration to define surface crack development before the

appropriate methods were selected. Subsequently, a pavement system was designed, modeled, and analyzed in the ABAQUS finite element computer program. The stress responses on the corresponding asphalt layer depth were evaluated. Authors also investigated fracture characteristics and critical conditions that accelerate crack growth.

#### Summary:

Authors agreed that the combination of finite element modeling and fracture mechanics was the most suitable approach to evaluate crack growth mechanisms and critical conditions at the crack tips. Another method employed was the distortion energy approach, but it was reported that this procedure always computes the highest distortion energy at the bottom, not at desired top asphalt layer. Authors stressed that it is necessary to utilize methods that model the physical characteristics of the cracks to identify critical conditions, predict stress distress distributions, and estimate crack direction.

### **Key Results:**

Authors have concluded that TDCs were primarily a tensile failure mechanism. Shear stress caused development of the crack tips but was not significantly enough to contribute to crack growth. In addition, realistic loading range and distance are critical to evaluate the pavement performance. Load wander must be considered for predicting failure and is critical in determining the future design conditions. The asphalt pavement structural characteristics showed significant effects on the tensile response of the surface cracks.

NDT methods used: No Case study: No Field: Visual observation and sample coring only. Lab: Cored samples from site were taken to the lab and visually analyzed to look for either TDC or reflective cracking. Analysis: Yes, finite element (ABAQUS)

# **Reference Number:** [19]

Year: 2003

**Commentary:** Authors carried out research on a highway pavement section in Portugal. Dr. Uddin witnessed some cores with TDC and took photos after the conference in July 2003.

#### **Reference:**

Freitas, E., P. Pereira, and L. Picado–Santos. Assessment of Top-down Cracking Causes in Asphalt Pavements. *Proceeding, MAIREPAV*, Maintenance and Rehabilitation of Pavements and Technological Control, University of Minho, Guimaraes, Portugal, July 7-10, 2003.

#### **References Cited:** 12 **Study Sponsor:** Not available

#### Abstract:

Cracks observed at the surface may have several origins and causes. A crack may either begin at the bottom or at the top of an asphalt layer. Cracking originated at the top of asphalt layers (top-down cracking) observed in temperate-climate countries is a degradation mechanism which has

not been fully researched. In order to assess this "new" degradation in Portugal, a sampling plan has been set in thick highway pavements, including the extraction of cylindrical cores and slabs. Cracks were carefully identified and several laboratory tests were performed on grading, bitumen content and air voids, fatigue strength and stiffness. Pavement bearing capacity was also measured. The assessment and comparison of the results show, in a first approach, that all cracks are surface-originated and top layers contains excessive fine aggregates and voids. A second approach concerning modulus, fatigue strength and bearing capacity is less conclusive, which leaves a long way to go. Nevertheless, it seems that construction quality continues to be the most probable cause of top-down cracking.

**Objectives:** To assess top-down cracking causes.

# Methodology:

Case study: No, Laboratory test: Yes, Field test: No (Only visual, extraction of cylindrical cores and slab), NDT: No, Numerical Analysis: No

This paper characterizes the initiation and propagation of top-down cracking on a thick, highly trafficked road in Portugal. About 45 cores were extracted from cracked areas both inside and outside the wheel path. In addition, 8 slabs (80 cm x 80 cm) were extracted from a sampling area that stretched 7 km of a 20 km motorway, which has aged 9 years since final asphalt installation. The visual condition, stiffness, and fatigue characterizations were investigated. Authors also measured physical properties and bearing capacity of the pavement.

### **Summary:**

Freitas, et al. (2003) performed an assessment of top-down cracking causes in asphalt pavements in temperate climate countries. Top-down cracking was reportedly, caused by climatic condition, traffic, aging, structure deficiency, and construction quality. According to the authors, the probable factor that contributed to the initiation and propagation of top-down cracking was construction quality. They believed that the differences between inter-layer modulus values did not initiate top-down cracking.

#### **Key Results:**

Freitas, et al. (2003) concluded that top-down cracking is one of the most important degradation mechanisms, as far as thick pavement is concerned. Their findings indicated that construction quality was a major cause of top-down cracking, while traffic load contributed less to crack progression. No significant difference between stiffness moduli were observed between control specimens and the ones taken from the cracked area. However, a phase angle analysis found that aging contributed to the top-down cracking mechanism, while fatigue did not initiate top-down cracking. But, authors stated that fatigue may contribute to crack progression.

NDT methods used: None Field: Sample coring and slab extraction, Yes Lab: Apparatus fabrication: No Sample preparation and test: Yes Analysis: No detail analysis reported

# Reference Number: [20]Year: 2005Commentary: Research on top-down cracking of thick asphalt highway pavements in Portugal.

## **Reference:**

Freitas, E., P. Pereira, L. Picado – Santos, and A. Thomas Papagiannakis. Effect of Construction Quality, Temperature, and Rutting on Initiation of Top-down Cracking. In *Transportation Research Record No. 1929: Journal of Transportation Research Board*, National Research Council, Washington, DC, 2005, pp. 174-182.

### **References Cited:**17 **Study Sponsor:** Not available

### Abstract:

Top-down cracking (TDC) is a flexible pavement distress caused by a number of factors, including high contact stresses from truck tires, mix design characteristics (e.g., binder type and aggregate gradation), and poor construction quality (e.g., segregation and compaction methods). This paper presents the findings of a study seeking to quantify the effect of those factors on TDC. The study consists of a laboratory component involving an accelerated wheel-tracking device and a modeling component involving a 3-D nonlinear viscoelastic finite element model. The laboratory component of the study involved 17 asphalt bituminous slabs constructed to simulate the variation in material properties observed in the field as part of an earlier forensic TDC study. The effects of air voids, bitumen content and type, aggregate gradation, and segregation on TDC were studied under three temperature conditions. Air voids, segregation, and binder content were found to have a significant effect on TDC for all temperatures tested. Modeling the TDC involved laboratory testing to establish the viscoelastic and tensile strength properties of the asphalt mixtures tested. It was found that the rutted surface contributes significantly to TDC initiation.

# **Objectives:**

This study evaluates the effect of the factors identified (binder type, binder content, aggregate gradation, void content, aggregate-binder adhesion, and temperature) on TDC initiation.

# Methodology:

Case study: No, Laboratory test: Yes, Field test: No, NDT: No, Numerical Analysis: Yes

This study utilized an accelerated wheel-tracking device and a 3-D nonlinear viscoelastic finite element model. The air voids content, bitumen content and type, aggregate-binder adhesion, temperature, and gradation were quantified. The specimens were prepared and tested at 30°C, 40°C, and 50°C, respectively. It is reported that the effect of binder aging was not considered during specimen preparation. The specimens were subjected to 0.69 kN, and 627 kPa pressure of wheel load with a loading period equivalent to 1.397 seconds per pass. The number of wheel passes it took to initiate the first crack (nf) and the total number of passes (nt) were recorded. The wheel tracking test was eliminated when the rut depth was equivalent to 1.5 cm or when 20,500 cycles were reached. Numerical simulation was adopted to investigate the effect of rutting on top-down cracking. A 3-D nonlinear dynamic finite element program (DIANA) was used to simulate wheel-tracking devices and implemented to validate rutted surface relationships with top-down cracking.

#### **Summary:**

Freitas, et al. (2005) defined top-down cracking as a flexible pavement distress indicated by cracks beginning at the surface and propagating downwards with time. In this study, they described the effects of construction quality, temperature, and rutting on initiation of top-down cracking. Authors stated that TDC was not well discussed with limited literature reviews available for reference. The interest in understanding TDC and its mechanism started from the initiative taken by NCHRP, an agency that considers TDC in new pavement design guide being developed by NCHRP Study 1-37A and ongoing NCHRP Study 1-42.

#### **Key Results:**

The findings showed that air voids, segregation, and binder contents have considerable effect on top-down cracking for all temperatures tested. Researchers also claimed that the rutted surface was a significant cause of top-down cracking and initiated earlier at higher temperatures. The 3-D nonlinear viscoelastic finite element model proved that rutted surfaces significantly caused and propagated top-down cracking.

NDT methods used: None Field: No Lab test: Yes, sample preparation and testing Analysis: Yes, 3-D Nonlinear viscoelastic finite element analysis

#### **Reference Number:** [21]

Year: 2002

**Commentary:** TDC field investigation was carried out by the Pavement Research Centre of Excellent (PRCE) and the Michigan Department of Transportation (MDOT) on flexible pavement and rubblized pavement.

#### **Reference:**

Svasdisant, T., M. Schorsch, G.Y. Baladi, and S. Pinyosunun. Mechanistic Analysis of Top-Down Cracks in Asphalt Pavements. In *Transportation Research Record: Journal of Transportation Research Board, No. 1809*, TRB, National Research Council, Washington, DC, 2002, pp. 126-136.

# **References Cited:** 13

Study Sponsor: Michigan Department of Transportation

#### Abstract:

Top-down cracks (TDCs) in flexible and rubblized pavements constitute a distress that has been reported in the United States and other countries. Researchers have reached different conclusions regarding the causes of TDCs. In this study, field and laboratory investigations were conducted on conventional flexible and rubblized pavements exhibiting TDCs. The engineering characteristics of the pavement layers were obtained from the analysis of the field data and the laboratory test results. Detailed mechanistic analyses were then conducted using these characteristics to determine the potential for TDCs. The results of such analyses were compared with the field data and which are presented and discussed in this report. The results and field data

show that (*a*) surface radial tensile stress are induced by wheel loads and enhanced by differential stiffness due to construction, temperature, and aging that can cause TDCs, (*b*) aging of the asphalt binder decreases the tensile strength and the tensile strain at failure of the asphalt mix, and (*c*) the locations of the maximum surface tensile stress predicted by the mechanistic analysis correspond very well to the locations of the TDCs observed in the field.

