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IDENTIFY CAUSES FOR UNDER PERFORMING RUBBLIZED CONCRETE PAVEMENT PROJECTS

PRCE

PHASE II

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FINAL REPORT

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16. Abstract

When an asphalt concrete is placed on top of an existing concrete pavement, within a relatively short time period (3 to 5 years depending on the thickness of the AC overlay and the pre-overlay repairs of the original concrete pavement), the resulting composite pavement would typically exhibit reflective cracking from the underlying concrete pavement. Since 1986, the Michigan Department of Transportation (MDOT) and other State Highway Agencies are rubblizing concrete pavements to prevent reflective cracking through the bituminous surfaces. Over time, special provisions for rubblizing concrete pavements have evolved (see Appendix A). However, some rubblized pavement projects are very successful and are expected to last their intended design life. Others are under performing and have shown a reduced service life. The under performing pavement sections have shown various types of distress including cracking, rutting and raveling. The overall objective of this study is to determine the causes of under performance of rubblized concrete pavements.

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ABBREVIATIONS

Abbreviations	Meanings
2-D	Two dimensional
3-D	Three dimensional
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
AR	Aged residue
ASTM	American Society for Testing and Materials
BBR	Bending beam rheometer
BMP	Beginning mile post
CRCP	Continuous reinforced concrete pavement
CS	Control section
CV	Coefficient of variation
δ	Phase angle
D1	Deflection at sensor 1
D2	Deflection at sensor 2
D3	Deflection at sensor 3
D4	Deflection at sensor 4
D5	Deflection at sensor 5
D6	Deflection at sensor 6
D7	Deflection at sensor 7
DOT	Department of Transportation
DSR	Dynamic shear rheometer
DTT	Direct tension tester
E	Modulus
EMP	Ending mile post
FEM	Finite element
FWD	Falling weight deflectometer
G'	Storage modulus
G"	Loss modulus
G*	Complex shear modulus
GPR	Ground penetration radar
HMA	Hot mix asphalt
ITCLT	Indirect tensile cyclic load test
ITST	Indirect tensile strength test
ITT	Indirect tensile test
JN	Job number
JPCP	Jointed plane concrete pavement
JRCP	Jointed reinforced concrete pavement

ABBREVIATIONS (continued)

Abbreviations	Meanings
LTDC	Longitudinal top-down cracks
LVDT	Linear variable differential transducer
MC	Medium curing
MDOT	Michigan Department of Transportation
MDT	Mid-depth temperature
MSU	Michigan State University
MR	Resilient modulus
MTS	Mechanical testing & simulation
NDT	Nondestructive deflection test
PAV	Pressure aging vessel
PG	Performance grade
PMS	Pavement management system
PRCE	Pavement Research Center of Excellent
RB	Roadbed
RC	Rapid curing
RCS	Rubblized concrete slab
RMS	Root mean square error
RTFOT	Rolling thin-film oven test
RV	Rotational viscometer
SBR	Styrene-butadiene rubber
SBS	Styrene-butadiene-styrene
SC	Slow curing
SGC	Superpave gyratory compactor
SHA	State highway agency
SHRP	Strategic highway research program
SIS	Styrene-isoprene-styrene
SST	Superpave shear test
STDEV	Standard deviation
TCAC	Temperature corrected asphalt concrete (modulus)
TDC	Top-down cracks
TTDC	Transverse top-down cracks

EXECUTIVE SUMMARY

Rubblization is one of the rehabilitation options for distressed concrete pavements. The main objective of rubblization is to eliminate or to reduce reflective cracking potential. Two types of rubblizing equipment are being used the resonant frequency and the multi-head breakers. Since 1986, the Michigan Department of Transportation (MDOT) has rubblized more than 80 deteriorated concrete pavement projects and, in the main time, has developed and recalibrated special provisions for rubblizing pavements. Some rubblized projects are relatively successful and are expected to last their intended design life. Others are under performing and have shown a reduced service life. The under-performing rubblized pavement sections have shown various types of distress including Top-Down Cracks (TDC), joint reflective cracks, rutting and raveling. Note that TDC is not a unique problem in rubblized pavement. The occurrences of TDC in conventional flexible pavements have been reported by several highway agencies including MDOT.

The main objective of this two-phase study is to identify the causes for the under performing rubblized concrete pavements and to recommend implementable solutions. During the study, several rubblized pavements projects were thoroughly investigated during the rubblization and construction phases and after opening the pavements to traffic. The investigation consisted of:

- Excavating trenches in the rubblized pavements.
- Conducting nondestructive deflection testing and coring.
- Performing laboratory investigation.
- Conducting two manual distress surveys.
- Analyzing rubblized pavements using two and three dimensional finite element models.

Results of the analyses and the laboratory and field investigations indicated that:

1. TDC, joint reflective cracks and raveling are the major distresses contributing to the underperformance of rubblized pavements. The majority of TDC and raveling was found in segregated areas where the AC mix has low density and low tensile strength.

2. The underperformance of rubblized pavements is caused by:

    - Poor and non-uniform quality of the rubblization operation, which leads to joint and reflective cracks and TDC in the rubblized pavements. In this regard, the resonant frequency and the multi-head breakers did not deliver the best possible quality of rubblized concrete, although the resonant frequency breaker delivers, on average, better and more uniform rubblized products than the multi-head breaker. Further, the operation of both breakers and the resulting products often violate the MDOT special provisions for rubblizing pavements.
    - Lack of calibration of the rubblizing equipment.
    - Poor construction quality causing segregation in the AC mix which leads to TDC and raveling.

- Inadequate selection of deteriorated concrete pavement projects for rubblization.

Based on the results of the investigations and the analyses, it is strongly recommended that the following steps be adopted for immediate implementation:

1. Revise the acceptance criteria of the MDOT special provision for rubblizing concrete pavements to include:

   - The scoring scheme of the quality of rubblization presented in chapter 4.
   - The calibration procedure presented in chapter 4.
   - Maximum variation of 20 percent in the peak pavement deflection measured at any 10 points spaced at 5-feet along the pavement and at any 5 points spaced at 2-feet across the pavement.

2. Strictly enforce the MDOT special provision for rubblizing concrete pavements.

3. Strictly enforce quality control measures to eliminate segregation in the asphalt courses. This could be achieved by officially adopting the implementation of the segregation program.

4. Provide the Regions and the Transportation Service Centers a list of deteriorated concrete pavements that should not be selected for rubblization (see chapter 4).

5. Implement the layer coefficients and/or modulus values of the rubblized materials presented in chapter 6.

As an alternative to method specifications, the following performance measures are highly recommended for inclusion in a 5-year warranty period.

1. No longitudinal and/or transverse top-down cracks.
2. No reflective or regular transverse or longitudinal cracks.
3. No faulting (differential elevation) between two adjacent lanes.
4. No shear failure.
5. No raveling
6. Less than 0.25-inch rut depth.

CHAPTER 1
INTRODUCTION AND BACKGROUND

1.0 INTRODUCTION

Substantial resources are required to preserve and rehabilitate the aging highway systems, which are subjected to increasing traffic demand. Over time, various alternatives have been developed and used for the rehabilitation of deteriorated concrete pavements. These include:

- Bonded and unbonded concrete overlays.
- Full depth repair with and without asphalt overlay.
- Crack and seat with asphalt overlay.
- Joint and crack repairs with and without asphalt overlay.
- Rubblization with asphalt surface overlay.

When an asphalt concrete is placed on top of an existing concrete pavement, within a relatively short time period (3 to 5 years depending on the thickness of the AC overlay and the pre-overlay repairs of the original concrete pavement), the resulting composite pavement would typically exhibit reflective cracking from the underlying concrete pavement. Since 1986, the Michigan Department of Transportation (MDOT) and other State Highway Agencies are rubblizing concrete pavements to prevent reflective cracking through the bituminous surfaces. Over time, special provisions for rubblizing concrete pavements have evolved (see Appendix A). However, some rubblized pavement projects are very successful and are expected to last their intended design life. Others are under performing and have shown a reduced service life. The under-performing pavement sections have shown various types of distress including cracking, rutting and raveling. The overall objective of this study is to determine the causes of under performance of rubblized concrete pavements (detailed research plan and objectives are presented in Chapter 2).

This study was originally divided into two phases. In the Phase I Study, rubblized concrete pavements were investigated by mainly excavating trenches through the rubblized materials before the asphalt concrete (AC) was placed. Some trenches were made at mid-slab while others were made at old transverse joints and cracks. In some trenches, drainability tests were conducted. The objectives of the trenches were to determine:

- The depth of rubblization
- The degree of debonding of the temperature steel
- The integrity of the concrete joints
- The size distribution of the rubblized material
- The permeability of the rubblized material

In addition, few rubblized projects that were constructed earlier and were showing signs of early distress were subjected to nondestructive deflection tests (NDT) and then cored. The NDT data were used to assess the variation in the structural capacity of the pavement along and across the traffic lane. The cores, which were taken over cracks, were examined to determine the status of the cracks (e.g., bottom-up or top-down cracks (TDC)). Results of the investigation were included in an interim report that was submitted to MDOT at the conclusion of the Phase I Study. The report presents and discusses the advantages and shortcomings of the rubblization procedure. It is shown that well-executed rubblization and construction practices (rubblization and asphalt placement) lead to good performing pavements. Further, for certain concrete pavements rubblization is not a viable option, as it may lead to inadequate pavement performance.

The investigation in the Phase II Study consisted of four activities as follows:

1. Field Investigation - Extensive NDT were conducted and cores over cracked and non-cracked areas were extracted. The deflection data were used to backcalculate the pavement layer moduli and to determine the variation in the deflection data along and across the pavements. The cores obtained from cracked areas were examined to confirm the existence of TDC.

2. Lab Investigation – The cores that were extracted from non-cracked areas were subjected to indirect cyclic tensile stress and indirect tensile strength tests. The data were used to calculate the laboratory resilient modulus and the indirect tensile strength of the asphalt concrete.

3. Mechanistic Analysis – The layer moduli obtained from the backcalculation and the layer thicknesses were used in two- and three-dimensional finite element programs to determine the load-induced stresses in the pavement structure. The analyses were designed to study the effects of the thickness of the rubblized material and the geometry of the interface between the rubblized and the fractured portions of the concrete on the magnitude of the load-induced stresses.

4. Pavement Performance – Available historical rubblized pavement distress data were obtained from MDOT and examined against those obtained from manual distress surveys. The data were used to determine the predominant type of distress in rubblized pavements and the possible causes of premature distress.

2.0 BACKGROUND

Three of the rehabilitation options that are used to preserve distressed concrete pavements are concrete repair and bituminous overlay, crack and seat and bituminous overlay and rubblization and bituminous surfacing. In general, the pavement design life for the first two options ranges from 8 to 12 years compared to 20 years for rubblized pavements. Since 1988, MDOT has constructed 86 rubblized projects. Each project was designed to perform for a 20-year period. The original rigid pavements that were selected for rubblization had a variety of distress conditions, traffic volumes and base/subbase and roadbed soil support.

Using the pavement management system, MDOT has analyzed the performance of rubblized pavements constructed to date. Based on a network type analysis, the data indicates that

some rubblized pavement projects are very successful and are expected to last their intended design life of 20 years. Others are under performing and have shown a reduced service life. The poor performance of some rubblized projects was investigated by MDOT. Cores obtained from under performing pavements were examined. The investigation did not yield consistent results relative to the causes of the poor performance. Subsequently, the problem was referred to the Pavement Research Center of Excellence (PRCE) at Michigan State University (MSU). Various projects that were rubblized over the last 14-year period as well as projects that were rubblized during the 1999, 2000, and 2001 construction seasons were investigated. This report presents and discusses the results of the investigation.
The report is organized in eight chapters and eleven appendices as follows:

Chapter 1 - Introduction and Background
Chapter 2 - Research Plan
Chapter 3 - Field and Laboratory Investigations
Chapter 4 - Rubblization
Chapter 5 - Backcalculation of Layer Moduli
Chapter 6 - Pavement Design Parameters
Chapter 7 - Mechanistic Analysis
Chapter 8 - Conclusions and Recommendations

Appendix A - Special Provision for Rubblizing Portland Cement Concrete Pavements
Appendix B - Field Investigation Conducted During the Rubblization Operation
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Appendix F - Core and Specimen Measurements
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Appendix I - Indirect Tensile Strength Test Results
Appendix J - Backcalculated Layer Moduli
Appendix K - Literature Review

CHAPTER 2
STUDY OBJECTIVES AND RESEARCH PLAN

1.0 STUDY OBJECTIVES

The objectives of this study are divided into four categories and are presented below.

1.1 The Rubblization Procedures

Although the Phase I Study identified various equipment and rubblization procedure factors that affect the quality of rubblization, the relative impact of each factor on pavement performance and their interaction are not known. Hence, the objectives include:

1. Prioritize the various equipment and rubblization procedure factors that affect the quality of rubblization.

2. Develop detailed procedures to calibrate those factors before the commencement of rubblization.

3. Assess, if possible, the impact of each factor on the quality of rubblization and perhaps on pavement performance.

4. Identify when possible those factors that produce good and poor rubblization procedure, based on pavement performance and/or distress data.

1.2 Project Selection Process

The objective in this category is to develop an engineering investigation plan for the selection and construction of rubblized projects. The plan should address two areas as follows:

1. **Engineering Investigation** – Determine the types of distress data that need to be analyzed and the type of investigation, tests, and field sampling that need to be undertaken before a decision is made to consider rubblization as an alternative fix.

2. **Special Provision** - Based on the results of the engineering investigation, develop a plan detailing the steps that must be taken during rubblization and construction that lead to good pavement performance. The details of each step could be used by MDOT to develop performance-based specifications for rubblized pavements.

1.3 Factors Affecting Pavement Performance

During the Phase I Study, both successful and under-performing rubblized projects were investigated and nondestructive deflection data were collected. Although the data were used to compare various rubblized projects, due to time constraints (short duration of the Phase I

Study), complete analysis and assessment of the data were not undertaken. In this phase, the data were fully analyzed to accomplish the following objectives:

1. Determine rubblization and construction procedures, equipment and material factors that influence pavement performance.

2. Delineate and rank the above factors based on their impact on pavement performance.

3. Identify and rank the factors that have contributed to the under performance for each under performing rubblized project that was included in the Phase I Study.

4. Identify, when possible, the steps that must be taken to resolve the problem for each factor affecting pavement performance.

The results could be used by MDOT to develop performance-based specifications for rubblized pavements.

1.4 Pavement Design and Design Parameters

The design of rubblized pavement sections is typically constrained by the existing pavement cross-section. That is the pavement designer has no control over the thickness of the existing subbase material or the rubblized material. During the pavement design procedure, the pavement designer could determine the required thickness of fresh aggregate to be placed and compacted on top of the rubblized material prior to placing the AC and the required AC thickness if accurate input data are available. Hence, there is a need to determine the engineering properties of the existing and rubblized materials using deflection data. In lieu of this, the objectives of this part of the study are:

During the Phase II Study, the deflection data that were collected during the Phase I Study will be analyzed along with the pavement cross-section. The objectives of the analysis are:

1. Design and implement NDT test layout for the collection of representative deflection data.

2. Use the deflection data to determine the engineering characteristics (layer coefficient and resilient modulus) of the rubblized material to be used in the design process.

3. Conduct full engineering analysis of various rubblized pavement projects to determine the most likely design service life. The outcome of the analysis should indicate whether or not a rubblized pavement could be designed using a 20-year design life period.