#### **Objectives:**

The main objective of this study was to determine the causes of TDCs. The investigation engaged nondestructive deflection testing and pavement coring over potential longitudinal and transverse TDCs.

#### Methodology:

Case study: Yes, Laboratory test: Yes, Field test: Yes, NDT (Falling Weight Deflectometer, FWD): Yes, Finite Element Analysis: Yes

Evaluations for the possible causes of TDC were carried out on traditional flexible and rubblized pavements, both in field and laboratory evaluations. Detailed mechanistic analyses have the shown potential causes of TDCs. In this study, the authors identified eight different sites with potential top-down cracking. The specified points were marked, cored, and the samples were tested in the laboratory. The locations of the cores were categorized into two groups. First, the cores were taken at the same locations of the FWD loading plate. AC thickness was measured on site, and the base and subbase thickness data obtained from the MDOT records were used for backcalculate the layer moduli. The MICHBACK computer program was used to backcalculate the layer moduli. Other cores were taken exactly on the longitudinal and transverse cracks. These cores were used to observe the extent of TDCs in the AC layer. The data observed included 249 sets of deflection data and 67 cores. Authors summarized the various measurements that were taken from both the longitudinal and the transverse cracks. Measurements for the transverse cracks were taken from certain reference points to the cored location. Authors also included the data from the rubblized pavement site investigated in a previous study by Baladi, et al. (2000) and Niederquell, et al. (2000).

Laboratory studies focused on the factors that affected the AC modulus which included temperature, aging, construction practices, asphalt grade, and mix types. Mechanistic analyses of TDC were carried out using three different computer programs which included CHEVRONX, MICHPAVE, and ABAQUS. In this study, only CHEVRONX and MICHPAVE analysis results were discussed due to space limitation. The analyses of tensile stresses at road surfaces were based on a 40 kN (9,000 lb) wheel load simulation.

#### **Summary:**

Authors stated that TDCs initiated at the pavement surface and propagate downwards, partially or to full depth. At the initial stage, the TDCs were single short longitudinal cracks just outside the wheel path. Over time, the cracks grew longer and more cracks developed 1 to 3 ft parallel to the initial cracks. This process reached the final stage when both the longitudinal cracks were connected via short transverse cracks. According to the authors, the TDC was caused by tensile stresses and strains induced at the top of the pavement structure. The combination of traffic load, temperature, and hardening of asphalt binder have caused shrinkage and stiffness variations between the asphalt surface, leveling, and base courses.

# **Key Results:**

Authors have listed the following findings.

- 1. Most TDCs were located just outside the wheel path and progressed in three stages.
- 2. TDC's caused by high surface tensile stresses induced by traffic loads and were enhanced by temperature, aging of the asphalt binder, construction material quality, temperature gradient, and compaction effort.
- 3. The magnitude of the surface tensile stress increases as:
  - a) Ratio between the AC surface course to the AC base course moduli increases.
  - b) The base layer modulus increased in established or rubblized bases.
  - c) The thickness of the AC layer increased in pavements with high base layer modulus values as in stabilized or rubblized pavements
  - d) The thickness of the AC layer decreased in pavements with conventional aggregate bases.
- 4. The aging of the AC binder caused a reduction in the tensile strength and strain at the failure point of the asphalt mix.
- 5. The quality of the rubblization process has a direct impact on the modulus of the rubblized layer, which affects the development of TDCs.

NDT methods used: Yes (FWD) Case study: Yes, 8 sites were evaluated. Field: Visual observation and sample coring only. Lab: Cored samples from the site were taken to the lab and visually analyzed to look for either TDC or reflective cracking. Analysis: Yes, finite element

**Reference Number:** [22] **Commentary:** None

Year: 2003

# **Reference:**

Wang, L.B., L.A. Myers, L.N. Mohammed, and Y. R. Fu. Micro-Mechanic Study on Top-down Cracking. In *Transportation Research Record No. 1853: Journal of Transportation research Board*, National Research Council, Washington, DC, 2003, pp. 121-133.

**References Cited:** 28 **Study Sponsor:** Not available

# Abstract:

Top-down cracking is a type of cracking that rivals the severity and prevalence of reflective cracking. It significantly reduces the pavement's quality service life. Yet the nature of top-down cracking has not been completely understood. Recent studies of the causes of top-down cracking have focused on identifying the mechanisms that induce tensile stresses at the surface by applying different combinations of surface tractions and the finite element method. Asphalt concrete is treated as a uniform linear elastic material. A new and different approach is presented for investigating the causes of top-down cracking by means of micromechanics. In this approach, asphalt concrete is viewed as a bonded granular material, and the microstructure, including aggregate particle configuration and mastic stiffness, is considered. Theories that predict the

existence of tensile stress under compressive loading were reviewed. Both qualitative and quantitative experimental methods were developed to observe the location of top-down cracking and to measure the tensile strains in the pavement. The experimental results indicate the following: (*a*) top-down cracking may initiate not only at the pavement surface but also at some distance down from the surface; (*b*) both tensile-type and shear-type cracking could initiate top-down cracking; and (*c*) top-down cracking may most likely initiate when the mastic is weaker or the pavement temperature is higher. Therefore, a mix sensitive to rutting may also be sensitive to cracking.

#### **Objectives:**

To investigate TDC from a micromechanics prospective, taking into account material microstructure.

### Methodology:

Case study: No, Laboratory test: Yes, Field test: Yes, NDT: No, Numerical Analysis: Yes, Discrete Element Method (DEM)

In the analysis, pavement systems under tire loads were simulated and studied using both micromechanics and the discrete element method. Researchers developed qualitative and quantitative experimental methods to observe the location where top-down cracks were initiated. An asphalt concrete beam measuring 125 mm wide, 305 mm long, and 75 mm thick was fabricated by adopting a roller compacter. The specimens were then cut into four sections and the cut surfaces were painted gray to ease visual observation. The cut surfaces were scanned prior to repetitive tire load test at 445 kN and 690kPa pressure configuration. Further qualitative observations showed that rut depths after 2000 loading cycles at all four sections are almost similar. The qualitative observations found that the cracking pattern for all four cut surfaces were relatively different.

The quantitative experiments were carried out using the image analysis approach, which showed the microstructure details of the asphalt specimen's cross sections. Specific observation on the subset of one of the cut surfaces, located under the edge of the tire, showed aggregate particles slide over each other. In addition, the aggregate at in the deeper section move away from each other. According to Wang, et al. (2003), both conditions caused weakness in mastic, developed, and initiated top-down cracking after repeated loading.

Wang, et al. (2003) also quantified relevancy of the approach taken to study top-down cracking. The tests for both qualitative and quantitative observations were implemented at 60°C. According to the authors, at higher temperature, the tendency of asphalt layers to crack is higher due to the weak binder or mastic and subsequent large deformation. Another duplicate specimen was tested at 25°C to investigate cracks at lower temperatures. The findings showed that there were no distinct cracks observed.

# **Summary:**

Wang, et al. (2003) has carried out a micromechanics study on top-down cracking. Aggregate microstructure and particle configuration are among the factors considered when asphalt layer was analyzed as a bonded granular material. Researchers defined top-down cracking as, a crack that rivals the severity and occurrence of reflective cracking. This study was carried out to investigate how significance material inhomogeneity would cause tensile stress. Wang, et al. (2003) stated that there are three different types of cracks; opening mode (Type 1), sliding mode

(Type 2), and tearing mode (Type 3). Currently, top-down cracking is assumed to be an opening crack mode, while the remaining type's correlations with top-down cracking remain unknown.

#### **Key Results:**

Wang, et al. (2003) concluded that top-down cracking propagated not only from the asphalt surface, but also from certain distances below the surface. The top-down cracking was initiated by both tensile type and shear type cracks. Researchers also found that top-down cracking occurred when the mastic was weaker, or when the pavement was exposed to higher temperatures. At lower temperatures, the probability for cracking to happen is less. Additionally, a mix that is sensitive to rutting is most likely also sensitive to cracking.

NDT methods used: None Field: No Lab Test: Yes Sample preparation and cut: Yes Analysis: Yes, analysis using DEM

# **Reference Number:** [24]

Year: 2008

**Commentary:** Authors carried out research on a pavement section in laboratory and analyzed using FEM.

# **Reference:**

Su, K., L. Sun., Y. Hachiya., and R. Maekawa. Analysis of Shear Stress in Asphalt Pavements under Actual Measured Tire-Pavement Contact Pressure. *Proceedings*, 6<sup>th</sup> ICPT, Sapporo, Japan, July 2008.

### **References Cited:** 15 **Study Sponsor:** Not available

# Abstract:

Rutting is one of the most important load-induced distresses found in asphalt pavements. The primary mechanism of rutting is associated with shear deformation rather than densification. Recently, top-down cracking probably attributed to shear failure has also been a frequent occurrence in asphalt pavements. Clearly, shear stress is one of the critical factors affecting pavements performance, and there is a great need to fully comprehend shear stress in asphalt pavements. However, most conventional pavement design methodologies assume tire- pavement contact stress is equivalent to tire inflation pressure and uniformly distributed over a circular contact area. In fact, tire-pavement contact is not circular and contact pressure is neither uniform nor the same as tire inflation pressure. To obtain an accurate account of the influence of actual tire-pavement contact pressure on pavement response, this study evaluates the shear stress in asphalt mixture layers produced by non-uniform stresses applied to the pavement surface, in a simulation of field conditions. Then a solid response analysis is carried out for a semi-rigid asphalt pavement. The calculated results indicate the maximum shear stress occurs at a point approximately 60 mm under the tire edge, and that both tire inflation pressure and load distinctly

affect shear stress. Bonding at the interface between the asphalt mixture layer and the base course obviously affects shear stress as well.

### **Objectives:**

To investigate the effect of shear stress on pavement performance using tire-pavement contact pressure method in laboratory.

# Methodology:

Case study: No, Laboratory test: Yes, Field test: No, NDT: No, Numerical Analysis: Yes (FEM)

Su, et al. (2008) described an analysis of shear stress in a semi-rigid asphalt pavement under actual measured tire-pavement contact pressure. The laboratory scale equipment was fabricated to simulated actual tire-pavement contact. The tire load was applied using servo-hydraulic actuators. All related data was automatically recorded using a data logger. They claimed that the pavement surface rutting related to surface shear deformation rather than densification, while top-down cracking was caused by shear failure of the pavement system and decreased pavement performance. To obtain a firm understanding of the effect of shear stress on pavement performance, they applied tire-pavement contact pressure in laboratory scale test. The effect of the tire pressure, both vertical and horizontally applied stresses on corresponding shear stress were studied and further analyzed using a 3D finite element method (3D FEM) by ANSYS. The variables observed include loading condition, tire pressure, layer thickness, and interface conditions between the tire and the pavement surface. The combination of tire pressure and tire loading studied varied between 0.46/25 to 1.05/25 MPa/kN.

#### **Summary:**

Instead of assuming pavement contact stress equivalent to tire inflation pressure and uniformly distributed over a circular contact area, Su, et. al (2008) simulated non-uniform stresses on pavement surface, which is most likely present in field conditions. The findings showed that in all cases observed, maximum shear stress occurred at the tire edge. This initiated rutting and top-down cracking. In addition, both tire pressure and vertical loads recorded caused significant effect on shear stress while horizontal loads showed less influence. Horizontal stress significantly affected shear stress and was more pronounced at higher horizontal stress magnitudes. Further analysis revealed that pavement thickness and shear stress correlation is not significant. Poor interlayer bonding between pavement and base course increased the shear stress, which eventually propagate rutting and top-down cracking.

#### **Key Results:**

Authors concluded that maximum shear stress occurred at the tire edges which was responsible for rutting and TDC development. The shear stress was significantly affected by tire pressure and vertical load, with vertical load having more pronounced effect. In addition, higher magnitude horizontal stress significantly affected shear stress while the thickness of asphalt layer had least effect on shear stress. The shear stress increased between asphalt and base course layers due to poor bonding which eventually exaggerated rutting and TDC.

NDT methods used: None Field: No Lab: Apparatus fabrication: Yes

Mississippi DOT State Study 255 – Asphalt Pavement Top-Down Cracking The University of Mississippi – CAIT / Final Report – December 2013 Sample preparation: Yes Analysis: Yes, parametric study using FEM

### **Reference Number:** [25]

Year: 2004

**Commentary:** Authors have evaluated TDC in the U.S. This project was conducted in cooperation with the Indiana Department of Transport and the U.S. Department of Transportation, Federal highway Administration.

### **Reference:**

Pellinen, T.K., Rowe, G. and Boswas, K. Evaluation of Surface (Top-down) Longitudinal Wheel Path Cracking. *Final Report*, Joint Transportation Research Program, Purdue University, Indiana, 2004.

# **References Cited:** 41

Study Sponsor: Indiana Department of Transportation

### Abstract:

This research involved evaluating three surface cracked pavements during 2002 and 2003. A 500m section of I-65 North in Lafayette was chosen as the first site (designated as Site 1), an I-65 section in downtown Indianapolis was the second site (Site 2), and a section of US-421 in Madison was the third site (Site 3). Site 1 had 11-year old pavement, Site 2 had 12-year old pavement, and Site 3 had 4.5-year old pavement. All three sites exhibited longitudinal wheelpath cracking, which was later identified as top-down cracking. All three sites had excellent structural capacity, indicating that the top-down cracking was confined in the pavement surface. This was confirmed by the visual inspection of cores. The causes of the top-down cracking in the surface layer were identified as follows: 1) non-uniformities in the material properties caused by construction practices such as segregation; 2) high in situ air void content; 3) low amount of fines in the mixtures, and 4) the aging of the binder. However, the study was not able to identify or verify any structural causes for the top-down cracking.

# **Objectives:**

This study focused on evaluating pavement sections with top-down cracking. Detailed laboratory tests and analysis were conducted to evaluate the structural capacity of cored pavement specimen. In addition, in-place materials were analyzed to propose the best identification of distress type, material selection, and rehabilitation methods for implementation in Indiana.

# Methodology:

Case study: Yes, Laboratory test: Yes (X-Ray tomography), Field test: Yes, NDT: Yes (FWD), Finite Element Analysis: Yes

In 2002 and 2003, researchers observed and took several cores from an asphalt pavement with a surface crack at both interstate and national highway routes. Three longitudinal wheel path surface cracks were evaluated from the following sites: a 500 meter section of I-65 North in Lafayette (site 1), an I-65 section in downtown Indianapolis (site 2), and US-421 in Madison (site 3). The pavement sections at site 1, 2, and 3 were in service for 11, 12, and 4.5 years, respectively. The research was carried out by visual surveys, Falling Weight Deflectometer

(FWD) testing, and coring the cracked and non-cracked pavement areas. Initially, cored specimens were inspected and tested in laboratory to measure rheology and fracture properties of the binders used in the surface mixtures. Subsequently, the measured material properties were used as inputs in a Layered Elastic Analysis of Pavement Structures, LeapsPro<sup>TM</sup>) to investigate stresses and strains in the top of the pavement surface. Complex wheel loading models were analyzed using a 3D FEM.

**Key Results:** (These detailed results are copied from the executive summary of the report.) The cores obtained from the cracked areas were examined visually and also using x-ray tomography. The visual inspection and x-ray tomography indicated that the cracks were confined in the thin surface mix and did not penetrate deeper into the pavement at any of the sites. This confirms that the observed surface cracking is top-down cracking. Based on the visual survey, none of the sites seem to exhibit load-end segregation. However, this finding was not verified by laboratory testing. The systematical pattern in the longitudinal surface cracking in all three sites may indicate some longitudinal mix segregation caused by screed extensions in the paver. The FWD testing indicated that all three sites had excellent structural capacity and the computed effective structural numbers, SNeff, were 8.5, 10.2, and 6.1 for sites 1, 2, and 3, respectively. The thickness of the full depth asphalt pavement was 368 mm, 530 mm, and 203 mm for the sites 1, 2, and 3, respectively.

The pavement thickness and structural capacity at sites 1 and 2 indicate "perpetual" pavement; therefore, they will not exhibit bottom-up cracking. Site 3 in Madison was also very strong structurally to the layer of rubblized concrete underneath the asphalt layers. Therefore, it is not expected that bottom-up cracking develops in these pavements. Binder testing was done only for the binder extracted from the 1.5-2 mm thick surface mix. The original binder grade for site 3 was PG 70-22 and PG 64-22 binder was used for sites 1 and 2. Based on Dynamic Shear Rheometer (DSR) testing it was estimated that the high temperature performance grade for site 1 binder was PG 82, PG 76 for site 2, and PG 82 for site 3. Thus, site 1 had aged three PG grades, while site 2 and 3 had aged two PG grades. Therefore, site 2 binder aged the least and site 3 binder aged relatively the most. Compared to binder properties found in the literature, the binder stiffness data does not seem to differ significantly from the "normally" aged binder stiffness values.

The mixture properties were also measured from the thin surface mix layer. Site 3 had the highest air void content, average of 10.1%, while site 1 and 2 had binder content 8.1% and 7.4%, respectively. It can be concluded that the high air void content in site 3 accelerated the binder aging compared to the other sites, although it had the highest binder content of 6.3%, while site 1 and 2 had binder content 5.4% and 5.9%, respectively. All mixtures were 9.5 mm surface mixtures and the amount of fines passing the 0.075 mm sieve was 2.5 to 2.9% for sites 1 and 3, and 5.8% for site 2. The mixtures had effective binder volumes between 8 to 10%, and voids filled with asphalt ranging from 50 to 55%. Literature suggests that a better mix cracking performance may be obtained by increasing the mix density by compaction. In addition, mixtures with more fines may be more crack resistant compared to mixtures with low amounts of fines. The crack propagation in all three sites was confined to the surface layers. Research suggests that when the thickness of the pavement is above 200 mm, the top-down cracks are not likely to propagate through the entire pavement layers. Based on the rankings of the sites, none of them seemed to have properties far better than the others. The binder in site 2 is the softest, but does not have good low temperature cracking properties. The hard binder of site 3 aged significantly

compared to the other sites. The air void content in the mixes seems to point in the direction that the binder aging has accelerated when the air void content exceeded 7.5%. The higher amount of fines in the mix may prevent the binder and mix aging as site 2 properties suggest.

NDT methods used: Yes (FWD) Case study: Yes Field: Yes Lab: Sample testing and Scanning (X-Ray tomography) Analysis: Yes, FEM

#### **Reference Number:** [26]

Year: 2004

**Commentary:** Authors carried out research on composite pavements in the UK.

#### **Reference:**

Nesnas, K. and Nunn, M. A Model for Top-down Reflection Cracking in Composite Pavements. *Proceeding in* 5<sup>th</sup> International RILEM Conference on Cracking in Pavements – Mitigation, Risk Assessment and Prevention, Limoges, France, May 2004, pp. 409-416.

### **References Cited:** 4

Study Sponsor: Transportation Research Foundation, UK

#### Abstract:

Investigation of as-laid composite roads in the UK have demonstrated that reflection cracks generally initiate at the surface and propagate down to the existing crack in the underlying concrete layer rather than travel up from the crack. The asphalt surfacing is normally treated as a passive layer that responds to the thermal movements of the crack in the cement bound base. This approach will predict bottom-up cracking. This paper presents a new response model, which treat the cement bound and asphalt layers as a complete system and recognises that:

- \* The asphalt thermal expansion coefficient is much higher than that of concrete;
- \* Larger temperature changes occur in the asphalt surfacing;
- \* Age hardening results in asphalt close to the surface becoming the most brittle region of the asphalt.

This response model predicts top-down cracking and, furthermore, it predicts that bottom-up cracking from the existing crack will not normally occur. Field data is also presented to support these predictions.