4. Assess the impact of the as-designed pavement section on achieving the desired design service life.

5. Validate whether or not the AASHTO design procedure can be used to determine the thickness of the asphalt layer on rubblized pavement.

2.0 RESEARCH PLAN

To accomplish these objectives, a research plan was drawn and successfully executed. The plan consisted of the following tasks:

Task 1 – Quality of Rubblization – In this task, the term "quality of rubblization" will be defined. Several factors are proposed to be included in the definition are listed below.

After complete removal of the AC overlay, AC patches and filler material, and after only one pass of the rubblizing equipment, the quality of the rubblized concrete pavement should be determined based on several factors including:

- The maximum size of the rubblized material or the number of large concrete pieces that need to be broken using a grid roller or a jackhammer.
- The depth of the rubblized material and the thickness of the fractured concrete.
- The degree of debonding of the reinforced steel.
- The number of occasions where large concrete pieces rotate and/or penetrate the subbase material.
- The degree of segregation (coarse versus fine) that can be observed on the surface of the rubblized material.
- The variation in the density and perhaps the thickness of the rubblized material and/or fractured concrete.

This task can be accomplished based on:

1. Visual observations of the rubblization procedure using the considerable data that have been accumulated in the Phase I Study.

2. Examination and analysis of the nondestructive deflection data that have been collected during the Phase I Study. Based on this analysis, a nondestructive test procedure will be developed and implemented to verify the quality of rubblization and to assess the variation in the structural capacity along and across the rubblized pavement and before placing the AC layer. Although a Ground Penetrating Radar (GPR) could be used to detect the thickness and density of the rubblized material and the thickness of the fractured concrete, its costs are not included in the cost estimates of this proposal. If the GPR industry is willing to demonstrate the equipment potential, the findings will be included in the final report of the study.

This task will also explore the possibility of defining the quality of rubblization based on pavement performance.

Task 2 – The Rubblization Factors – In this task, the impact of the various rubblization factors such as speed, frequency, height of hammer drop, degree of overlapping, shoe width and compaction on the quality of rubblization will be prioritized. The activities in this task will also explore the possibility of prioritizing the rubblization factors based upon their impact on pavement performance.

Task 3 – Distress Data – In this task, available historical distress data will be examined against the deflection data that were collected during the Phase I Study. Given that the magnitudes and variations of the deflection data are indicators of the structural capacity of the pavement, the objective of the examination is to determine whether or not the deflection data can be used as a predictor or as an early warning of premature distress.

Task 4 – Compaction - Analysis of the deflection data collected during the Phase I Study indicates that the density and stiffness of the rubblized material are highly variable across the pavement. Such variations are likely the direct results of variation in the compaction of the rubblized material and the variation in the thickness of the fractured concrete. Hence, better compaction procedure, compaction specification, or quality control measures should be developed. The implementation of this recommendation would reduce the relatively high variation in the pavement deflection and it would likely results in enhanced pavement performance. In this regard, note that because of the presence of temperature steel, nuclear density gauges cannot be used to estimate the density of the compacted rubblized material. Hence, a new procedure must be developed. Such procedure could be based on the variation in the deflection data.

Task 5 – Factors Affecting Pavement Performance – The factors that affect pavement performance could be divided into four categories. Three of these categories are directly related to the three steps of rubblizing pavements stated in the introduction of this proposal. The fourth one is related to material and project selection.

The activities in this task will include:

1. Careful examination of all rubblization-related data (rubblizing procedure, deflection, distress, and material) that were collected during the Phase I Study.

2. Collecting other data elements such as the asphalt mix design and the type of binder used in the mix and the as-designed cross-section data.

3. Although various projects were visited during the Phase I Study, in all visits, only the rubblization procedure was observed and examined. During the Phase II Study, several projects will be visited and the construction of the asphalt layer will be carefully observed. The objective is to determine the differences, if any, between the constructions of the asphalt layer in conventional flexible pavement and in rubblized concrete pavement.

4. All projects that were visited during the Phase I Study will be revisited again. The purpose is to examine the pavement surface where trenches were excavated in the rubblized material. Since the locations of the trenches and the variation in the thickness of the fractured concrete were well documented during the Phase I Study, such examination would indicate the impact, if any, of the variation of the fractured concrete on pavement surface distress.

5. The detailed nondestructive deflection data that were collected during the Phase I Study on various rubblized projects will be examined against the pavement surface condition. The purpose of such examination is to determine the effects of the variation in the as-constructed deflection data on the pavement surface condition.

6. Some of the projects that were FWD tested during the Phase I Study will be FWD tested again. Differences in the deflection data would indicate differences in the structural capacity of the pavement and the effects of one or two years of traffic.

7. The historical distress data collected on projects that were rubblized prior to the 1999 construction season and were included in the Phase I Study will be analyzed against all other data, in general, and the FWD data, in particular.

The outcome of this task is to determine the true causes of the underperformance of some rubblized projects. Those causes will be classified in the four categories stated above. If possible, the differential impact of each cause on pavement performance will also be determined.

One other objective of conducting FWD tests (item 6 above) is that analysis of the historical FWD data would lead to 5-year performance based criteria, which can be used in future design and warranty projects. Such analysis must include the backcalculation of the layer moduli and the variation of the deflection data collected across and along the pavement structure.

Task 6 – Finite Element Analysis – Through the use of the measured deflection data and the three dimensional topography of the trenches that were excavated during the Phase I Study, three-dimensional finite element analysis will be conducted to obtain the pavement response due to single and multiple loads. The objective of the analysis is to determine the impact of the variation in the thickness of the fractured concrete on pavement response. It should be noted that during the Phase I Study, the potential of finite element analysis was explored using a single load (single tire) configuration. In the Phase II Study, multiple loads (dual tires) will be used in the analysis. The results of the analysis will be used to determine whether or not dual tires apply reverse bending action, which causes cracks to initiate at the pavement surface.

Task 7 – Implementation Plan – Based on the results of the study, an implementation plan will be developed. Some of the results could be implemented and verified during the study. Others could be implemented by MDOT after the proper approval.

3.0 HYPOTHESES

To this end, it was hypothesized that:

1. The average and the range of performance of rubblized concrete pavements are similar to conventional flexible pavements. This hypothesis is based on the assumption that the rubblized materials would have similar performance as that of conventional aggregate bases. When rubblized materials do not perform like conventional aggregate base, there exists a relationship between the rubblization procedure and the degree of under performance of the rubblized materials. Such relationship is affected by various factors including:

    - The operating parameters of the rubblizing equipment.
    - The type and the state of distress of the original concrete pavements being rubblized.
    - The degree of support provided by the existing subbase and roadbed soil.

2. There is a relationship between top-down cracks (TDC) potential and differential stiffness among the various asphalt concrete courses and among the asphalt concrete layer and the rubblized material. Said differential stiffness causes higher load-induced tensile stresses and higher TDC potential. Differential stiffness between the asphalt concrete courses and between the asphalt concrete and the rubblized material is affected by several factors including:

    - Construction, which may cause particle and temperature segregations in the asphalt mixes.
    - The types of the asphalt mixes.
    - Temperatures.
    - Differential aging.
    - The quality of the rubblization procedure.
    - Combination thereof.

    This hypothesis is based on field observation where the majority of cracks found in under performing rubblized concrete pavements were TDC that initiate at the top of the asphalt surface and over time propagate downward and outward.

3. There exists a relationship between the pavement's deflection response function and the degree of under performance of the rubblized concrete pavements in the form of the variability of the deflection along and across the pavements and the shape of the deflection basins. The characteristics of such variability and shape indicate the different manners by which the pavement attenuates energy induced by the passage of

a vehicle. Such relationship is affected by various variables including:

- The quality of the rubblization procedure and the type of the rubblized material produced.
- Differential stiffness between the various asphalt courses and between the asphalt concrete layer and the rubblized material.
- The as-designed pavement thickness.
- The type of the asphalt mixes.
- Construction variability such as segregation of the asphalt mix and high variability in the asphalt mat thickness
- Combination thereof

To accomplish the above stated objectives and to verify the hypotheses, a research plan was drawn and is presented in the next section.

4.0 ACTIVITIES

To accomplish the objectives and to verify the hypothesis of this study, various activities were designed to be undertaken. These include:

4.1 Literature Review

4.2 Field Investigation

The field investigation in this study consists of four activities as follows:

1. **Falling Weight Deflectometer (FWD) Tests** - For each selected 100-ft long test site, 30 to 40 FWD tests will be conducted along and across the pavement. The deflection data will be used to determine the engineering characteristics of the various layers and to assess the variability of the pavement support.

2. **Pavement Cores** – 6-in. diameter cores will be extracted from the pavement at each test site. The number of cores per site will be determined after visual examination of the pavement and review of the pavement management distress data. The average thickness of the cores will be used in the backcalculation and the cores will be tested in the laboratory to determine the resilient moduli of the asphalt mixes.

3. **Trenches** – Trenches will be excavated in the rubblized concrete slab prior to the placement of the AC layer and the variability of the rubblized material will be examined.

4. **Distress Survey and Distress Data** – Two distress surveys will be conducted to fill the time gap in the MDOT distress data. The data will be used to determine the degree of underperformance of rubblized pavements.

4.3 Laboratory Investigation

The lab investigation in this study consists of four major activities as follows:

1. Core Examination - All cores that were taken in distressed areas such as cracks will be thoroughly examined to determine the extent of distress and the dimensions of the crack. Special attention will be given to the depth and width of the crack. Crack depth would indicate the extent to which the bituminous courses have been cracked. Variation in crack width would indicate whether the crack was initiated at the top or bottom of the pavement. This information is very critical to determine the location of the highest tensile stress in the pavement and the boundary conditions.

2. Specific Gravity Tests - All pavement cores will be subjected to specific gravity tests. The results will be used to determine variations in the compacted AC mix along and across the pavement.

3. Indirect Tensile Cyclic Load Test (ITCLT) – ITCLT will be conducted to determine the resilient modulus of each asphalt mix.

4. Indirect Tensile Strength Test (ITST) - ITST will be conducted to determine the indirect tensile strength of each asphalt mix.

4.4 Analysis

The analysis in this study involves both empirical- and mechanistic-based investigations of the root causes and mechanisms of premature distress. The analyses address the high number of variables involved in rubblizing concrete pavements and surfacing with bituminous material. Said variables affect the pavement's performance and the type and mechanisms of premature distress. Such effects vary from one project to another. Therefore, the data analysis plan to be used in this study must be flexible in nature and it must be adjusted and calibrated to fit each project scenario.

In addition, the outcome of the analysis must address the engineering properties (modulus) and structural capacity (AASHTO layer coefficient) of the rubblized material. Such outcome is also affected by an unknown degree of variability along and across the pavement structure. Therefore, the following steps of the proposed data analysis plan are presented in generic terms.

1. Variability along the Project - The variability along a pavement section will be assessed using the FWD data, the distress data, the nuclear density data and the lab test data. The FWD data will yield information regarding the variability of the structural capacity of the pavement. The variability in the distress data indicates the over all variability that affects pavement performance. The nuclear density data would identify variability in the bituminous surface course only. The lab data would describe variability due to compaction, segregation and strength.

2. Cracks will be investigated through examination of those pavement cores that were taken over the cracks. The initiation of the crack is important in determining the cause of the distress. A thorough investigation of the cores will be done to determine:

   - The widths of the cracks at the pavement surface and at the bottom of the bituminous course (the crack end). This will help to determine the location of the highest tensile stress and the direction of bending.
   - The crack spacing in both the horizontal and vertical directions. Horizontal cracks indicate shear failure and/or lack of adhesion. Vertical cracks indicate either fatigue or bearing capacity types of failure.

3. The engineering properties of some pavement cores will be determined using cyclic load tests. The results will be compared to the modulus values obtained from MICHBACK. The results will be used to:

   - Conduct mechanistic analysis of the pavement sections to assess the magnitudes of the induced stresses and strains.
   - Characterize the properties of the various pavement layers and suggest design values (layer coefficients and modulus). These include the properties of the asphalt layer as well as the properties of the rubblized concrete slabs. It should be noted that the modulus values of the rubblized concrete slabs are currently not known and the validity of their correlation to the layer coefficient will be investigated.
   - Verify the findings of the study titled "The Engineering Characteristics of Michigan's Asphalt Mixtures."

   In addition, some cores will be subjected to indirect tensile strength to determine the field applied stress ratio due to traffic load. Results from the cyclic load and tensile strength tests will be used to calculate the modulus value of the asphalt layer. From the modulus values, the layer coefficients could be determined. The layer coefficient of the rubblized concrete slab is the desired value as little is known about its validity.

During the analysis, special efforts will be used to assess the mechanisms and the root causes of distress. Based on the results, remedial actions will be recommended to the rubblization and asphalt paving processes. Further, current MDOT specifications and regulations will be reviewed in lieu of the findings and possible modifications will be recommended.

4.5 Verification

All developed procedures will be verified using measured deflection data along and across a pavement section. The results of empirical and/or statistical equations will be verified using the measured deflection data. The performance of rubblized pavements will be analyzed using both the MDOT distress survey data and manual survey

CHAPTER 3
FIELD AND LABORATORY INVESTIGATIONS

1.0 GENERAL

During the Phase I and Phase II study, 88 rubblized and 3 flexible pavement projects were investigated to determine the causes of underperforming rubblized pavements. The investigations consisted of 2 categories; field and laboratory. The field investigation consisted of the following activities:

- Excavating trenches in the rubblized concrete slab prior to the placement and compaction of the AC layer.
- Conducting nondestructive deflection tests along and across the pavements in a predesigned pattern.
- Extracting cores from the pavements.
- Conducting manual distress surveys of rubblized pavements

The laboratory investigation consisted of the following tests:

- Measurements of the thickness of each AC course in the core and the total thickness of the cores.
- Specific gravity tests of the total cores and each of the AC courses.
- Indirect tensile cyclic load tests to determine the resilient modulus of the cores.
- Indirect tensile strength tests.

Details of the field and laboratory investigations are presented in this chapter.

2.0 FIELD INVESTIGATION

All pavement projects that were rubblized between the 1987 and 2001 construction seasons were investigated in this study. In addition, three conventional flexible pavement projects were also investigated. Two of these projects were constructed in 2000 and one in 1994. As stated above, the field investigation consisted of excavating trenches during the rubblization operation, conducting FWD tests and pavement coring after the completion of construction, and manual distress surveys. Details of the investigation are presented below.

2.1 Investigation during the Rubblization Operation

In this study, fifteen rubblized projects were investigated during the rubblization operation. The main objective of the investigation is to evaluate whether or not the rubblization operation satisfied the following four objectives of rubblizing pavements:

1. Breaking the concrete slabs into small pieces (less than 6-in. maximum dimension). This would eliminate independent movement of large pieces and would increase the degree of interlocking between the broken concrete pieces.

2. Debonding the temperature steel to decrease the amount of temperature expansion and contraction of the rubblized concrete slab and, hence, to eliminate the potential of reflective cracking.

3. Destroying the integrity of the concrete joints to prevent reflective cracking.

4. Eliminating or decreasing the potential of rubblizing the concrete slab into two distinctive layers; a rubblized layer and a fractured concrete layer. The two layers when capped with asphalt concrete would behave like a sandwich model (a soft layer between two hard layers). The differential stiffness between the three layers causes high load-induced tensile stress at the top of the AC causing top-down cracks (TDC).

During the rubblization operation, several trenches were excavated in the rubblized concrete slabs. Some trenches were located at mid-slab, others were located at joints and still others were located at a transverse crack. After excavation, the rubblized materials were piled to form the walls of a pool, the floor of the pool consisted of the fractured concrete. The pool was filled with water to test the permeability of the fractured concrete. Results of the investigation indicated that:

1. The rubblization operation produces two different layers in the rubblized concrete slabs, a rubblized material layer at the top and a fractured concrete layer at the bottom as shown in figures 3.1 and 3.2. The thickness of each layer varied from one location to another. In some areas, the fractured concrete extended to the original pavement surface while in other locations the rubblized material extended to the bottom of the original concrete slab. Further, the stiffnesses of the two layers were substantially different. It was estimated that the stiffness of the fractured concrete is an order of magnitude higher than that of the rubblized material layer. Such differential stiffness causes high load-induced tensile stress at the top of the AC surface, which increases the potential for TDC.

2. At a few locations, the temperature steel was debonded from the original concrete as shown in figure 3.3. However, at most locations, the integrity of the bond was not broken.

3. At some longitudinal and transverse joints, the integrity of the joints in the original slabs was not completely destroyed (see figure 3.4) and some dowel bars were found embedded in the concrete on both sides of the joint. These may cause the development of reflective cracks.

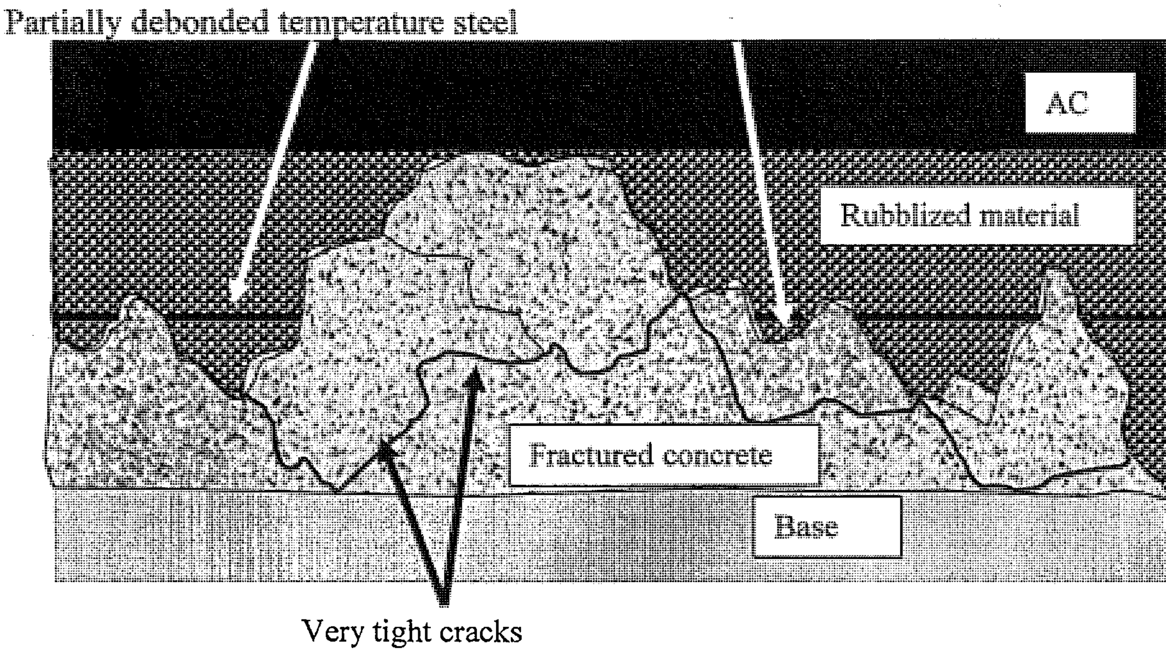


Figure 3.1 Schematic of rubblized concrete slab showing rubblized and fractured layers

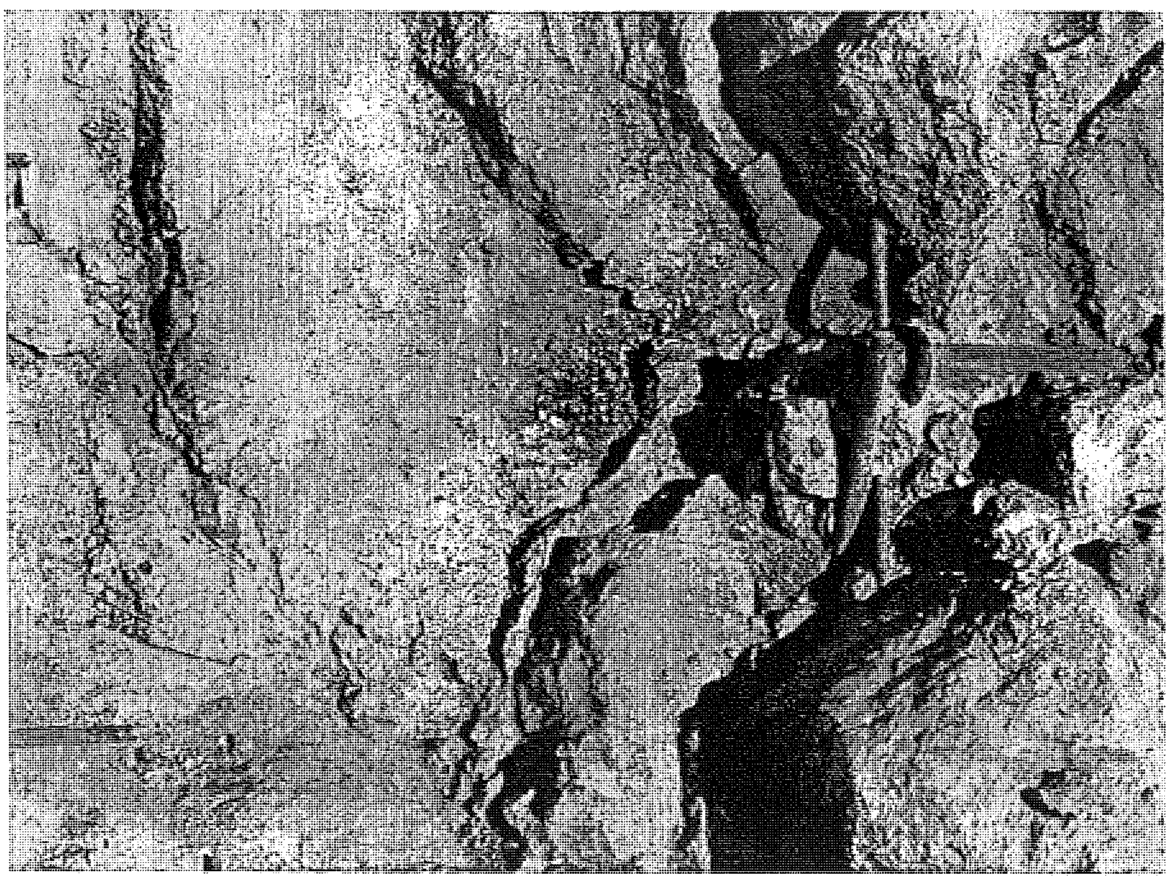


Figure 3.2 Close-up of the fractured concrete in a trench (M50)

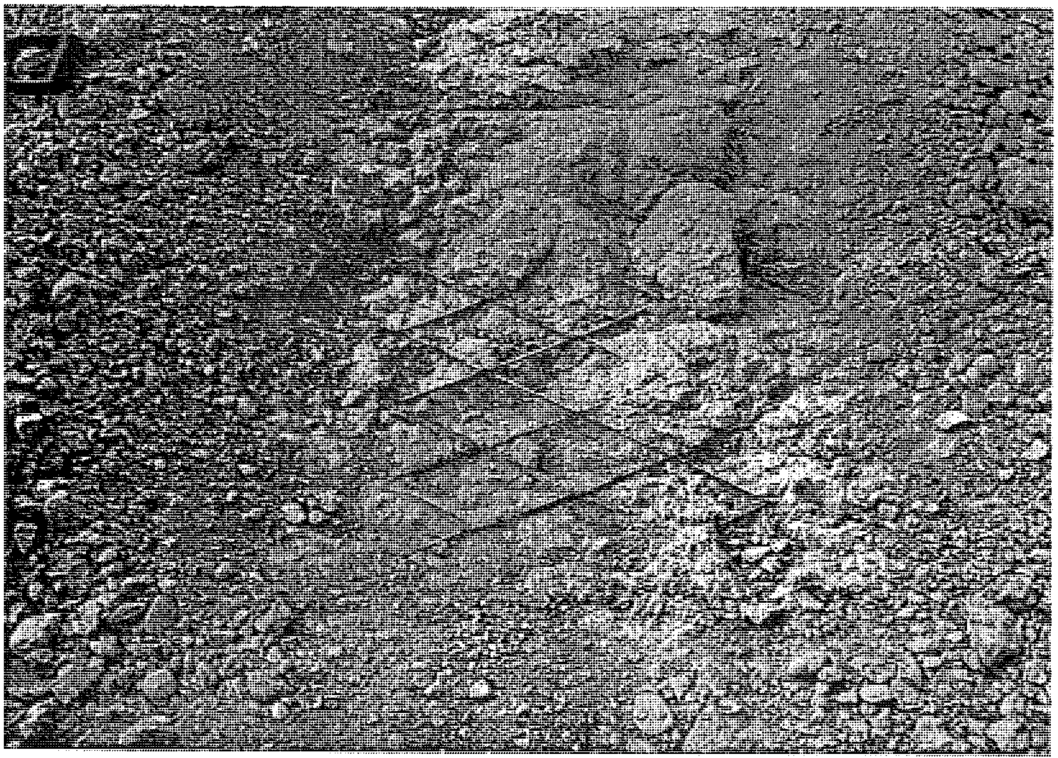


Figure 3.3 Partial debonding of the temperature steel (M21)

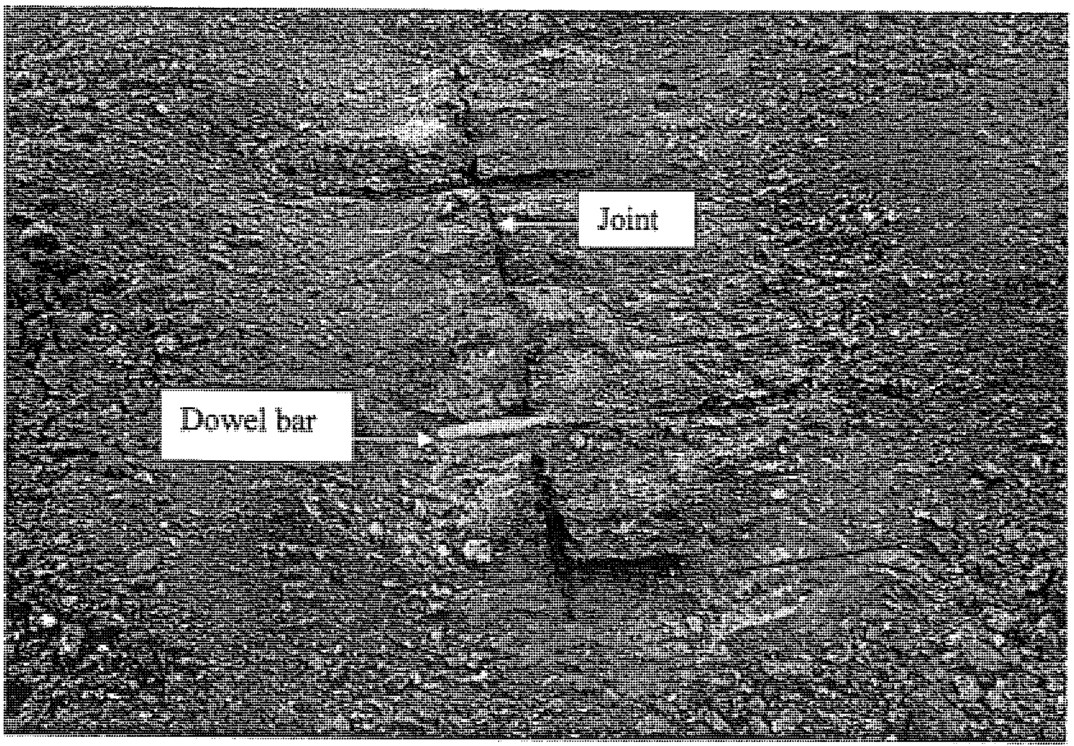


Figure 3.4 Partial destruction of the joint integrity (US 131)

4. On some projects, the drainability of the fractured concrete layer was poor (see figure 3.5). The layer would trap water that infiltrates through cracks in the asphalt layer. The trapped water under the asphalt layer would increase the stripping potential of the asphalt layer.

5. At some locations, the rubblization procedure caused some large concrete pieces (larger than 6 in.) to rotate and penetrate the underlying base or roadbed material. This implies that the base and/or the roadbed soil have failed in shear action (bearing capacity). This failure is mainly caused by soft base and/or roadbed soil.

6. For some projects, the frequency of the hammer drops and the speed of the equipment were set such that some large concrete pieces that were broken due to the impact of the first row of hammers were often struck again by the second row of hammers. At some locations, the second strike drove the broken concrete into the base/subbase layer causing shear failure. Such localized shear failure may cause depression in the AC. Calibration of the rubblizer speed and the drop frequency can overcome this problem.

7. On four projects (Old US-131, M-18, M-21 and M-53), after the water was placed on the fractured concrete surface, air bubbles were observed coming out of the cracks. When the cracks were saturated, the air bubbles stopped and the water did not drain. Another observation is that the water did not drain or permeate horizontally through the loose rubblized material, which made the pool walls. The implication of this observation is that if water infiltrates the asphalt layer through cracks, it could be trapped. This trapped water may cause softening of the loose rubblized material and stripping in the asphalt layer, which may lead to a lower pavement performance.

Tables 3.1 and 3.2 provide a summary of observations made during the Phase I Study of this investigation. The details were reported in an interim report that was submitted to MDOT at the conclusion of the Phase I study and are included in Appendix B of this report.

As can be seen from table 3.1, some of the pavement projects included in the investigation were rubblized using the multi-head breaker (for equipment details, see chapter 4) while others using the resonant frequency breaker. Examination of the rubblized materials and the fractured concrete and results of the permeability tests conducted in the trenches revealed two sets of information regarding concrete rubblization using the resonant frequency breaker and the multi-head breaker. The information is presented below along with the observations made during the drainability tests. The detailed observations are included in Appendix B.

2.1.1 The Resonant Frequency Breaker

The following observations are related to the operation of the resonant frequency breaker.