#### **Objectives:**

This study was carried out to highlight the capability of the response model to predict top-down reflection cracking in composite pavement. This new response model treats the cement bound and asphalt layers as a complete system. Traditional models of flexible composite pavement assume that a reflection crack will propagate upward from an existing crack in the cement base. Researchers concluded that, the traditional approach treats asphalt pavement as a passive layer that only responds to thermal movements of a crack in the cement base.

## Methodology:

Case study: Yes, Laboratory test: No, Field test: No, NDT: No, Finite Element Analysis: Yes

An evaluation of the effect of temperature gradient out on an in-service composite pavement layer was carried out. Visual observations of road conditions were conducted and road surfaces with reflection cracks were cored and sent to the laboratory for detailed analysis. A finite element model that represents a flexible composite pavement was created with 30 m long x 4.97 m wide mesh. A strong concrete base layer with regular transverse cracks at 3 m intervals and lean concrete sub-bases were assumed for the analysis. The mesh was built using first order brick elements and infinite elements were used for the boundary elements. Authors assumed full grip between the concrete base and the composite asphalt. All layers were assumed to be isotropic elastic materials. The analysis focused on the effects of thermal coefficients and the aging of asphalt, asphalt thickness, and the effect of crack spacing on thermal stress distribution.

#### **Summary:**

Authors highlighted the contradictory finding by TRL researches about their field observation. They agreed that the reflection cracks initiated at the surface of the asphalt layer and propagated downward. Researchers believed that these cracks were caused by thermally induced stresses instead of traffic induced stresses. These cracks were due to higher thermal expansion coefficients and larger temperature changes in the asphalt layers, and were also accelerated by the aged asphalt mix close to the road surfaces. Explanations on cracking mechanisms and how thermal gradient and cyclic temperature accelerate cracking are also discussed in this paper.

Field observations revealed that in nine as-laid composite pavements (90-175 mm asphalt surfacing), reflection cracks started from the surface propagated downward. Most of the cored specimens showed that the crack in the composite pavement closed before reaching the crack in the underlying concrete layer. Nesnas and Nunn (2004) stated that the properties of wearing course rather than thinner asphalt layers, determine the start of reflective cracking. Further investigation showed that reflection cracking caused by binder aging accelerated due to direct exposure to environment conditions throughout the year. A finite element model was developed to describe reflection cracking.

# **Key Results:**

Authors found that the maximum thermal stress decreased with smaller crack spacing. High thermal tensile stress at the pavement surface resulted in top-down cracking. The maximum tensile stress occurred at the top of the asphalt layer above the crack in the concrete base. In general, the model was able to explain top-down reflection cracking that was caused by thermal effect alone. Binder aging, surface brittleness, and the surrounding temperature determine the point at which the surface cracks originate.

NDT methods used: None Case study: Yes, 9 sites were evaluated. Field: Visual observation and sample coring only. Lab: Cored sample from the site were taken to lab and visually analyzed to look for either TDC or reflective cracking. Analysis: Yes, finite element

#### Year: 2008

Reference Number: [27]

**Commentary:** Authors carried out research on a pavement section near a section of I-25 between Colorado State Highway 7 and 120<sup>th</sup> Avenue near Denver, Colorado.

### **Reference:**

Harmelink, D., S. Shuler, and T. Aschenbrener. Top-Down Cracking in Asphalt Pavement: Causes, Effects, and Cures. *Journal of Transportation Engineering*, Vol. 134, No. 1, ASCE, January 2008, pp. 1-6.

### **References Cited:** 5

Study Sponsor: Colorado Department of Transportation

### Abstract:

A section of I-25 north in Denver was rehabilitated by cold milling the existing surface to a depth of three inches and then replaced with new hot mix asphalt. The contractors received bonuses for the quality and smoothness; and the mixture passed both Hamburg and French LCPC rut tests. Within one year, longitudinal cracks appeared in the pavement surface. The cracking appeared in the driving lanes of both the north and south-bound directions. The severity of the cracking ranged from very low to very high. An investigation revealed that the cracking on the project was initiated at the surface of pavement and caused by a number of factors. One factor was the segregation observed at the bottom of the upper pavement lift that was not visible from the surface. After this so-called "top-down cracking" was discovered on this first project, other pavements began manifesting similar traits. Therefore, a state-wide evaluation was conducted to determine the extent of this distress in other pavements. As a result of this study 28 sites were evaluated, and of these 28 sites, 18 contained top-down cracking. Based on these findings, a change in the mix design process was implemented to allow for increased asphalt content in hope that the richer mixtures would not be as prone to segregate. In addition, a segregation task force was created to develop a specification for segregation problems. This task force is currently in the process of developing a specification to identify sub-surface segregation with the elimination of top-down cracking as the goal. Paving equipment manufacturers have also identified areas within the laydown equipment that can promote segregation. As a result, manufacturers have taken the initiative to develop an anti-segregation retrofit for some laydown machines. The topdown cracking has been generally eliminated, or greatly reduced.

# **Objectives:**

This study was carried out to determine the extent of the TDC phenomenon in Colorado, the causes, and how to rectify, as well as, prevent the problem. The authors also attempted to find out when the distress needed to be treated to keep the asphalt pavement in good condition.

#### **Methodology:**

Case study: Yes, Laboratory test: Yes, Field test: No, NDT: No, Numerical Analysis: No

Detailed locations for TDC evaluations were reported by Harmelink, et al. (2008). Basically, the evaluations started by visual observation of cracked surfaces on site. Subsequently, 150 mm thick specimens were cored over the longitudinal crack. In addition, the longitudinal crack's relationship to the longitudinal construction joints was measured to determine if the location of the paver might cause longitudinal cracks. The cores from TDC sites were analyzed in the

laboratory. Aggregate segregation and crack patterns, were observed. Also, segregated specimens were heated in an ignition oven to remove the asphalt binder before further tests were introduced on mix gradation.

#### **Summary:**

Harmelink, et al. (2008) assessed road sections of I-25 between Colorado State Highway 7 and 120<sup>th</sup> Avenue near Denver in 1997 to analyze TDC behavior. The road section was rehabilitated by cold milling 3 inches of the existing asphalt layer and laid with new HMA. Once the rehabilitation project was complete, the road surfaces were accessed by local authorities for material quality, durability, and road surfaces smoothness. The project received rewards for passing all of the requirements. However, longitudinal cracks started to appear on the road surfaces, after only 1 year in service. Initial observations from three cores revealed that the cracks reflected through the surface from the underlying pavement, which were induced by the daily traffic and caused by moisture trapped within pavement particles. After 3 years, the crack severity increased and caused rapid deterioration to the pavement system. These conditions led to detail investigations of both the distress and the non-distressed area of pavement.

#### **Key Results:**

The analysis concluded that the cracking on the asphalt surface was caused by several factors which include segregation, percent air voids in the mix, the volume of the effective asphalt binder and the physical properties of asphalt binder itself. Out of 25 sites evaluated, 18 sites were judged to have experienced TDC. Of these 18 sites, 12 had visual evidence of aggregate segregation. The paver configuration also had significant effects on the surface cracks. According to the authors, TDC appeared in pavements that were constructed using different paver models by different manufactures. The authors also stated that the changes made to the Superpave mix design process in 2003 have significantly reduced surface distressed related to TDC.

#### NDT methods used: None

Case study: Yes, 28 sites were evaluated and 18 contained TDC

Field: Visual observation and sample coring only.

Lab: Cored samples from the site were taken to the lab and visually analyzed to look for either TDC or reflective cracking. The cores taken from the cracked and uncracked areas were also inspected for possible segregation. The gradations of the segregated specimens were determined after the asphalt extraction by an ignition oven.

Analysis: No detailed numerical analysis, only data from the visual observation was reported.

#### **Reference Number:** [30]

**Year:** 2008

**Commentary:** Authors had carried out research on a pavement section near Kharagpur on National Highway No. 6 in India.

#### **Reference:**

Raju, S., S. Satya Kumar, K. Sudhakar Reddy, S. Bose, and B.B. Pandey. Analysis of Top-Down Cracking Behavior of Asphalt Pavements. 87<sup>th</sup> TRB Annual Meeting, Transportation Research Board, National Research Council, Washington, DC, 2008, pp. 1-15.

## **References Cited:** 21 **Study Sponsor:** Not available

## Abstract:

Construction of four-lane and six-lane national highways under the Indian National Highway Development Program is being taken up in a massive way. Several stretches of asphalt pavements constructed under this program have already been opened to traffic. Premature surface cracks were observed on some stretches within a year or two of construction and these cracks were found to initiate from the top and progress downwards which is generally known as top-down cracking. In the present study, an effort was made to examine the causes of top-down cracking susceptibility of asphalt layers. Temperature gradients of typical asphalt layers were measured in the field, as well as, in the laboratory under high pavement temperature conditions. A finite element analysis of typical asphalt pavements was carried out for the evaluation of the influence of high pavement temperatures on surface tensile strains in the asphalt layer. The effect of heavy axle loads in combination with high pavement temperatures was analyzed for the evaluation of the initiation of surface cracking. Surface traction forces developed during rolling and braking were also considered. Parametric analytical studies indicated that temperature was a critical parameter influencing the top-down cracking susceptibility of an asphalt layer, especially in combination with heavy axle loading.

### **Objectives:**

This study was carried out to verify factors that initiate top-down cracking (TDC) in asphalt layers. Normal and heavy axle loads in combination with high pavement temperature and surface traction forces developed during rolling and braking were among the factors evaluated. Two different types of binder were used to prepare the mixes. The study also aimed to find correlations between field and laboratory temperature data, which was eventually used to predict field pavement temperatures at different depths for data obtained from the laboratory experiment.