Table 3.1 Rubblizing equipment and the locations of trenches excavated at each project investigated during the Phase I Study

No	Project	Control section	Job number	Region	BMP	EMP	Rubblizing equipment	Trench locations
1	US-10 EB	67022	44986	North	9.657	12.087	Multi-head	19+867 - MS 20+144 - MS 20+389 - MS
2	US-23 SB	01052 04031 04031 04031 04031	32335 32335 32335 32335 44350	North	16.369 0.000 0.449 1.404 4.218	16.393 0.241 0.908 2.248 7.893	Resonant	465+21 -MS 465+85.5 - TJ
3	US-31 NB	10032	44113	North	11.430 13.905	13.874 14.340	Multi-head	26+130 - MS 26+652 - MS 26+680 - MS 27+324 - TJ 27+385 - TJ
4	US-31 SB	05011	44109	North	0.923	3.019	Multi-head	2+200 - MS 2+637 -MS
5	US-131 SB	41133 59012	33914	Grand	3.200 0.000	8.691 4.214	Resonant	37+558.5 - MS N/A - TJ N/A - MS
6	Old US-10 EB	56555 56041	48370	Bay	7.114	9.513	Resonant	25+064 - MS 25+594 - MS
7	Old US-131 NB	41401 41013	49321 45797	Grand	2.669 0.000	2.820 2.232	Resonant	9+858 - MS 10+690 - MS 11+641 - MS
8	M-18	26011	45410	North	4.860	12.000	Multi-head	3+180 - MS 3+194 - MS 4+034 - TJ
9	M-21	25081	38028	Bay	4.981	7.285	Multi-head	1+200 IL - MS 1+200 OL - MS 1+309 IL - TC 1+684 IL -MS
10	M-50	58042	43523	Univ.	0.143	4.521	Multi-head	10+441 -MS 10+803 - MS 11+151 -MS 12+000 - TJ
11	M-53	50012 44031	36021	Metro Bay	4.438 0.000 2.820 6.466	4.458 1.588 6.130 6.940	Multi-head	53+621 - MS 53+886 - TJ 53+900 - MS 54+210 - MS
12	Portage Road	39405	49551	SW	0.000	1.125	Resonant	3+609 - MS 3+901.5 - MS
13	Chicago Drive			Grand			Resonant	149+22 MS and 146+26 MS
14	US 27	37014	38205	Bay	0.00	1.53	Multi-head	1 trench MS and 1 at TJ
15	Beecher Road	STU25 402	50078 A	Bay			Multi-head	1+480 MS, 1+485 TJ, 1+322 MS and 1 + 140 MS

IL =Inner lane, OL =Outer lane, TJ =Transverse joint, MS =Mid-slab, TC =Transverse crack

Table 3.2 A summary of rubblization variables and observations made during the investigation of various projects

No.	Project	Rubblization process	Results of drainability tests
1	US-10 EB	• The quality of rubblization of the original concrete lane and widening strip varies from one location to another.	• Good drainage.
2	US-23 SB	• The quality of rubblization was poor along the concrete widening strip. • The original concrete lane was well rubblized to depths below the temperature steel., well-fractured concrete at the bottom • Poor rubblization at a transverse joint.	• No tests were conducted.
3	US-31 NB	• Most aggregates were broken, which indicates that the strength of the aggregate is less than that of the cement paste. • The quality of rubblization was good in all five trenches.	• Good drainage.
4	US-31 SB	• Shallow rubblization. • No steel was debonded in two trenches.	• Water drained laterally because of super-elevation.
5	US-131 SB	• Good rubblization in all three trenches. • Dowel bars were exposed.	• No tests were conducted.
6	Old US-10 EB	• Excellent rubblization through the entire concrete thickness in both trenches.	• Excellent drainage.
7	Old US-131 NB	• Good rubblization in two trenches. • Fair rubblization at the third trench.	• Poor drainage in 2 trenches
8	M-18 NB	• High amount of dust. • Poor quality of rubblization especially along the shoulder. • Few fractures were observed in the fractured concrete. • Dowel bars were exposed.	• Poor drainage in 2 trenches
9	M-21 WB	• Poor rubblization of the inner lane. • Fair rubblization of the outer lane. • A transverse crack had no apparent effect on the rubblization.	• Poor drainage in 2 trenches • Excellent drainage along the 4-ft concrete widening strip.
10	M-50 EB	• The quality of rubblization was excellent. • Dowel bars were exposed.	• No tests were conducted.
11	M-53 NB	• Poor rubblization at speed of 275-m/hr. • Good rubblization at speed of 245-m/hr. • The steel was poorly debonded.	• Poor drainage.
12	Portage Road	• Excellent rubblization through the entire concrete thickness in both trenches.	• No tests were conducted.
13	Chicago Drive	• Maximum of 4.5-in. rubblized material • Large pieces (1.5 to 2 ft)	• No tests were conducted
14	US 27	• Hammer bounces • Frequent large pieces (more than 6 in.) • No temperature steel debonding	• No tests were conducted
15	Beecher Road	• Poor rubblization at MS, TJ and cracks • Large pieces (more than 6 in.) throughout the project • Asphalt patches at cracks were not removed	• No tests were conducted

Figure 3.5 Trapped water above the fractured concrete in a trench (M-18)

1. On most projects, longitudinal strips of fine and coarse particles were found on the surface of the rubblized materials. The strips were evenly spaced at 175 mm (7 in.), which is almost the width of the resonant shoe. Further, on some projects, the rubblized material was about 1 in. higher than the adjacent unrubblized slab. This was expected because the rubblized material has a higher air void content than the original concrete slab.

2. In trenches made at transverse joints or cracks, large rubblized pieces of up to 250 mm (10 in.) were found above the temperature steel. The average coarse particle size was about 100 mm (4 in.). While in trenches made at mid-slab, the average rubblized particle size above the temperature steel was approximately 50 mm (2 in.).

3. In most trenches, steel debonding was achieved almost throughout the trench. However, in areas where the temperature steel overlaps, the two steel layers hindered the rubblization process by absorbing and/or deflecting part of its energy.

4. The rubblized concrete beneath the temperature steel appeared to be fractured concrete. The surface of the fractured concrete consists of peaks and valleys that extend in both longitudinal and transverse directions.

5. The cement mortar was stripped clean from a fair amount of aggregate.

6. In some trenches, the permeability of the rubblized concrete slabs was poor; water did not drain in more than 4 hours. This low permeability increases stripping potential.

2.1.2 The Multi-Head Breaker

The following observations were made in trenches excavated in pavement projects while being rubblized using the multi-head breaker:

1. In several areas along several projects, the strength of the subbase and/or subgrade material was exceeded. Hence, shear failure (bearing capacity failure) was evident upon the impact of the hammers (some large pieces of the concrete were broken off, rotated and penetrated the subbase material or the roadbed soil damaging both. Further, on some projects, the rubblized concrete was about 1 in. below the surface of the adjacent unrubblized concrete slab. This implies that on some projects, the rubblized concrete has penetrated the subbase or roadbed soils (shear failure).

2. In trenches that were made at mid-slab, the typical rubblized particle size above the temperature steel ranged from about 50 to 305 mm (2 to 12 in.). Some of the large pieces that were removed for more detailed inspection showed internal fractures.

3. Steel debonding was poor, in most trenches; about fifteen percent of the temperature steel was debonded. In areas where the temperature steel overlaps, no steel debonding was found. The two steel layers hindered the rubblization process by absorbing and/or deflecting part of its energy.

4. The rubblized concrete beneath the temperature steel appeared to be fractured concrete. The surface of the fractured concrete consists of peaks and valleys that extend in both longitudinal and transverse directions.

5. In some trenches, the permeability of the rubblized concrete was poor (water did not drain in more than 4 hours). This increases stripping potential.

2.2 FWD Testing and Coring

Nondestructive deflection tests were conducted on 18 rubblized projects. All tests were conducted using approximately 9,000-lb load. Each test consisted of four drops. The first drop was for instrument seating, which was not recorded while the last three drops were recorded. The layout of the FWS tests and core locations is shown in figure 3.6. The objectives of the tests were to:

1. Examine the structural capacity of the pavements.

2. Analyze the variation in the deflection data and hence in the structural capacity along and across the pavements.

3. Backcalculate the pavement layer and roadbed soil moduli.

4. Relate, if possible, variations in the deflection data to variation in the quality of rubblized pavements.

5. Compare the rubblized pavement responses to load to those of conventional flexible pavements.

At the conclusion of the FWD tests, several 6-in. diameter asphalt cores were extracted from the pavement. Some cores were located over a crack to verify whether or not the crack is a top-down crack. For these cores, the extent of the crack into the leveling and base course was also measured. The other cores were mostly located under the center of the load plate of the FWD. The cores were transported to the Pavement Research Center of Excellence where each core was examined and its thickness and the thickness of each asphalt course were measured and recorded. The average core thickness was then calculated and used in the backcalculation of the layer moduli. The cores were then tested to determine the physical and engineering properties (the specific gravity, resilient modulus and indirect tensile strength) of the asphalt concrete.

The breakdown of the FWD tests and coring between the Phase I and Phase II studies are listed in table 3.3. Seven rubblized pavement test sites were cored and nine

Table 3.3 List of rubblized and flexible pavement projects and the number of FWD tests conducted and cores obtained from each project.

Route	Control section	Job number	Test site*	Investigation date	Number of Cores			FWD test stations
					Total	Intact	With cracks /defects	
Investigated during Phase II								
I-69	76023	36020	10692-11	6/12/2001	12	10	0/2	40
I-69	76023	36020	10692-12	6/12/2001	12	9	0/3	40
I-75	16092	25559	10753-11	10/24/2001	14	11	3/0	42
I-75	16092	25559	10753-12	10/24/2001	15	12	3/0	43
I-194	13033	29670	11941-21	11/07/2001	15	10	5/0	43
I-194	13033	29670	11941-22	11/07/2001	15	8	5/2	43
US-10	53022	37974	20102-11	6/28/2001	12	12	-	40
US-10	53022	37974	20102-12	6/28/2001	12	12	-	40
US-23	04031	44350	20233-11	6/23/2001	11	10	0/1	52
US-23	04031	44350	20233-12	6/23/2001	10	7	0/3	30
US-27	37013	28116	20273-21	6/04/2001	15	11	4/0	45
US-27	37013	38205	20273-31	6/06/2001	12	12	-	40
US-27	37014	38205	20273-41	7/12/2001	12	12	-	40
US-31	70013	38179	20311-11	6/26/2001	12	12	-	40
M-15	25092	45534	30153-11	11/21/2001	16	12	4/0	43
M-37	41033	31068	30373-21	3/28/2001	10	7	0/3	24
M-37	41033	31068	30373-31	3/28/2001	9	3	4/2	-
M-37	41033	38190	30373-51	6/19/2001	12	12	-	40
M-37	41033	38190	30373-52	6/19/2001	12	12	-	40
M-37	41033	26691	30373-61	11/6/2001	18	15	2/1	42
US-27 [2]	37014	38205	20273-11	6/04/2001	12	-	-	39
M-37 [2]	61024		30373-41	6/08/2001	7	-	-	33
M-53	44031	36021	30531-11	11/02/1999	20	14	6/0	45
Investigated during Phase I								
I-96	23152	29581	10962-11	8/24/1999	-	-	-	28
I-96	33084	28213	10962-21	8/24/1999	5	-	5/0	29
I-96	33084	28213	10962-31	8/24/1999	7	2	5/0	37
I-96	33084	28213	10964-51	10/21/1999	2	-	2/0	36
I-194	13033	29670	11941-11	1999	10	0	10/0	-
US-131	41133	33914	21313-11	10/26/1999	-	-	-	30
US-131	03112	28143	21311-21	11/03/1999	-	-	-	34
US-131	03112	32373	21311-31	9/01/1999	-	-	-	51
M-37	41033	26691	30371-11	11/04/1999	5	0	5/0	-
M-37	41033	26691	30373-11	11/04/1999	4	0	4/0	83
I-96 [2]	23151	29581	10962-41	10/11/1999	-	-	-	34

1 A seven-digit designation number was assigned to each test site. The first digit represents the road type (1 = Interstate, 2 = U.S., 3 = Michigan). The second through the fourth digits represent the highway/route number. The fifth digit represents the traffic direction (1 = North, 2 = East, 3 = South, 4 = West). The sixth digit represents test section the number. The seventh digit represents test site number. For example, a designation number of 1194-12 implies I-194, northbound section 1 test site 2

2 Conventional flexible pavements

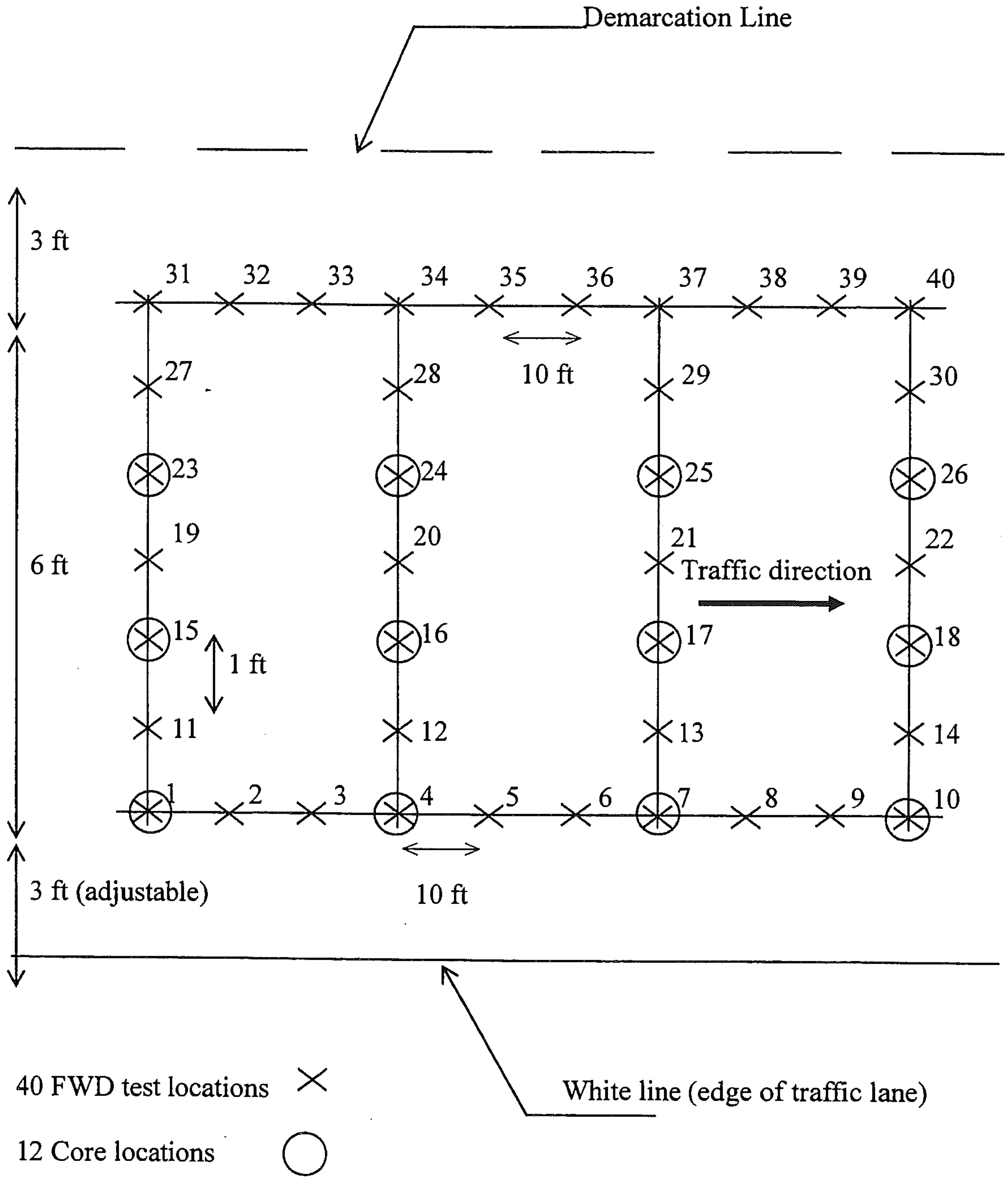


Figure 3.6 Standard layout of the FWD tests used in this study

rubblized and one flexible test sites were FWD tested during the Phase I study. In the Phase II study, twenty rubblized and two flexible test sites were cored and nineteen rubblized and two flexible test sites were FWD tested. Note that, in the Phase II study, the majority of the FWD tests were conducted according to the test location layout shown in figure 3.6. The letter "X" in the figure indicates an FWD test location while the letter "O" indicates a core location. At some test sites, the standard FWD tests and cores layout was slightly modified by adding few core locations (e.g., over a crack) and/or conducting additional FWD tests when required (e.g., repeatability and linearity). Detailed information regarding the test sites such as location, distresses observed within the test site area and others are presented in Appendix C. The measured deflection data at each test site are tabulated in Appendix D.

As stated above, during the Phase II study, special FWD tests were conducted on four test sites to check the accuracy of the FWD deflection data and the linearity of the pavement material response to load. In these tests, ten to twenty FWD tests were conducted at the same location at each of the following load levels: 5,500, 9,000, 16,000 and 21,000 lb. Table 3.4 provides a list of the number of the repeatability and linearity tests conducted at the four test sites. The measured linearity and repeatability deflection data are tabulated in Appendix E.

2.3 Distress Survey

Since MDOT collect distress data every other year and since rubblized projects are relatively new, only limited historical distress data were available in the PMS data files. Consequently, two manual distress surveys were undertaken by the research team to obtain two additional distress points in time. The first survey covered seventy five rubblized concrete pavement projects and was conducted between August 17 and September 2, 2001. The second survey was conducted in early May of 2002 and covered 79 rubblized projects. Note that only 70 rubblized projects were surveyed in both 2001 and 2002. Five rubblized projects that were surveyed in 2001 were not surveyed in 2002, on the other hand, nine rubblized projects that were surveyed in 2002, were not surveyed in 2001. By transferring the distress data from 2001 to 2002 and visa versa, manual distress data for 84 rubblized projects were obtained. Finally, in both surveys, the research team consisted of two persons and used the following procedure:

1. For each rubblized project, the inventory data (project location and boundaries, project age, asphalt mix types and rubblizing equipment) and the pavement historical distresses data were obtained from MDOT.

2. At each project location, the distress along the entire project was observed by driving on the right pavement shoulder at creep speed. During the drive notes were taken as to the consistency and uniformity of the pavement condition along the project.

3. After observing the general pavement condition, the survey crew walked along one to three 300-ft long segments located along the project. When the overall pavement condition was inconsistent, the research team walked or drove at creep speed along three 300-ft segment located at the beginning, middle and end of the project. On the

Table 3.4 A summary of the repeatability and linearity tests

Test sites	Load (lb)	Number of drops	Load (lb)	Number of drops	Load (lb)	Number of drops	Load (lb)	Number of drops
20273-21			9000	20	16000	10	21000	10
10692-12	5500	10	9000	20	16000	10	21000	10
30373-52	5500	10	9000	20	16000	10	21000	10
20102-11	5500	10	9000	20	16000	10	21000	10

other hand, when the pavement condition was uniform, the research team surveyed only one representative 300-ft long segment.

4. For each segment, detailed distress data were observed and recorded and digital images were obtained when needed for later verification. The distress data included the location, type, extent and severity of longitudinal and transverse cracks, raveling, segregation, patching, depression and other condition that adversely affect pavement performance. For transverse cracks, notes were made whether the cracks were reflective or regular (non-reflective). For longitudinal cracks, notes were made as to whether or not the cracks are likely TDC. Notes were also taken when longitudinal and/or transverse cracks have initiated in segregated areas.

5. For each surveyed segment, rut depth measurements were made at several locations using a 6 ft long beam.

6. For some projects, the research team drove along the project at the posted speed limit and observed and recorded the ride quality in terms of driving comfort.

The objectives of the distress survey were to:

1. Select pavement sections to be cored and FWD tested in late 2001 and early 2002.

2. Fill up the historical gaps in the MDOT PMS distress data and check its accuracy.

3. Determine the number of underperforming rubblized pavement projects exhibiting premature distresses.

4. Determine the number of rubblized project exhibiting TDC.

5. Determine the causes, if possible, of underperformance.

6. Estimate the rate of pavement deterioration.

7. Estimate the pavement structural and functional conditions in 2001 and 2002.

Summaries of the distress surveys conducted in August 2001 and 2002 are respectively provided in tables 3.5 and 3.6 in terms of the number of projects exhibiting certain types of distress. As can be seen from table 3.6, the distress data collected in May 2002 (all pictures were obtained in May 2002 unless indicated otherwise) indicate that:

1. Ten rubblized projects (about 11 percent of a total of 84 rubblized projects) showed no signs of distress.

2. Since 1988 when concrete pavement rubblization started, capital preventive maintenance and rehabilitation actions were taken on ten rubblized projects. These actions included mill and fill, AC overlay, chip seal and micro surfacing. Hence, for

Table 3.5 The number of projects exhibiting the indicated distress observed during the August 2001 distress survey

Distress type	No of projects	JTC	TTDC	RTC	LTDC	RLC	ALC	S	R	P	PH	RJ	Rut	B	BC	B-up	D
LTDC/TTDC/S/JTC/R/RTC/RLC/P/PH	1	1	1	1	1	1		1	1	1	1						
LTDC/TTDC/S/JTC/R/P/PH/Rut	1	1	1		1			1	1	1	1		1				
LTDC/TTDC/S/JTC/R/P/Rut/Break up	1	1	1		1			1	1	1			1			1	
LTDC/TTDC/S/JTC/Bleeding	1	1	1		1			1						1			
LTDC/TTDC/S/JTC/R/P	1	1	1		1			1	1	1							
LTDC/TTDC/S/JTC/R/RJ	1	1	1		1			1	1			1					
LTDC/TTDC/S/JTC/RLC/Rut	1	1	1		1	1		1					1				
LTDC/TTDC/S/JTC/Rut	2	2	2		2			2					2				
LTDC/TTDC/S/JTC/RTC	1	1	1	1	1			1									
LTDC/TTDC/S/JTC	3	3	3		3			3									
LTDC/TTDC/S/R/P/Rut	1		1		1			1	1	1			1				
LTDC/TTDC/S/Block crack	1		1		1			1							1		
LTDC/TTDC/S/R/RLC/Rut	1		1		1	1		1	1				1				
LTDC/TTDC/S/R	1		1		1			1	1				1				
LTDC/TTDC/S/R/Rut	1		1		1			1	1								
LTDC/TTDC/S/RJ/Rut	1		1		1			1				1	1				
LTDC/TTDC/S/RTC	1		1	1	1			1									
LTDC/TTDC/S/RLC	1		1		1	1		1									
LTDC/TTDC/S/Rut	1		1		1			1					1				
LTDC/TTDC/S	3		3		3			3									
LTDC/JTC/S/R/RTC	1	1		1	1			1	1								
LTDC/JTC/S/R/RLC/Rut	1	1			1	1		1	1				1				
LTDC/JTC/S/RTC/RLC/Rut	1	1		1	1	1		1					1				
LTDC/JTC/S	2	2			2			2									
LTDC/S/R/RTC/RLC	1			1	1	1		1	1								
LTDC/S/R/RLC/P/PH/RJ	1				1	1		1	1	1	1	1					
LTDC/S/RTC	1			1	1			1									
LTDC/S/RLC	1				1	1		1									
LTDC/S/RLC/RJ	1				1	1		1				1					
LTDC/S/RLC/P	1				1	1		1		1							
LTDC/S/Rut	1				1			1					1				
LTDC/S	5				5			5									
LTDC/RTC/P	1			1	1					1							

Table 3.5 The number of projects exhibiting the indicated distress observed during the August 2001distress survey (continued)

Distress type	No of projects	JTC	TTDC	RTC	LTDC	RLC	ALC	S	R	P	PH	RJ	Rut	B	BC	B-up	D
LTDC/RLC/RJ	1				1	1						1					
LTDC/Rut	1				1								1				
LTDC	2				2												
TTDC/JTC/S/RLC	1	1	1			1		1									
JTC/ALC/Rut	1	1					1						1				
JTC/RTC	1	1		1													
JTC/RLC/Rut	1	1				1							1				
JTC/RLC	1	1				1											
JTC	1	1															
S/Rut/Bleeding	1							1					1	1			
S/P	1							1		1							
S/PH	1							1			1						
S/RLC	2					2		2									
S/Depression	1							1									1
S	4							4									
RTC/RLC	1			1		1											
RLC	2					2											
RJ/Rut	1											1	1				
RJ	2											2					
Rut	2												1				
Bleeding	1													1			
No distress	12																
Total	**84**	**24**	**26**	**10**	**47**	**20**	**1**	**53**	**13**	**9**	**4**	**8**	**19**	**3**	**1**	**1**	**1**
Did not survey	2																
Not rubblized	2																

LTDC = Longitudinal top-down cracks, TTDC = Transverse top-down cracks, S = segregation, JTC Joint transverse crack, R = Raveling, RTC = Regular transverse crack, RLC = Regular longitudinal crack, P = Patch, PH = Pothole, RJ = Rough joint, D = Depression, B = Bleeding, ALC = Alligator cracks, BC = Block cracking, and B-up = Break up

Table 3.6 The number of projects exhibiting the indicated distress observed during the May 2002 distress survey

Distress type	No of projects	JTC	TTDC	RTC	LTDC	RLC	ALC	S	R	P	PH	RJ	Rut	B	BC	B-up	D
LTDC/TTDC/S/JTC/R/RTC/RLC/P/PH	1	1	1	1	1	1		1	1	1	1						
LTDC/TTDC/S/JTC/R/P/PH/Rut	1	1	1		1			1	1	1	1		1				
LTDC/TTDC/S/JTC/R/P/Rut/Break up	1	1	1		1			1	1	1			1			1	
LTDC/TTDC/S/JTC/R/P/Bleeding	1	1	1		1			1	1	1				1			
LTDC/TTDC/S/JTC/R/P	1	1	1		1			1	1	1							
LTDC/TTDC/S/JTC/R/RJ	1	1	1		1			1	1			1					
LTDC/TTDC/S/JTC/R/Rut	1	1	1		1			1	1				1				
LTDC/TTDC/S/JTC/RLC/Rut	1	1	1		1	1		1					1				
LTDC/TTDC/S/JTC/Rut/Bleeding	1	1	1		1			1					1	1			
LTDC/TTDC/S/JTC/Rut	2	2	2		2			2					2				
LTDC/TTDC/S/JTC	3	3	3		3			3									
LTDC/TTDC/S/R/P/Rut	1		1		1			1	1	1			1				
LTDC/TTDC/S/R/RLC/P/Block crack	1		1		1	1		1	1	1					1		
LTDC/TTDC/S/R/RLC/Rut	1		1		1	1		1	1				1				
LTDC/TTDC/S/R/Rut	1		1		1			1	1				1				
LTDC/TTDC/S/R	2		2		2			2	2								
LTDC/TTDC/S/RTC	1		1	1	1			1									
LTDC/TTDC/S/RLC	1		1		1	1		1									
LTDC/TTDC/S/Rut	1		1		1			1					1				
LTDC/TTDC/S	3		3		3			3									
LTDC/JTC/S/R/RTC	1	1		1	1			1	1								
LTDC/JTC/S/R/RLC/Rut	1	1			1	1		1	1				1				
LTDC/JTC/S/RTC/RLC/Rut	1	1		1	1	1		1					1				
LTDC/JTC/S/RTC	1	1		1	1			1									
LTDC/JTC/S	2	2			2			2									
LTDC/S/R/RTC/RLC	1			1	1	1		1	1								
LTDC/S/R/RLC/P/PH/RJ	1				1	1		1	1	1	1	1					
LTDC/S/R	1				1			1	1								
LTDC/S/RLC/RJ/Break up	1				1	1		1				1				1	
LTDC/S/RLC/RJ	1				1	1		1				1					
LTDC/S/RLC/P	1				1	1		1		1							
LTDC/S/Rut	1				1			1					1				

Table 3.6 The number of projects exhibiting the indicated distress observed during the May 2002 distress survey (continued)

Distress type	No of projects	JTC	TTDC	RTC	LTDC	RLC	ALC	S	R	P	PH	RJ	Rut	B	BC	B-up	D
LTDC/S	4				4			4									
LTDC/RTC/P	1			1	1					1							
LTDC/RLC/RJ	1				1	1						1					
LTDC/Rut	1				1								1				
LTDC	2				2												
TTDC/JTC/S/RLC/RJ	1	1	1			1		1				1					
TTDC/JTC/ALC/Rut	1	1	1				1						1				
JTC/RTC	1	1		1													
JTC/RLC/Rut	1	1				1							1				
JTC/RLC	1	1				1											
JTC	1	1															
S/R/RLC/P/PH	1					1		1	1	1	1						
S/P	1							1		1							
S/PH	1							1			1						
S/RJ	1							1				1					
S/RLC	1					1		1									
S/Depression	1							1									1
S	3							3									
RTC/RLC	2			2		2											
RTC	1			1													
RLC/RJ	1					1						1					
RLC	1					1											
RJ/Rut	2											2	2				
RJ	2											2					
Rut	1												1				
Bleeding	1													1			
No distress	10																
Total	**84**	**26**	**28**	**11**	**48**	**22**	**1**	**53**	**19**	**12**	**5**	**12**	**20**	**3**	**1**	**2**	**1**
Did not survey	2																
Not rubblized	2																

LTDC = Longitudinal top-down cracks, TTDC = Transverse top-down cracks, S = segregation, JTC Joint transverse crack, R = Raveling, RTC = Regular transverse crack, RLC = Regular longitudinal crack, P = Patch, PH = Pothole, RJ = Rough joint, D = Depression, B = Bleeding, ALC = Alligator cracks, BC = Block cracking, and B-up = Break up those ten projects, the distress data listed in tables 3.5 and 3.6 were those observed on the new maintained or rehabilitated surface.

3. Fifty-three projects (58 percent) exhibited various degrees of segregation. On most of these projects, longitudinal and transverse TDC can be found in the segregated areas. Further, nineteen of these projects have developed various degrees of raveling in the segregated areas (see figures 3.7 and 3.8).

4. Longitudinal and transverse cracks are the dominant types of distress. Several types of longitudinal and transverse cracks were found as follows:

   a) Forty eight projects exhibited longitudinal TDC as shown in figure 3.9.
   b) Twenty eight projects exhibited transverse TDC as shown in figure 3.9.
   c) Twenty six projects exhibited joint reflective cracking as shown in figure 3.10.
   d) Eleven projects exhibited regular transverse cracks that are likely reflected from old cracks in the original concrete pavement as shown in figure 3.11.
   e) Twenty two projects exhibited regular longitudinal cracks (no TDC), seventeen of which are located near the longitudinal paving joints as shown in figure 3.12
   f) Only one project exhibited alligator type cracks in the wheel paths as shown in figure 3.13, which was taken in June 2001.

   Almost all the longitudinal and transverse TDC (items "a" and "b") are located in segregated areas. The reflective cracks in items "c" and "d" imply that the integrity of the joints in the concrete pavement was not destroyed and/or the temperature steel was not debonded.

5. Twelve projects exhibited roughness over transverse joints of the original concrete pavements of which eight projects did not develop transverse cracks as of August 2001. Further, on four projects, the reflective transverse cracks have already developed across some portions of the lanes while in the other portions the pavement exhibited rough joints only. A rough joint is a forerunner of reflective transverse cracks and is defined as a slight but measurable hump in the AC surface along the joint.