#### **Methodology:**

Case study: No, Laboratory test: Yes, Field test: Yes, NDT: No, Numerical Analysis: Yes

Evaluation of the effect of temperature gradient was carried out on an in-service asphalt pavement layer and also on a laboratory model. Pavement road sections near Kharagpur on National Highway No. 6 were drilled at different depths, and at a spacing of 0.3m. The thermometers were placed into the holes before the holes were completely sealed using insulating material. In the laboratory, the insulting box of internal dimensions 101 mm x 101 mm x 200 mm to accommodate 101 mm diameter and 200 mm long asphalt specimen. The asphalt specimen was placed inside insulating box with one end of the sample exposed to the air and the other side covered with aggregates. A heat blower was used to simulate high surface temperature on the pavement specimen. Consequently, lateral holes were drilled at the equivalent distances adopted in the field.

The temperature data obtained from the field were then compared with the laboratory test results. The laboratory data and field data were used to develop a correlation between laboratory and field temperatures at any given depth. The authors stated that the correlation between the field data and laboratory data can be used to predict the field pavement temperatures at different depths using laboratory test results.

According to the authors, the information of the elastic moduli for an asphalt specimen at temperatures higher than 50°C is limited. Thus, the cylindrical specimens were exposed to repeated indirect tensile stress tests at different temperatures. A cyclic load of fixed amplitude, a duration of 0.1 second, and a rest period of 0.9 second was applied to the specimen. The resilient modulus and Poisson's ratio were calculated using an established model (ASTM D 4123). Analysis of asphalt pavements for top-down cracking susceptibility was established by implementing a parametric analysis of the pavement using the finite element model.

#### **Summary:**

An analysis of top-down cracking behavior in asphalt pavement by Raju, et al. (2007) has included detailed analyses using the finite element model. The finite element analysis includes evaluations of the influence of high pavement temperatures (>  $55^{\circ}$ C) on the surface tensile strain in the asphalt layer. The temperature variations within the asphalt layer were analyzed both in the laboratory and the field. The initiation of surface cracking was then evaluated based on the effect of heavy axle loads in combination with high pavement temperature. In addition, the authors also observed surface traction forces developed during rolling and sudden braking actions. Typical shapes of the tire contact area were used as part of the inputs for further analysis using the finite element model.

In this study, the pavement layers analyzed were made of 50 mm thick asphalt concrete, 150 mm thick dense bituminous macadam (DBM), 500 mm thick granular layer (base and subbase) and 2500 mm thick sub-grade. The layers were characterized by thickness, elastic modulus (E), and Poisson's ratio ( $\mu$ ). The authors assumed that all of the layers are linear elastic and isotropic with fully bonded interface between each layer.

The 3-D finite element model was developed using ANSYS. The finer meshes were applied near the load and the coarser meshes were considered away from the load to observe critical stress around the wheel loads. The pavement section was discretized using SOLID45 brick elements which are defined by eight nodes having three degrees of freedom at each node. The author considered single axle, dual-wheel configuration with the half-symmetric model for analysis. To be more precise, the tire imprint considered for the analysis was 100kN with 0.7MPa tire pressure for normal conditions. While 200kN axle load and 0.91MPa tire pressure were adopted to simulate a typical overloading case.

#### **Key Results:**

The temperatures measured in the field were observed to have good correlation with the data obtained in laboratory. The key results of the parametric study show that for normal load axle tested at 35°C the surface tensile strains are not significant for different combinations of AC and DBM. The use of a different binder type resulted in a marginal difference in the surface strain. In addition, the surface strain values increased significantly due to consideration of overloading and sudden braking action, especially at higher temperatures. Horizontal surface forces applied during braking significantly contributed to the initiation of TDC. The authors concluded that temperature was a vital parameter influencing the initiation of TDC in asphalt layers. Higher temperature at the pavement surface caused high tensile strains at the surface and was believed to initiate TDC.

NDT methods used: None Field: Sample coring, Yes Lab: Apparatus fabrication: Yes

Sample preparation and coring: Yes Analysis: Yes, parametric study using 3-D finite element model

# Reference Number: [31]

**Year:** 2010

Commentary: Authors carried out numerical analyses using multi-domain hybrid boundaries.

# **Reference:**

Miao, Y., T.G. He, Q. Yang, and J.J. Zheng, Multi-Domain Hybrid Boundary Node Method for Evaluating Top-Down Crack In Asphalt Pavements. *Journal of Engineering Analysis with Boundary Elements*, 2010, pp. 755-760.

# **References Cited:** 21

Study Sponsor: Natural Science Foundation of China

# Abstract:

Top-down crack is a type of crack that rivals the severity and prevalence of reflective cracks. This significantly reduces a pavement's service life. The initiation of these cracks was explained by the high-contact stresses induced under radial truck tires; however, the mechanism for top-down crack propagation has yet to be explained. A combination of the multi-domain hybrid boundary node method (Hybrid BNM) and fracture mechanics was selected for a physical representation and analysis of a pavement with a top-down crack. The hybrid BNM is a boundary-only, truly meshless method, which does not require a 'boundary element mesh', either for the purpose of interpolation of the solution variables or for the integration of 'energy'. In order to simulate the singularity of the stress on the crack tip, enriched basis functions were used. The factors, which influence the stress intensity factor (SIF) and the expansion path, e.g. horizontal load, thickness of asphalt concrete (AC) layer and base, AC layer and base modulus, are studied through numerical results. It was concluded that the Hybrid BNM, which has high convergence rates and high accuracy was able to solve top-down crack problems.

# **Objectives:**

This study adopted new numerical approach to predict the stress intensity factor, K\*, a description of crack-tip stresses level and conditions of cracks in pavement sections.

# Methodology:

Case study: No, Laboratory test: Yes, Field test: No, NDT: No, Finite Element Analysis: Yes Computational Technique and Models: Yes

The computational technique and models were determined based on the assumption that a pavement system consists of a 16, 20, and 20 cm depths of asphalt surfaces, base, and sub-base layers, respectively. All layers were assumed to be homogenous, isotropic, and linear elastic. A static tire load with vertical pressure of 0.7 MPa and 30 cm width was applied at 45 cm from the tire's center line to the initial crack. In addition, both vertical and horizontal loads were applied to analyze the affects of horizontal loads on crack propagation in the AC layer. Detailed multi-domain formulation of hybrid BNM at the tip of a crack in the TDC model are described in this paper.

#### **Summary:**

Authors have presented a multi-domain formulation for the hybrid boundary node method. This is a meshless boundary type method that is implemented to predict the stress intensity factor, K\* which can be used to simulate the propagation of top-down cracking. The K\* is descriptive of the crack-tip stress states and conditions in cracked pavement sections. Previous studies have adopted the finite element method (FEM) and boundary element method (BEM), and non-meshless methods to study top-down cracking mechanisms. In this study, authors have adopted meshless methods where approximate solutions are constructed in term of scattered nodes. This approach provided flexibility and resulted in significant cost and time savings in both simulation and modeling tasks. In addition, this approach did not require an element mesh for field variable interpolation. Nonetheless, this method requires a background mesh for the integration used to obtain a system matrix. In this research, the following factors were considered: the effects of horizontal loads, AC thickness, AC modulus value, and base layer thickness, base layer modulus.

#### **Key Results:**

The findings showed that the stress intensity factor  $K^*$  of cracks for the same depth increased by approximately 2MPa.mm<sup>1/2</sup> when the horizontal load is applied. The value of  $K^*$  decreased as the thickness of the AC layer increased, while the increased AC modulus contributed to a higher  $K^*$  value. Increments in the base layer thickness reduced  $K^*$ , while base layer modulus was reported to have no significant effect on  $K^*$ . It was proven that the multi domain formulation is capable of capturing the critical tensile stresses at the top of the pavement section.

NDT methods used: None Case study: No Field: No Lab: Sample testing Analysis: Yes, FEM and multi-domain hybrid boundary node method

#### **Reference Number:** [34]

Year: 2013

**Commentary:** Paper presented at 2013 IJPC conference. **Reference:** Uddin, W. and Z. F. Mohamed Jaafar. Achieving Sustainability Without Compromising Long-Term Pavement Performance for Road Infrastructure Assets. *Proceedings, First IJPC*, International Journal of Pavement Conference, São Paulo, Brazil, December 9-10, 2013, pp. 1-11.

**References Cited:** 53 **Study Sponsor:** CAIT, University of Mississippi

#### **Abstract:**

This paper reviews current aspirations to achieve sustainability goals in asphalt pavement technology by reducing consumption of energy and natural resources. Recycled asphalt pavement is required in 10-20% for asphalt paving by many U.S. state highway agencies. Warm mix asphalt is being promoted worldwide in the quest of reduced energy consumption. Many such paving technologies claim environment friendly and high sustainability ratings, sometimes

without analyzing long-term effects on performance and useful life of these asphalt pavements. Questions arise if top-down cracking and rutting distresses are caused by reduced asphalt binder content in the top layer, faster binder aging, and/or the use of recycled asphalt pavements. In practice there are high uncertainties in traffic predictions and high spatial and seasonal variability in subgrade soil properties, which are shown to affect thickness design as well. This paper discusses several sustainable highway practices that can reduce "heat-island" effects and emissions.

### **Objectives:**

The objective of this paper is to discuss environmentally sustainable road construction and maintenance strategies which may be competing with long-term pavement performance attributes of surface distress (cracking, rutting), roughness, structural capacity, skid resistance, and noise. The scope of study is limited to asphalt pavement technologies and reuse of waste glass for pavement marking applications.

#### Methodology:

Case study: No, Laboratory simulation: Yes, Field test: No, NDT: No, Numerical Analysis: Yes (PADAP computer program).

Parametric study of asphalt design thickness was carried out using the Program for Analysis and Design of Asphalt Pavements (PADAP) software. Pavement temperature and seasonally adjusted asphalt, base, subbase and subgrade modulus values were predicted based on climatic simulation algorithm of the PADAP.

#### **Summary:**

The authors discussed top-down cracking in asphalt pavement related to poor asphalt mix design and construction process. Surface distress, roughness, friction and skid resistance, and noise were among the factors that contributed to poor pavement performance. In the recent 25 years, there has been an apparent increase in awareness regarding pavement distress related to top-down cracking. Nonetheless, the primary mechanism of top-down cracking remains mysterious and no proven explanation and mitigation has been universally applicable.

Authors agree that binder aging was one of the primary reasons behind this issue and questioned whether recent implementation of recycled asphalt pavement (RAP) in new asphalt mixes accelerated pavement surface layer deterioration, especially on heavily trafficked roads. In addition, it is also pointed out that up to this date, nondestructive evaluation at highway speed for top-down cracking has not yet been established. Unlike rutting and fatigue cracking that has been assumed to propagate upward, researchers have not found the exact mechanism of top-down cracking although top mix degradation is believed to be a major cause.

During construction, all specifications must be followed strictly to create durable pavements. Parametric studies of asphalt thickness proved that it is vital to have reliable values of design traffic applications. For a weaker subgrade with higher traffic volume, a thicker asphalt layer is needed. In this paper, the effect of seasonal monthly temperature on modulus values of pavement surface, base, subbase and subgrade layers were studied. The findings showed that at higher temperatures, asphalt modulus values decreased significantly compared to the designed value (500,000 psi).

# **Key Results:**

Authors stated that achieving excellent long-term pavement performance and reducing greenhouse gas (GHG) emissions throughout the process are equally important for sustainable future. Poor asphalt pavement performance or early deterioration of pavement can be avoided if traffic prediction and subgrade soil properties assumptions were close to the real values. Decision maker should consider more sustainable construction processes in all aspects. A cost-effective pavement investment decision must include life-cycle costs and benefits analysis and emission inventory, especially at network-level pavement asset management.

NDT methods used: Review only Field measurement: Review only Lab test: Review only Analysis: Yes, Parametric Study

**Reference Number:** [40] **Commentary:** This is Mississippi DOT State Study 182 – GPR, Phase 1, 2006.

**Year:** 2006

**Reference:** Uddin, W. Ground Penetrating Radar Study-Phase 1: Technology Review and Evaluation. Final Report FHWA-DOT-RD\_06-182, Mississippi Department of Transportation, August 2006.

**References Cited:** 91 **Study Sponsor:** Mississippi DOT

#### Abstract:

In December 2005, Mississippi Department of Transportation (MDOT) initiated State Study No. 182 on review and evaluation of ground penetrating radar (GPR) technology. This phase 1 study has reviewed GPR equipment and data interpretation methodologies used for nondestructive determination of pavement layer thickness values. An extensive literature review was supplemented by review reports from two study consultants, and a comprehensive GPR technology evaluation survey of GPR manufacturer and users in the United States and abroad. There is adequate experience available with data interpretation methodologies and FCC certified or "grandfathered" technologies for reliable and reasonable accurate field assessment of asphalt pavement layer thicknesses. The MDOT is planning to evaluate this technology together with the nondestructive falling weight deflectometer (FWD) tests to enhance the evaluation of asphalt highway pavements and rehabilitation design. A preliminary cost-effectiveness study shows a high benefit/cot ratio of 80-200 based on overlay thickness design of a 10-mile asphalt pavement section. Based on favorable assessment in this study, a follow up larger Phase II study is recommended for field evaluation of the candidate GPR technology with 1-GHz and 2-GHz airlaunched horn antennas. A ground-coupled 400/500 MHz antenna is also recommended considering 30-inch or thicker pavements and the lime-treated subgrade layer. A pilot field study in Phase II should be conducted on a test section of a candidate asphalt highway pavement. Upon successful results and validation of improved pavement evaluation and resulting potential cost savings, the MDOT will consider implementing the GPR technology for routine use.
NDT methods used: Review only (GPR, FWD) Field measurement: Review only (Cores) Lab test: No Analysis: Yes, structural response analysis, benefit-cost analysis

## **Reference Number:** [43]

**Year:** 2005

Commentary: Evaluation of top-down cracking on asphalt pavements using ultrasonic method.

### **Reference:**

Khazanovich, L., R. Velasquez, and Edouard G. Nesvijski. Evaluation of Top-Down Cracks in Asphalt Pavements by Using a Self-Calibrating Ultrasonic Technique. *In Transportation Research Record No. 1940: Journal of Transportation Research Board*, National Research Council, Washington, DC, 2005, pp. 63-68.

#### **References Cited: 7 Study Sponsor:** Not available

### Abstract:

To select the optimal strategy for treatment of a cracked asphalt pavement, it is important to determine the extent of cracking (partial depth or full depth). This paper presents the results of an explanatory study aimed at examining the applicability of the ultrasonic technology for evaluation of cracks and longitudinal joints in flexible pavements. It was shown that this technology, which has been used successfully for many years for the evaluation of concrete structures, could provide a simple, quick, and objective procedure for evaluation of surface distresses in asphalt concrete pavements. The results of laboratory testing and field testing at the Minnesota Road Research Project test facility demonstrate the potential of this technology.

## **Objectives:**

The objective of this paper is to present the results of an explanatory study aimed at examining the applicability of the ultrasonic technology for evaluation of partial depth cracks and longitudinal joints in asphalt pavements.

#### Methodology:

Case study: No, Laboratory test: Yes, Field test: Yes, field measurement, NDT: Yes, (Ultrasonic Tester UK 1401) Numerical Analysis: No

This study provides information on the nondestructive test methodology that can be used to measure the extent of surface cracks. Ultrasonic testing uses high-frequency (greater than 20,000 Hz) sound waves to characterize the properties of materials or detect their defects. Sound waves, generated by a piezoelectric transducer, travel through the material and were received by a receiver. Analysis of the received signals provided vital information about the media through which the signal has propagated. A falling weight deflectometer (FWD) might not detect even a shallow crack, since FWD deflections are sensitive to many parameters, including thicknesses, sub-grade, and base properties. Authors claim that the ground-penetrating radar (GPR) might be an accurate tool for this task, but data interpretation of the GPR measurements requires special expertise.

#### **Summary:**

This paper highlights a new non-destructive test method to determine the extent of pavement surface cracks. The visual observation of surface distress is unable to identify full or partial depth cracks. In this initial study, the cracks were evaluated using an ultrasonic tester UK1401. The device measured the time of signal propagation between the transducers and automatically recalculates it into the wave velocity. This self-compensating technique eliminates the need for a local calibration. This 400 gram, pocket- sized device with dry point contact (DPC) provided time saving and objective procedures to evaluate



pavement surface distresses, which include a top-down cracking. Asphalt pavement cracking is caused by the action of repeated traffic loads (fatigue cracking), by sharp and rapid fluctuations in pavement temperature (thermal cracking), or combination of these effects. The study involved both in situ and lab scale researches. An explanatory study was conducted in the laboratory to confirm applicability of the ultrasonic tester.

### **Key Results:**

A strong correlation between the depth of the notch and the apparent reduction of the wave velocity was observed for all four beams. A 0.75-inch-deep notch reduced the apparent velocity by 10%, and a 1.5-in.-deep notch reduced the apparent velocity by 20%. The average velocities in the transverse and longitudinal direction were computed and their ratios were obtained. One can observe that the ratio is close to 1 since no cracking was observed at test locations. At another location, the ratio was equal to 0.8, which suggests that the crack propagated about 2 inches below the surface. A significant reduction in the ratio of velocities indicates that although cracks have not propagated throughout the entire asphalt pavement layer thickness, it propagated to a substantial depth. As expected, the presence of a crack resulted in apparent decrease in the velocity of longitudinal ultrasonic waves.

NDT methods used: Yes Field measurement: Yes Lab test: Yes, sample preparation and testing Analysis: No

## **Reference Number:** [44]

#### **Year:** 2010

**Commentary:** Authors carried out a study using GPR numerical modeling to analyze pavement cracks.

#### **Reference:**

Diamanti, N., D. Redman, and A. Giannopoulos. A Study of GPR Vertical Crack Responses in Pavement Using Field Data and Numerical Modelling. *13th Int. Conf. Ground Penetrating Radar (GPR)*, Institute of Electrical and Electronics Engineers (IEEE), Lecce, Italy, June 21-25, 2010.

## **References Cited:** 12

## Study Sponsor: Not available

### Abstract:

The application of ground penetrating radar (GPR) as a nondestructive technique for characterization of pavement structure on road networks has gained considerable attention during recent years. High resolution ground coupled GPR has the potential to provide important additional information on pavement deterioration, defects and cracks, the last being the focus of this study. Crack geometry and the electrical properties of the pavement surrounding the crack can be quite variable, resulting in often complex and hard to interpret data. Therefore, numerical modeling has been employed to help understand a range of GPR vertical crack responses observed in a variety of pavements.

## **Objectives:**

This study addressed particular issue on detection and characterization of vertical pavement cracks and joints. Numerical analyses were carried out using GPRMax3D, a GPR simulator based on finite-difference time-domain (FDTD) method.

### Methodology:

Case study: No, Laboratory test: Yes, Field test: Yes, NDT: Yes (Three channel high speed ground coupled RoadMap system, Numerical Analysis: Yes, GPRMax3D

The data from this nondestructive test technique was obtained using the cart based multi-channel SPIDAR and high speed ground couples RoadMap system. The two channel SPIDAR Cart systems with 250 and 1000 MHz GPR data acquisition were carried out at a walking speed, while three-channel high speed ground-coupled RoadMap systems measured data at a speed of 60 to 100 km/hr. In this study, video data was also recorded, which enabled reiteration of pavement surface distresses.

## **Summary:**

The real GPR data sets were validated using numerical models which were performed on a simulated pavement cross-section. The GPR numerical modeling was carried out since real GPR data is complicated to interpret and analyze.