6. Twenty rubblized projects exhibited measurable rut. The rut depth varied from about 0.125 to slightly more than 0.5 in.

7. Potholes were found on five projects (see figure 3.14), patches on 12 projects (figure 3.15); three projects exhibited low severity bleeding; one project exhibited block cracking, pavement breakup was found on two projects, and one project exhibited depression along a limited area.

8. Shear failure (reported in the tables as patches) was found at three locations along I-196 south of Grand Rapids as shown in figure 3.16.

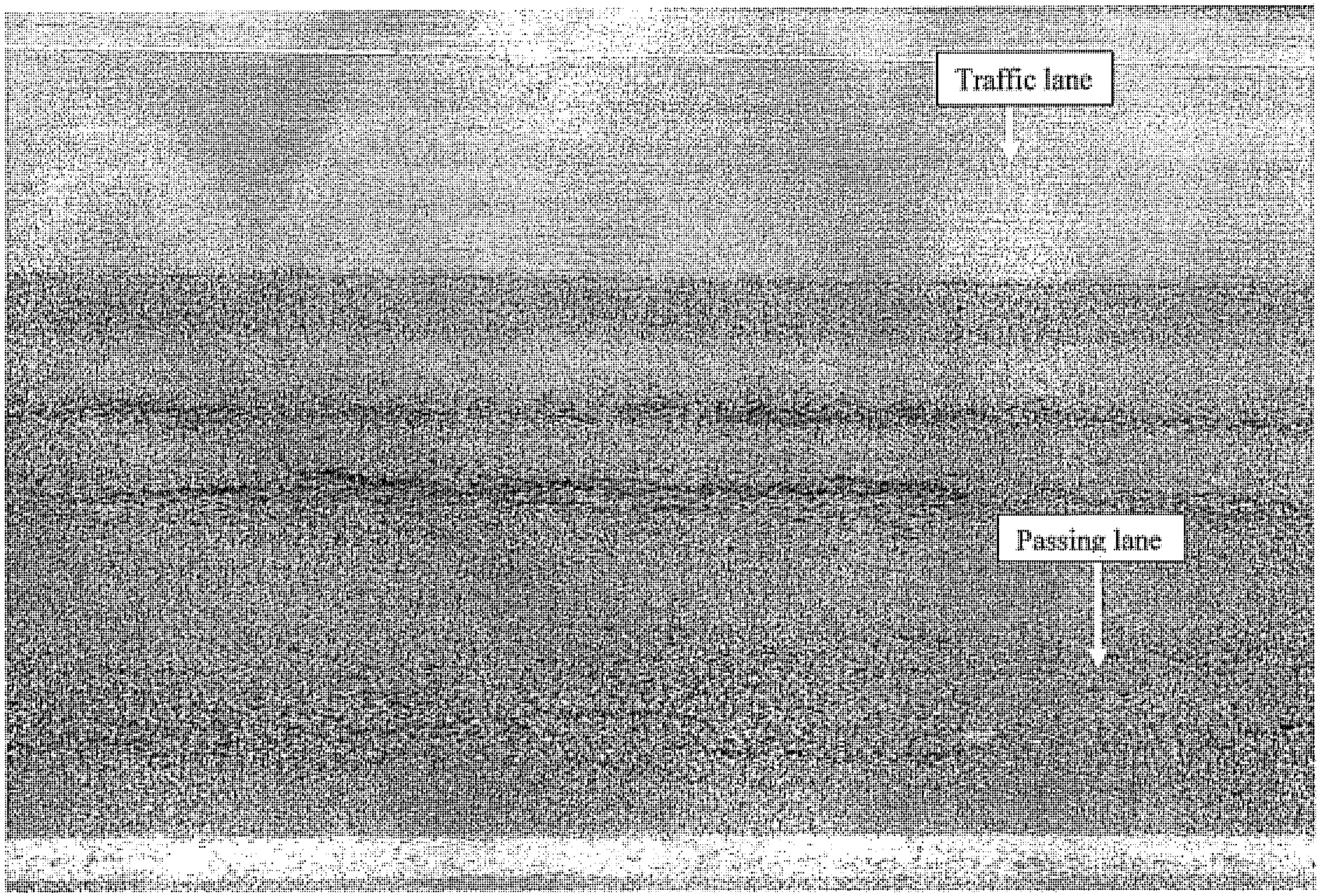


Figure 3.7 US-23 SB Control Section 47013, 47014 Job Number 29768 BMP 5.5, EMP 7.0; the relative pavement condition in segregated area (passing lane) and in a non-segregated area (traffic lane) 2-years after construction.

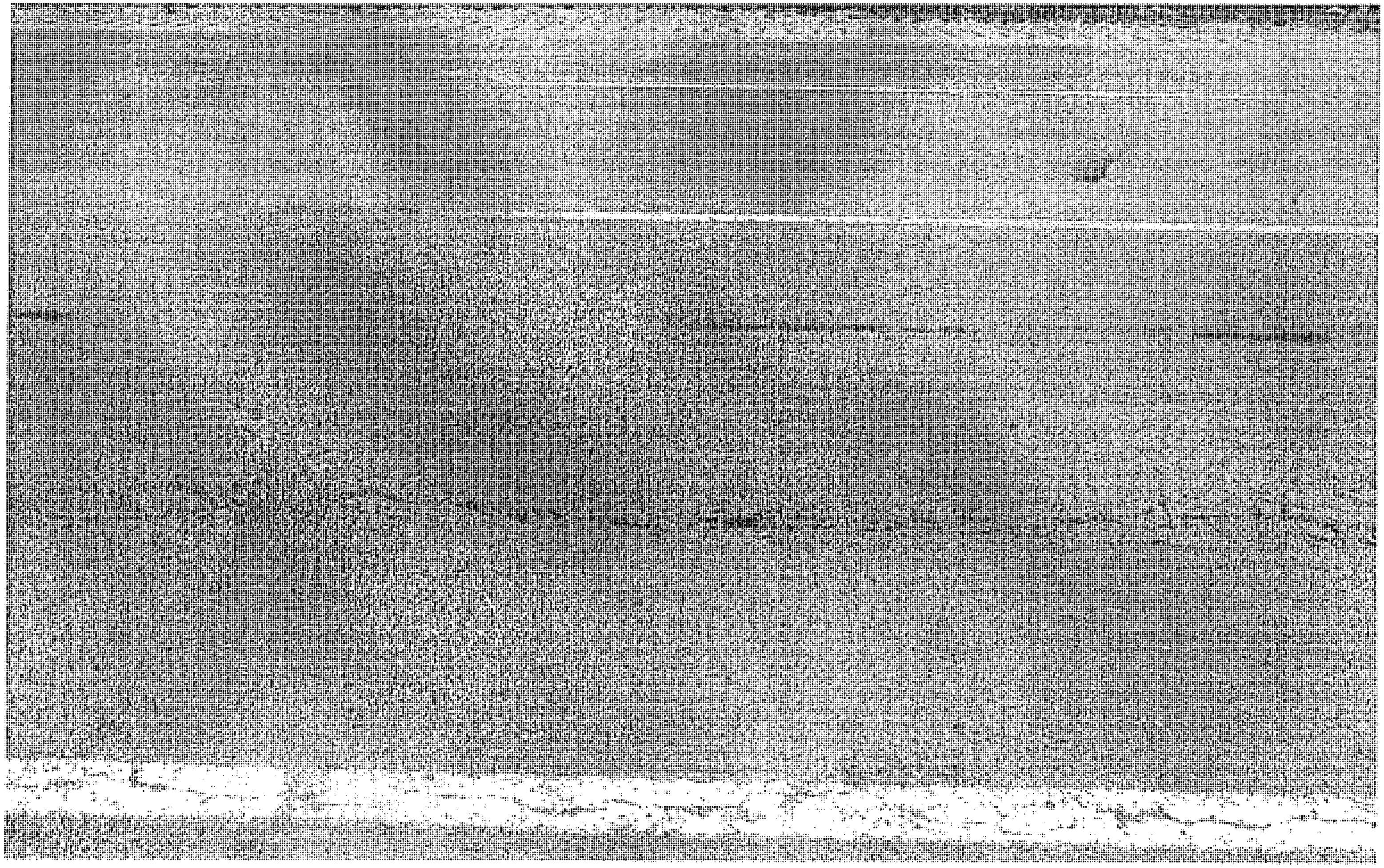


Figure 3.8 US 12 EB Control Section 81063 Job Number 26796 BMP 3.6, EMP 4.1; the pavement condition in segregated area

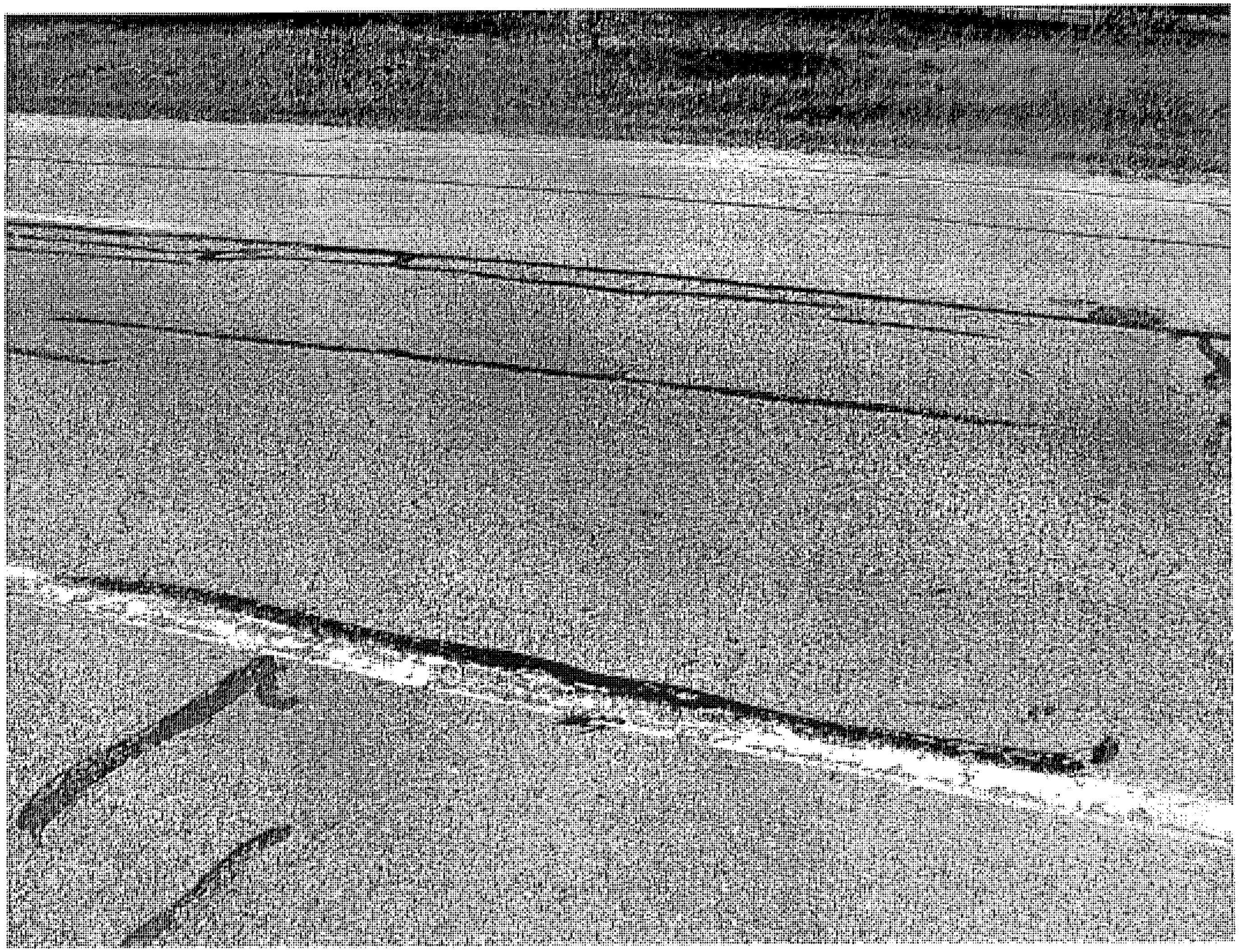


Figure 3.9 Longitudinal and transverse TDC on I-96 EB Control Section 33084 Job Number 28213 BMP 9.0, EMP 17.5

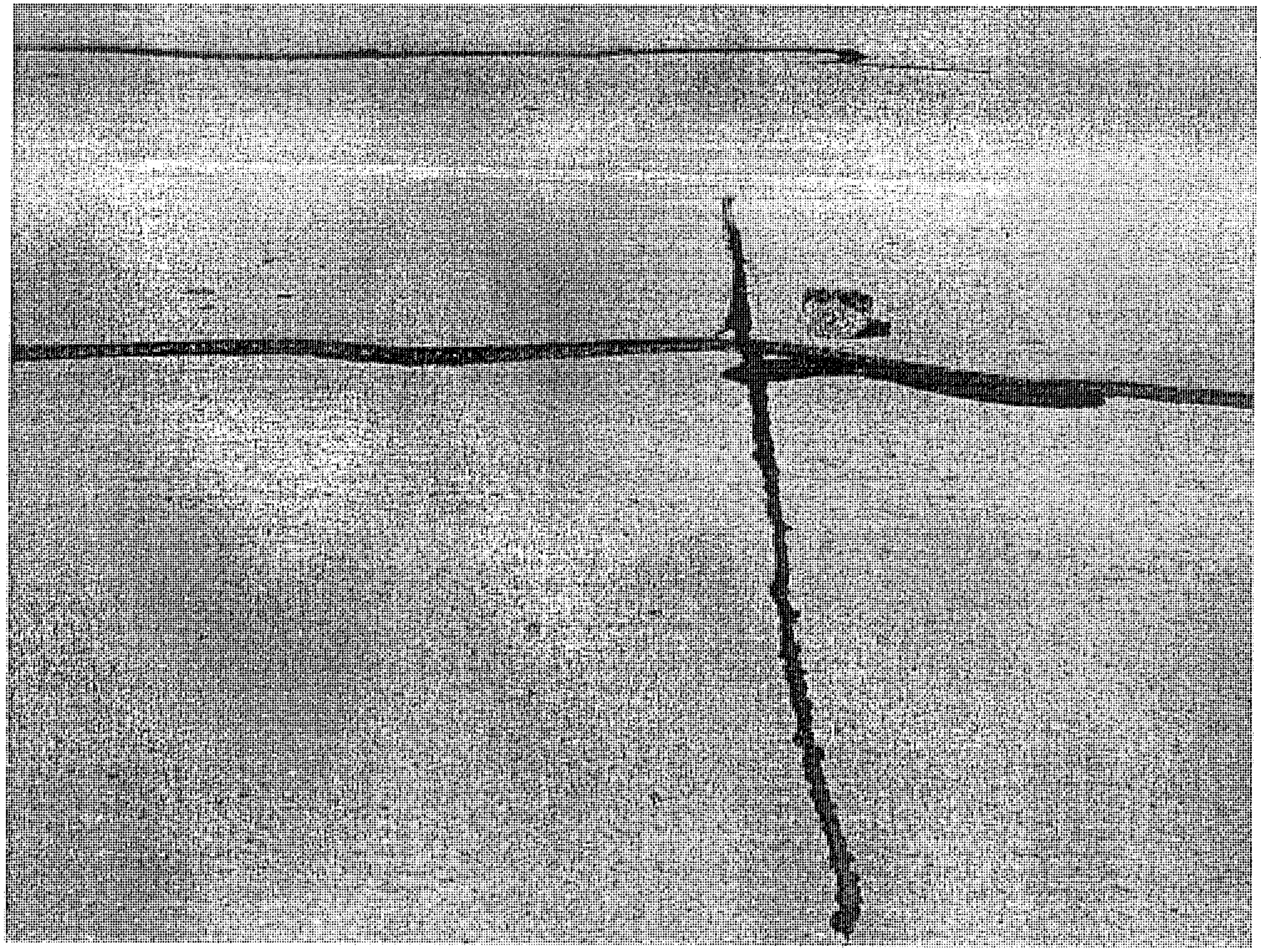


Figure 3.10 Reflective joint cracking on M-50, Control Section 46082 Job Number 30388 BMP 3.9 EMP 4.4