## **Key Results:**

The findings showed that the comparison between the cross-sections from the FDTD numerical models and actual GPR data. A good correlation was observed even though the numerically simulated data did not include traffic and environment noise. The results proved that GPR is another reliable tool to quantify crack propagation although no statistical analysis was shown to support the statement.

NDT methods used: Yes Field: Observation using high speed ground coupled RoadMap system. Lab: Apparatus fabrication: Yes Sample preparation and coring: Yes Analysis: Yes, GPRMax3D, a GPR simulator based on finite-difference time-domain method

### **Reference Number:** [45]

**Year:** 2013

**Commentary:** Driven at regular highway speed, the ultra wideband GPR method can be considered for TDC study. Unfortunately, no review on wave penetration depth found. But, laboratory studies revealed that the wave able to detect rebar approximately 110 mm from concrete slab surface with less than 10% error from the actual depth of rebar.

**Reference:** Xu, X., Xia, T., Venkatachalam, A. and Huston, D. Development of High-Speed Ultrawideband Ground-Penetrating Radar for Rebar Detection. *ASCE Journal of Engineering Mechanics*, Vol. 139, No. 3, March 1, 2013.

## **References Cited:** 24

**Study Sponsor:** U.S. Department of Transportation and U.S. National Institute of Standards and Technology

### Abstract:

This paper presents the development of a new air coupled ultra wideband (UWB) ground penetrating radar (GPR) for highway pavement and bridge deck inspections. Comparing with many existing highway GPRs of low survey speeds, this system can achieve high spatial resolution and high inspection performance while operating on vehicles driving at regular highway speed. For design validation, steel reinforcing bar detection experiments in different setup conditions are conducted.

**Objectives:** The focus of this paper is to locate buried rebars in different medium using UWB GPR.

## Methodology:

Case study: No, Laboratory test: Yes, Field test: No, NDT: Yes, Finite Element Analysis: No

This new technology includes dual-frequency band operation, 8 giga-samples per second highspeed real-time data acquisition, high-speed large volume data transmission and storage and customized signal-processing algorithms for GPR image enhancement and feature extraction. This radar is operated by launching short electromagnetic (EM) pulse from antenna. The reflected and scattered impulses are detected by antenna receiver, stored and analyzed to identify subsurface feature identification. In this study, authors considered a new approach to reduce spatial offset during the wave transition. The high-speed real-time sampling technique was implemented to realize single-shot data collection, where the deflection signal in a complete cycle is obtained in a single trigger event with high reliability.

A series of experimental studies were carried out to quantify the above method. Two rebars at 500 mm interval were tested at different width and using different mediums (air, sand, concrete).

#### **Summary:**

Authors developed a new method for rebar detection using high-speed ultrawideband (0.93-3.1 GHz) GPR. This technology achieved high spatial resolution with excellent inspection performance observed. This nondestructive method, or noninvasive as described by authors, provides beneficial information for highway and bridge deck maintenance and condition monitoring. Typically, there are two types of GPR, ground-coupled and air-coupled. The later is

described the technology introduced by authors. This air-launched ultrawideband (UWB) GPR avoids antennas damages due to rough ground surfaces. It covers longer distance since it is operated at highway speed and did not interrupt traffic flow. At 200 to 500 mm or higher above the pavement surfcae, air-coupled GPR antenna damages are not a major concern to operator. This new and small air-launched UWB GPR was able to be installed at the bottom side of the vehicle. Authors have configured data acquisition unit in multithread operating mode to collect and store more data. In addition, data preprocessing for systematic noise interference reduction were adopted to ensure radar operating efficiency and accuracy.

### **Key Results:**

The laboratory studies revealed that the GPR was able to detect the rebar at approximately 110 mm depth from the concrete slab surface with less than 10% error from the actual depth of the rebar. The error percentages were reduced when the rebar tested via sand and air medium. By using a real-time ADC converter (Agilent Acqiris U1065A) of 8 gigasamples per second (GSPS) sampling rate and 10-bit resolution, the GPR survey speed is significantly improved. It is applicable for highway and bridge inspection at regular highway speed.

NDT methods used: Yes (GPR) Case study: No Field: No Lab: Sample testing and scanning Analysis: Yes

## **Reference Number:** [47]

Year: 2013

**Commentary:** SHRP2 Report on research conducted by National Center for Asphalt Technology (NCAT), Auburn University, Alabama.

**Reference:** SHRP2 Renewal Research, Nondestructive testing to Identify Delaminations Between HMA Layers, Volume 1. Report S2-R06D-RR-1, Transportation Research Board, The National Academies, Washington, DC, 2013.

#### **References Cited:** 74

Study Sponsor: Federal Highway Administration

**Objective and Scope:** The main objective of the second Strategic Highway Research Program (SHRP2) Project R06D was to identify and develop rapid NDT techniques with near 100% continuous coverage that would identify and determine the extent and depth of delaminations and discontinuities in HMA pavements. To achieve this objective, this study examined NDT methods that could identify key indicators commonly associated with potential areas of delamination, including lack of bond, stripping, and segregation. This study focused on NDT technologies with the potential to measure the entire lane width in a single pass at acceptably safe operating speeds. As recommended by the research team's expert panel, the study focused on evaluating and developing any NDT technologies for construction and post-construction inspection and pavement forensic study applications that would be capable of identifying and determining the extent and depth of delaminations in HMA pavements. This study expanded the

number of technologies investigated but did not eliminate the value of speed and full-width coverage. The research team recognized the ultimate desire to develop equipment for network-level capability but first needed to determine that each technology could identify delamination in HMA pavements. The research fostered NDT developments by equipment manufacturers to improve the capability of each technology. The study evaluated NDT technologies for fully bonded and unbonded conditions. While varying degrees of bond exist in real pavements, the research focused on developing equipment that can first identify absolute conditions (i.e., bonded versus unbonded conditions). The research challenged the current state of the technology to develop NDT methods that could effectively determine the existence, extent, and depth of delamination.

### Methodology:

Case study: Yes, Laboratory test: Yes, Field test: Yes, NDT: Yes, Finite Element Analysis: No

Different NDT equipment were evaluated to detect delamination under controlled condition. The controlled condition included ten 25-ft pavement sections constructed at NCAT Test Track neat Auburn, Alabama. Two pavement slabs (8 ft x 4 ft x 8 ft thick) were evaluated in NCAT laboratory for the delamination study. Each equipment was tested at the NCAT Pavement Test Track and the measurements were done under warm-dry and cool-wet pavement conditions, respectively. The NDT equipment evaluated consisted of GPR, IR thermography, and mechanical wave technology. The candidate equipment that demonstrated the best potential towards reaching study's objective was selected for further NDT development and evaluation.

### **Summary:**

This report presents the findings of the first two phases SHRP2 Renewal Project R06D, using nondestructive testing approach, basically to identify delamination between Hot Mix Asphalt (HMA) layers. Initial detection of existence, severity, and depth of delamination in the candidate asphalt layer provide engineers ideas to determine appropriate rehabilitation strategy to extend pavement performance. Traditionally, coring is often used to measure severity, depth and type of delamination. This process requires longer duration and covers shorter test sections. Fortunately, application of nondestructive testing (NDT) was proven to provide quality results, shorter test duration and covers longer test section. In SHRP2 study, NDT hardware devices were able to measure changes in pavement response. However, GPR technology appears to be the only NDT technology that is capable of testing at full lane width and operating at moderate testing speeds.

## Key Results: (Mostly copied from report)

None of the NDT technologies can conclusively distinguish between types of pavement discontinuities. The measurement identifies a discontinuity, or change, in the pavement condition, but cannot determine from the measurement why the change occurred. GPR, Impact Echo (IE), and Spectral-Analysis of-Surface-Waves (SASW) each uses a unique signal measurement that is influenced by the pavement condition. The technician will need to interpret the data and understand how the pavement condition influences the signal. Coring will still be required to confirm the nature of the discontinuity. None of the NDT technologies is capable of identifying partial bond or no bond due to inadequate tack coat during construction.

GPR can identify variations in the pavement layers, isolate the depth of a discontinuity in the pavement, and provide a relative degree of severity. Severe conditions, such as stripping, can be observed with conventional analysis software. Detecting debonding between asphalt layers

with current analysis methodology is possible only when there is moisture trapped in the debonded area between the layers. Software to quantify the extent of discontinuities over a large survey area is needed. IE can identify variations in the pavement below a depth of 4 inches but reliable analysis requires the HMA to be cool and stiff. The measurement has limited ability to provide the degree of severity and cannot measure pavement condition below the top of the discontinuity.

SASW can identify variations in the top 7 inches of the pavement provided that the analysis uses a reasonable value for the stiffness of the pavement. Like IE, the SASW measurement has a limited ability to provide the degree of severity and cannot measure pavement condition below the top of the discontinuity. GPR, IE, and SASW can be valuable project-level tools used independently or in series. As the NDT industry continues to improve both hardware and software, these NDT tools will become more effective tools for pavement evaluation. For example, data analysis software development is needed to make NDT into a network-level tool for detecting delamination in HMA pavements.

NDT methods used: Yes (GPR, IE, SASW) Case study: Yes Field: Yes Lab: Yes Analysis: Yes

#### Reference Number: none

Year: 2013 . The 92nd Annua

**Commentary:** This paper is available in *Compendium of Papers DVD*, The 92nd Annual Meeting of Transportation Research Board, Paper 13-2434, Washington, DC, Jan. 13-17, 2013.

#### **Reference:**

Warren, G., Wix, R. and Leschinski, R. Assessment of Pavement Cracking in Real Time Using Three-Dimensional (3D) Laser Technology and Advances Image Analysis Algorithms, 92nd Annual Meeting of Transportation Research Board Compendium of Papers DVD, Paper 13-2434. Washington, DC, January 13-17, 2013, pp. 1-12.