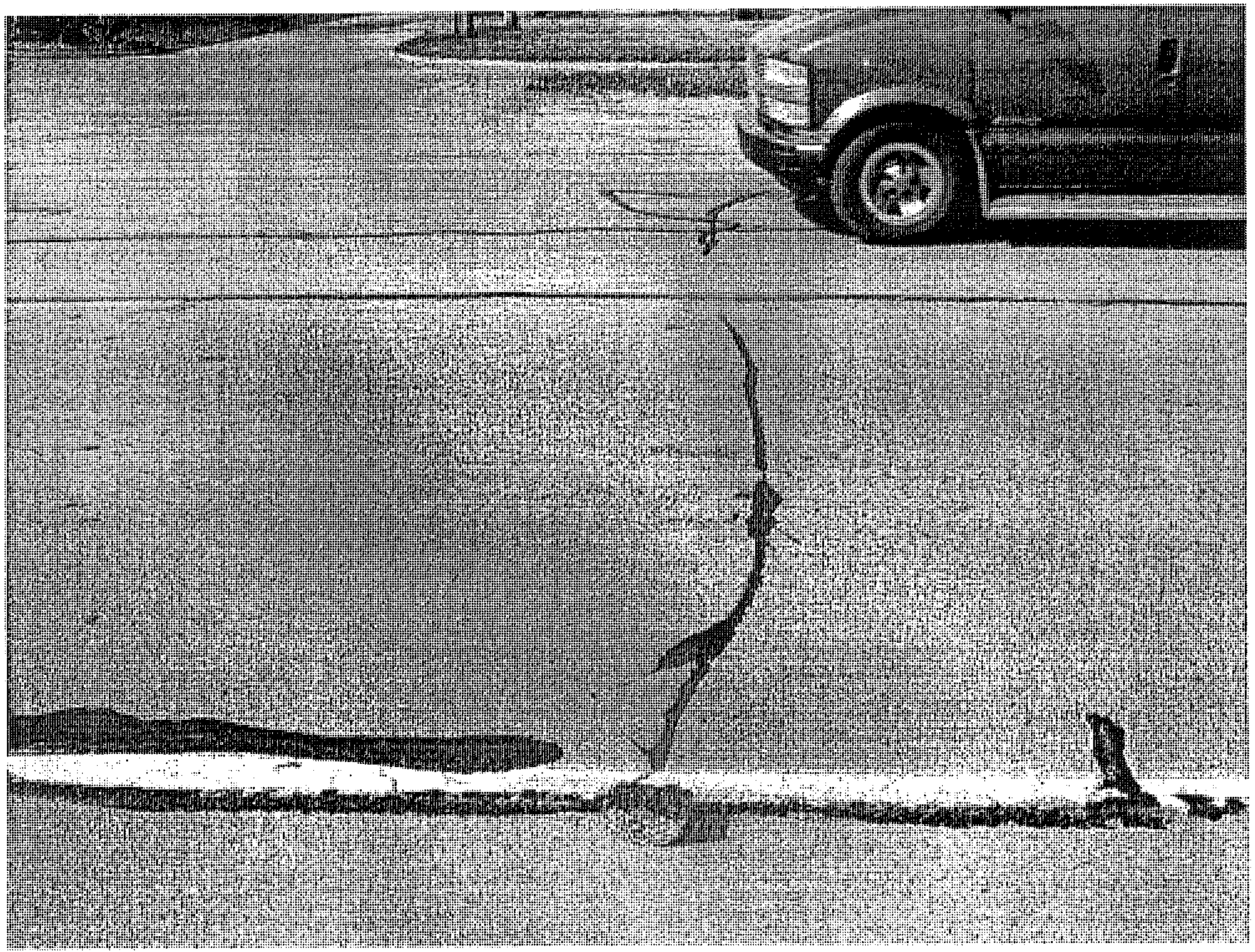


Figure 3.11 Reflective cracking on M-50, Control Section 46082 Job Number 32388 BMP 3.9, EMP 4.4

Figure 3.12 Longitudinal cracks by the paving joint on US-131, Control Section 83032 Job Number 34060 BMP 13.0, EMP 18.6

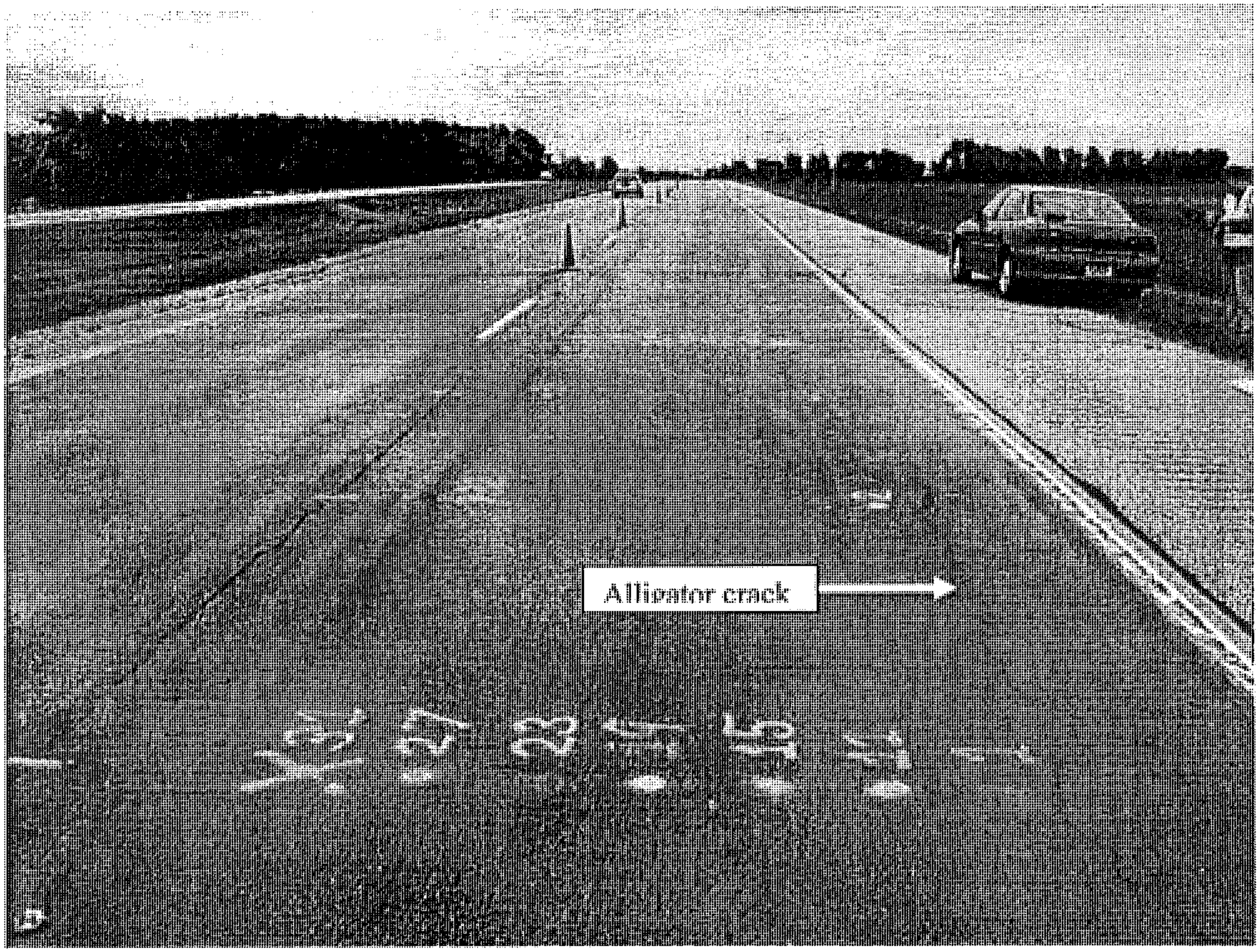


Figure 3.13 Alligator cracks in the wheel path, US-27, Control Section 37013 Job Number 28116 BMP 9.0, EMP 11.7, June 2001

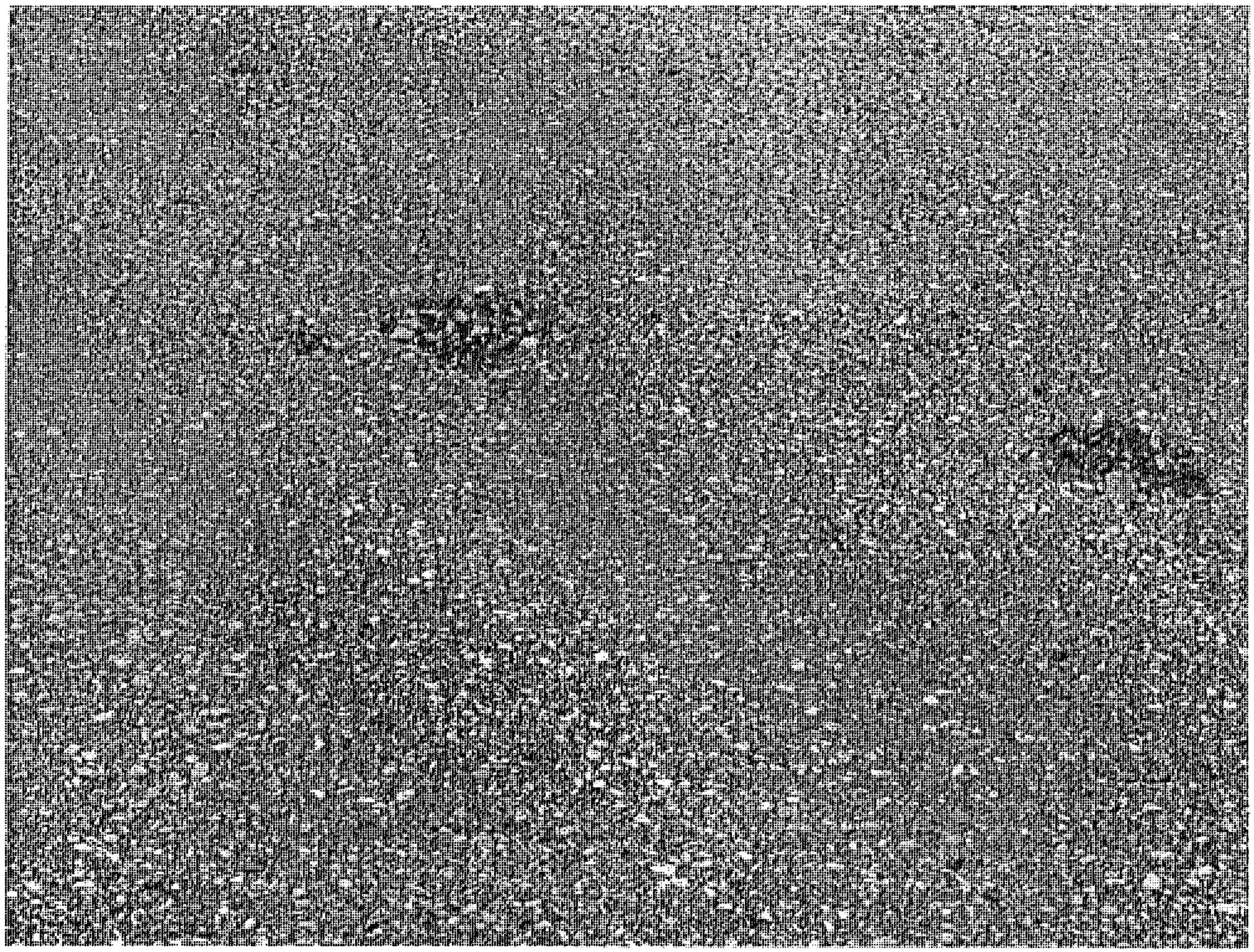


Figure 3.14 Pothole along US-131, Control Section 41133 Job Number 33914 BMP 3.2, EMP 8.7

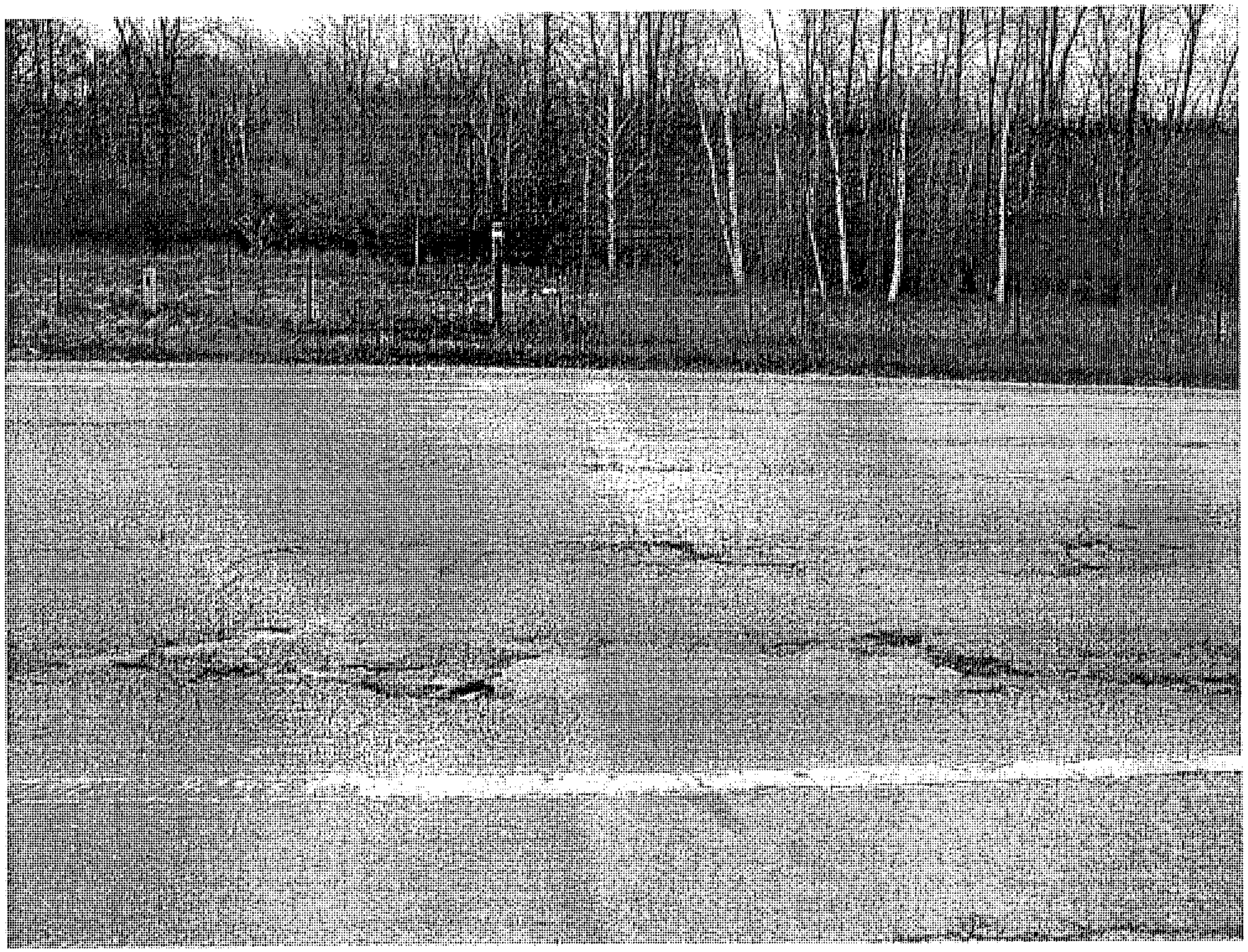


Figure 3.15 Patches along M-53, Control Section 74012 Job Number 29729 BMP 9.0, EMP 13.0