#### **References Cited:** 4

Study Sponsor: Australian Road Research Board (ARRB)

#### **Abstract:**

The analysis of pavement distress through cracking has provided major challenges for road authorities. Manual methods of analysis lack consistency due to the subjective nature of assessment and issues with image quality. Recent advances in image analysis and illumination have enabled automation of the data collection process, but have limitations in terms of data processing and classification. This paper compares two automated systems, RoadCrack and the Laser Crack 12 Measurement System (LCMS), and recent advances in the integration of these technologies to provide real time cracking analysis.

#### **Methodology:**

Case study: Yes, Laboratory test: Yes, Field test: Yes, NDT: Yes, Numerical Analysis: No

Mississippi DOT State Study 255 – Asphalt Pavement Top-Down Cracking The University of Mississippi – CAIT / Final Report – December 2013 The RoadCrack use high resolution machine vision and advance image analysis. Recently, the ARRB has upgraded the system to a trailer base that combined with lase a laser profiler to provide the full range of pavement condition monitoring findings. The RoadCrack collected real time cracking data and utilized four adjacent modules that are aligned across the pavement, fitted with high resolution line scan camera and lighting system. The images captured were processed in 500 x 600 mm frames and each image was analyzed in real time using the mathematical algorithms developed by Australian CSIRO. The type of crack and severity level were recognized and stored as a single record for each frame. However, the RoadCrack is only 2.4 meter width, thus part of the road surfaces for wider pavement section were not covered during scanning process.

A Pavemetrics 3D lasers mounted on survey vehicle provided another approach to detect surface cracking. This 3D laser technology comprises of two high performance 3D laser unit, fitted vertically to the pavement surface, at the rear of survey vehicle. The high power spread line laser projected onto pavement surface and the image is captured by the camera which interprets the distortions to the straight laser line as variations in the vertical surface profile. The authors reported that the measurements are possible to accuracies of 0.5 mm for depth and 1.0 mm for transversal width. The high frequency analysis identified cracks, while lower frequency analysis provided information to measure rut depth. The survey width is up to 4 meter.

#### **Summary:**

This paper highlighted a new technology used by Australian Road Research Board in the research and development of automated pavement survey system and data collection purposes on Australia's roads. This technology was built upon years of research through development of a number of prototype systems and software for automated cracks detection in 2007, 2008, and 2009. In this study, the automated RoadCrack and the Laser Crack Measurement System (LCMS) were compared and limitations in terms of data processing and classification were discussed. Both technologies enabled observations at normal driving speed.

#### **Key Results:**

The RoadCrack resolution for 4 transverse line scan cameras triggered every 1 mm produced an image pixel spacing of 1 mm x 1 mm at survey speeds up to 100 km/h. In comparison, LCMS's transverse pixel spacing is 1 mm with longitudinal spacing dependent on survey speed but typically 5 mm at 90 km/h. The RoadCrack was proven to produce highly repeatable and accurate results over a range of surfaces, asphalt, sprayed seal and concrete. The LCMS system tested provided good repeatability ( $r^2 = 0.98$ ) and acceptable 18 correlation ( $r^2 = 0.90$ ) with the RoadCrack system in trials on asphalt surfaces. The integration of three subsystems included: 1) the LCMS laser system, 2) the RoadCrack's patented machine vision analysis, algorithms and software libraries, and 3) ARRB's Hawkeye data acquisition and processing. Integrating these technologies can provide cracking type and severity over the full lane width in real time.

NDT methods used: Yes (RoadCrack, LCMS) Case study: Yes Field: Yes Lab: Yes Analysis: Yes

# COST ACTION TU 1208, CIVIL ENGINEERING APPLICATIONS OF GROUND PENETRATING RADAR, PROCEEDINGS, FIRST ACTION'S GENERAL MEETING, ROME, JULY 22-24, 2013 (GPR PAPERS)

No.	Working Group (WG)	References	References Cited	GPR	Surface Crack Evaluation
1		Daniels, D.J. GPR Design Challenges-TUD COST Action TU1208, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	27	Yes	No
2		Utsi, E.C. The Eurupean GPR Association, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	N/A	Yes	No
3		Giannopoulos, A. Ground Penetrating Radar: The Story So Far, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	N/A	Yes	No
4		Trinks, I., Neubauer, W., Hinterleitner, A., Seren, S. and Locker, K. Large-Scale Archaeological Prospection of The Roman Town of Carnuntum Using High-Resolution Ground-Penetrating radar Measurements, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	10	Yes	No
5	Working Group 1 (WG 1): Novel GPR Instrumentation	Manacorda, G., Simi, A., and Scoot, H.F. Design, Realization and Optimization of Innovative GPR Equipment for the Monitoring of Critical Transport Infrastructures and Buildings, and for the Sensing of the Underground Utilities and Voids-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	4	Yes	No
6	Working Group 1 (WG 1): Novel GPR Instrumentation	Gamma, L. Development and Definition of Advance Testing, Calibration and Stability Procedures and Protocols, for GPR Equipments- State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	4	Yes	No
7	Working Group 1 (WG 1): Novel GPR Instrumentation	Persico, R., Masini, N., Ciminale, M., and Matera, L. Reconfigurable Stepped Frequency Ground Penetrating Radar: A Preliminary Experimental Test, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	б	Yes	No
	Working Group 2 (WG 2)				

# COST ACTION TU 1208, CIVIL ENGINEERING APPLICATIONS OF GROUND PENETRATING RADAR, PROCEEDINGS, FIRST ACTION'S GENERAL MEETING, ROME, JULY 22-24, 2013 (GPR PAPERS)

No.	Working Group (WG)	References	References Cited	GPR	Surface Crack Evaluation
8	WG 2: GPR surveying of pavements, bridges, tunnels and buildings; underground utility and void sensing	Matula, R. and Stryk, J. Innovative Inspection Procedures for Effective GPR Surveying of Critical Transport Infrastructures (Pavements, Bridges and Tunnel)-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	33	Yes	No
9	WG 2: GPR surveying of pavements, bridges, tunnels and buildings; underground utility and void sensing	Derobert, X. and Plati, C. Innovative Inspection Procedures for Effective GPR Sensing and Mapping of Underground Utilities and Voids, with a Focus to Urban Area-State of the Art and open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	25	Yes	No
10	WG 2: GPR surveying of pavements, bridges, tunnels and buildings; underground utility and void sensing	Krysinski, L. Innovative Procedures for Effective GPR Inspection of Construction Materials and Structures-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	33	Yes	No
11	WG 2: GPR surveying of pavements, bridges, tunnels and buildings; underground utility and void sensing	Tosto, F. Determination, by Using GPR, of the Volumetric Water Content In Structures, Substructures, Foundations and Soil-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	38	Yes	No
	Working Group 3 (WG 3)				
12	WG 3: EM methods for near- field scattering problems by buried structures; data processing techniques	Ponti, C. Development of New Methods for the Solution of Forward Electromagnetic Scattering Problems By Buried Structures-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	12	No	No
13	WG 3: EM methods for near- field scattering problems by buried structures; data processing techniques	Randazzo, A. and Solimene, R. Development of New Methods for the Solution of Inverse Electromagnetic Scattering Problems By Buried Structures-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	56	No	No

# COST ACTION TU 1208, CIVIL ENGINEERING APPLICATIONS OF GROUND PENETRATING RADAR, PROCEEDINGS, FIRST ACTION'S GENERAL MEETING, ROME, JULY 22-24, 2013 (GPR PAPERS)

No.	Working Group (WG)	References	References Cited	GPR	Surface Crack Evaluation
14	WG 3: EM methods for near- field scattering problems by buried structures; data processing techniques	Lambot, S. Development of Intrinsic Modelsfor Describing Near-Field Antenna Effects, Including Antenna-Medium Coupling, for Improved Data Processing Using Full-Wave Inversion-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	31	No	No
15	WG 3: EM methods for near- field scattering problems by buried structures; data processing techniques	Catapano, I. and Slob, E. Shape-Reconstruction and Quantitative Estimation of Electromagnetic and Physical Properties From GPR Data -State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	50	Yes	No
16	WG 3: EM methods for near- field scattering problems by buried structures; data processing techniques	Economou, N., Vafidis, A. and Benedetto, F. Development of Advance GPR Data Processing Techniques -State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	77	Yes	No
	Working Group 4 (WG 4)				
17	WG 4: Different applications of GPR and Other NDT technologies in CE	Soldovieri, F. Applications of GPR and Other Non-Destructive Testing methods In Archaeological Prospecting and Cultural Heritage Diagnostics-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	51	Yes	No
18	WG 4: Different applications of GPR and Other NDT technologies in CE	Crocco, I. and Ferrara, V. Advanced Application of GPR to the Localization and Vital Signs Detection of Buried And Trapped People-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	15	Yes	No
19	WG 4: Different applications of GPR and Other NDT technologies in CE	Solla, M. Application of GPR In Association with Other Non-Destructive testing methods I Surveying of Transportation Infrastructures-State of the Art and Open Issues, Proceedings of The First Action's General Meeting - "Civil Engineering Applications of Ground Penetrating Radar", Rome, Italy, 22 <sup>nd</sup> to 24 <sup>th</sup> July, 2013.	40	Yes	No
20	WG 4: Different applications of	Dimitriadis, K. and Gracia, V.P. Applications of GPR In Association with other Non-Destructive	6	Yes	No

## COST ACTION TU 1208, CIVIL ENGINEERING APPLICATIONS OF GROUND PENETRATING RADAR, PROCEEDINGS, FIRST ACTION'S GENERAL MEETING, ROME, JULY 22-24, 2013 (GPR PAPERS)

No.	Working Group (WG)	References	References Cited	GPR	Surface Crack Evaluation
	GPR and Other	Testing Methods In Building Assessment and In			
	NDT technologies	Geological/Geotechnical Tasks-State of the Art			
	in CE	and Open Issues. Proceedings of The First			
		Action's General Meeting - "Civil Engineering			
		Applications of Ground Penetrating Radar",			
		Rome, Italy, $22^{nd}$ to $24^{th}$ July, 2013.			