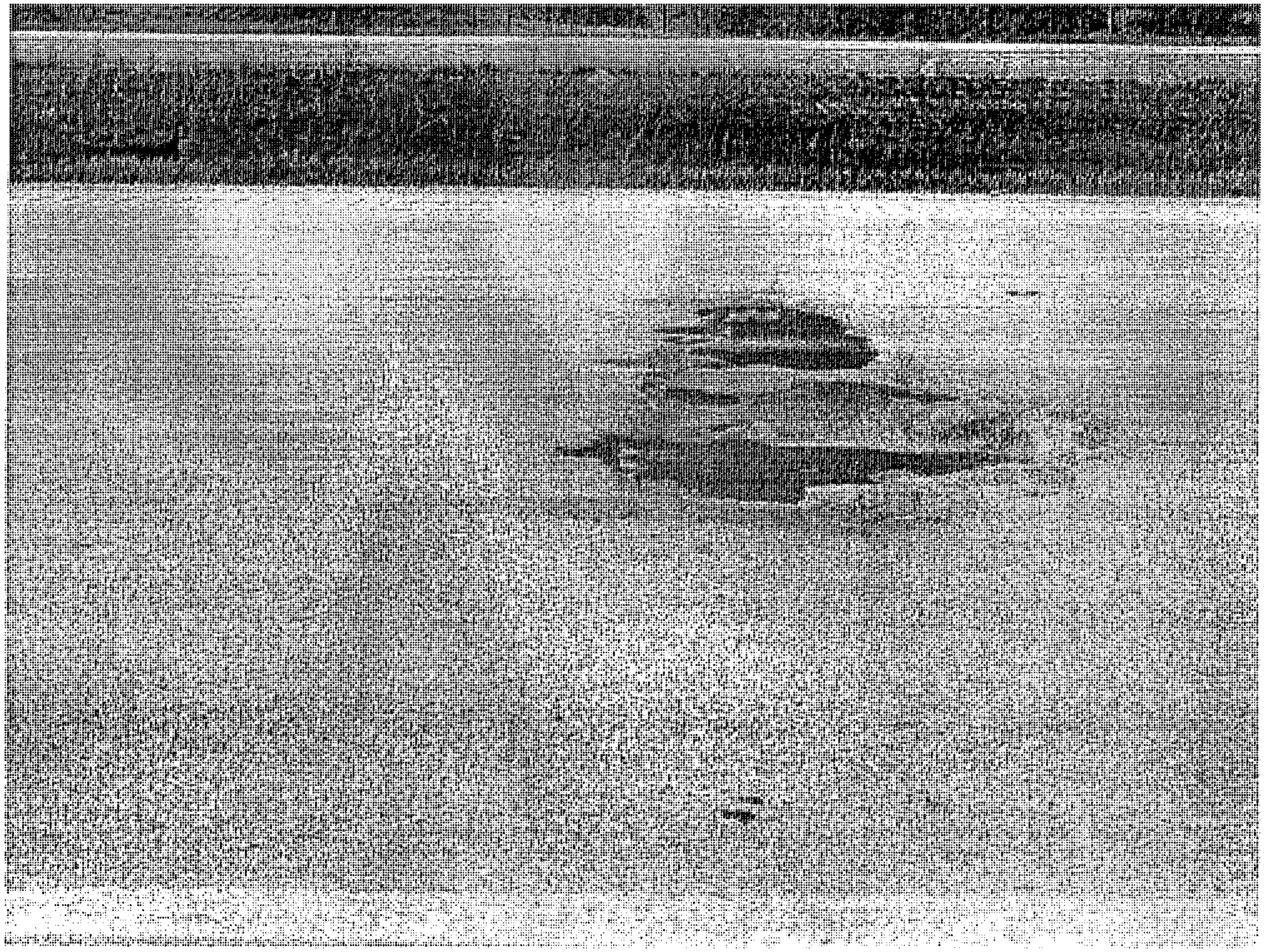


Figure 3.16 Shear failure along I-196 NB, Control Section 70024 Job Number 35987 BMP 12.6, EMP 15.6

Similar distress data were collected in 2001 and are summarized in table 3.5. The basic difference between the two tables is that, as expected, the total number of projects exhibiting certain type of distress has increased from 2001 to 2002 surveys.

Table 3.7 provides a list of the rubblizing equipment, the dominant types of distress, the type of asphalt mix, and the completion data of the 84 rubblized projects that were surveyed during this study.

3.0 LABORATORY INVESTIGATION

After the AC cores were extracted from the pavements during the field investigation, they were transported to the Pavement Research Center of Excellence (PRCE) to be tested in the laboratory. Each core was subjected to basically three tests in the following order:

1. Specific gravity test of the entire core and of each AC course. The data were used to estimate the percent air voids in the AC layer.

2. Indirect tensile cyclic load test (ITCLT) to determine the resilient modulus of each AC course and the weighted average modulus of the AC mat.

3. Indirect tensile strength test (ITST) to determine the tensile strength of the AC courses and the weighted average tensile strength of the AC mat.

The objectives of the tests were to:

1. Determine the weighted average physical and engineering characteristics of the AC mat.

2. Determine or calculate the physical and engineering properties of each AC course in the AC mat.

The steps that were taken during the sample preparation and details of each test are presented in the next sections.

3.1 Sample Preparation

In general, the AC cores that were extracted from the pavements could be divided into two categories; intact cores and cores with cracks and/or defects. Each core was carefully examined and cataloged. After cataloging all cores of one test site, the following steps were taken to prepare them for testing:

1. For each intact core, the diameter, the thickness of each AC course and the thickness of the core were measured. The latter was measured at the four ends of two orthogonal diameters and the average core thickness was calculated, recorded, and used in the backcalculation of the pavement layer moduli.

Table 3.7 List of rubblized pavement projects in Michigan

Control section	Job number	Route	Dir.[1]	Completion Date	POB	END	Rubblizer	Asphalt Mix			Distresses				
								Top	Level	Base	TTDC[2]	LTDC[3]	S[4]	Raveling	Rut depth (in)
10032	44113	US-31		9/30/1999	11.43	13.87	Multi -Head	4E3	4E3	3E3		Yes	Yes		
10032	44113	US-31		9/30/1999	13.91	14.34	Multi -Head	4E3	4E3	3E3		Yes	Yes		
21031	34050	M-35		7/23/1998	1.42	3.09	Multi -Head	4E3	3E3	3E3					
21031	34050	M-35		7/23/1998	8.70	10.43	Multi -Head	4E3	3E3	3E3					
38061	34106	M-60	EB	10/30/1998	12.65	16.41	Multi -Head	4E3	3E3	3E3		Yes	Yes		
38061	34106	M-60	WB	10/30/1998	12.65	16.42	Multi -Head	4E3	3E3	3E3		Yes	Yes		
58042	43523	M-50		6/15/1999	0.14	4.52	Multi -Head	4E3	3E3	3E3					1/8
58042	50711	M-50		7/6/2001	4.53	6.87	Multi -Head	4E3	3E3	3E3		Yes	Yes		
05011	44109	US-31		8/25/1999	0.92	3.02	Multi -Head	5E3	4E3	3E3			Yes		
25081	38028	M-21		10/30/1999	4.98	7.29	Multi -Head	5E3	4E3	3E3					
35032	35985	US-23		9/8/2000	19.12	22.01	Multi -Head	5E3	4E3	3E3			Yes		
41033	38190	M-37/M-46		5/12/2000	15.74	17.12	RMI	5E3	4E3	3E3	Yes	Yes	Yes		
53022	37974	US-10		9/28/2000	3.50	6.55	RMI	5E3	4E3	3E3					
53022	37974	US-10		9/28/2000	6.55	9.40	RMI	5E3	4E3	3E3					
61131	38190	M-37/M-46		5/12/2000	0.00	1.49	Multi -Head	5E3	4E3	3E3	Yes	Yes	Yes		
61171	38190	M-37/M-46		5/12/2000	0.00	0.57	RMI	5E3	4E3	3E3	Yes	Yes	Yes		
67022	44986	US-10		9/30/1999	9.66	12.09	Multi -Head	5E3	4E3	3E3					
41133	33914	US-131	NB	9/10/1999	3.20	8.69	RMI	4E10	3E10	3E10		Yes	Yes		
41133	33914	US-131	SB	9/10/1999	3.21	8.69	RMI	4E10	3E10	3E10		Yes	Yes		
41401	50230	Chicago Dr		10/31/2000	0.00	1.17	RMI	4E10	3E10	2E10			Yes		
59012	33914	US-131	NB	9/10/1999	0.00	4.21	RMI	4E10	3E10	3E10		Yes	Yes		
59012	33914	US-131	SB	9/10/1999	0.00	4.23	RMI	4E10	3E10	3E10		Yes	Yes		
37011	38205	US-27 BR		10/25/2000	0.00	0.46	Multi -Head	5E10	4E10	3E10			Yes		
37013	38205	US-27		6/1/2000	8.06	9.01	Multi -Head	5E10	4E10	3E10			Yes		

1, When no direction is specified, the pavement is rubblized in both directions; 2, TTDC = Transverse Top-Down Cracks; 3, LTDC = Longitudinal Top-Down Cracks; and 4, S = Segregation

Table 3.7 List of rubblized pavement projects in Michigan (continued)

Control section	Job number	Route	Dir.[1]	Completion Date	POB	END	Rubblizer	Asphalt Mix			Distresses				
								Top	Level	Base	TTDC[2]	LTDC[3]	SG[4]	Raveling	Rut depth (in)
37014	38205	US-27		6/1/2000	0.00	1.53	Multi -Head	5E10	4E10	3E10			Yes		
44031	36021	M-53		9/30/1999	0.00	1.59	Multi -Head	5E10	4E10	3E10		Yes	Yes		
44031	36021	M-53		9/30/1999	2.82	6.13	Multi -Head	5E10	4E10	3E10		Yes	Yes		
44031	36021	M-53		9/30/1999	6.47	6.94	Multi -Head	5E10	4E10	3E10		Yes	Yes		
50012	36021	M-53		9/3/1999	11.20	11.22	Multi -Head	5E10	4E10	3E10		Yes	Yes		
41026	35988	I-96	EB	10/30/1998	4.73	5.64	RMI	4E30	3E30	2E30					
41026	35988	I-96	EB	10/30/1998	5.87	6.10	RMI	4E30	3E30	2E30					
41026	35988	I-96	WB	10/30/1998	4.76	5.20	RMI	4E30	3E30	2E30					
41026	35988	I-96	WB	10/30/1998	5.51	6.07	RMI	4E30	3E30	2E30					
41131	35988	I-296	SB	10/30/1998	17.36	17.88	RMI	4E30	3E30	2E30					
41131	35988	I-296	NB	10/30/1998	17.59	17.76	RMI	4E30	3E30	2E30					
76023	36020	I-69		9/1/1998	0.04	5.93	Multi -Head	4E30	3E30	2E30		Yes	Yes		
16021	28111	M-68		11/14/1990	0.00	7.71	RMI	1100-20AA	1100-20AA	700 MOD-20C	Yes	Yes	Yes		1
20014	26755	I-75	SB	8/24/1990	0.00	3.73	RMI	1100-20AA	1100-20AA	700 MOD-20C					
34031	28115	M-66		10/24/1989	7.20	7.51	RMI	1100-20AA	1100-20AA	700 MOD-20C	Yes	Yes	Yes	Yes	3/8
34032	28115	M-66		10/24/1989	0.00	0.45	RMI	1100-20AA	1100-20AA	700 MOD-20C	Yes	Yes	Yes	Yes	3/8
34043	24662	I-96 Ramps		5/20/1987	11.63	12.03	RMI	1100-20AA	1100-20AA	700-20C					
56-52	33121	Saginaw Rd.		9/26/1992	13.27	13.74	RMI	1100-20AA	1100-20AA	700-20C	Yes	Yes	Yes		
17062	26637	M-28	EB	9/12/1989	18.69	22.29	RMI	1100-20AA	1100-20AA						
16032	26672	M-27		9/8/1990	1.00	2.57	RMI	1100-20AAA	1100-20AAA	700 MOD-20C	Yes	Yes	Yes	Yes	
16032	26672	M-27		9/8/1990	9.31	9.58	RMI	1100-20AAA	1100-20AAA	700 MOD-20C	Yes	Yes	Yes	Yes	
16032	26672	M-27		9/8/1990	9.66	11.38	RMI	1100-20AAA	1100-20AAA	700 MOD-20C	Yes	Yes	Yes	Yes	

Table 3.7 List of rubblized pavement projects in Michigan (continued)

Control section	Job number	Route	Dir.[1]	Completion Date	POB	END	Rubblizer	Asphalt Mix			Distresses				
								Top	Level	Base	TTDC[2]	LTDC[3]	SG[4]	Raveling	Rut depth (in)
16092	25559	I-75		12/6/1988	13.19	15.22	RMI	1300-20AAA	1300-20AAA	700-20C	Yes	Yes	Yes		
33403	33597	Jolly Road		6/1/1993	2.11	3.69	RMI	1300-20AAA	1300-20AAA	1300-20AAA					
61555	35396	Airline Rd.		6/25/1996	0.00	0.44	RMI	1300-20AAA	1300-20AAA	700-20C					3/8
61555	39233	Third Avenue		9/30/1996	0.40	0.84	RMI	1300T, 20AAA	1300L, 20AAA	700, 20C		Yes			3/4
25402	50078	Beecher Rd		10/15/2000	0.00	0.99	Multi -Head	13A	13A	700, 20C					
26011	45410	M-18		7/31/1999	4.86	12.00	Multi -Head	13A	13A	13A	Yes	Yes	Yes		
56200	35269	Saginaw Rd.		8/26/1994	9.52	12.11	RMI	13A	N/A	11A		Yes	Yes	Yes	
56555	35266	Saginaw Rd.		8/26/1994	0.00	3.57	RMI	13A	N/A	11A		Yes	Yes	Yes	
56555	48370	Saginaw Rd.		9/30/1999	7.11	9.51	RMI	13A	13A						
65555	39235	Old M-76		8/8/1996	5.24	6.60	RMI	13A	13A	11A	Yes	Yes	Yes		
65555	44467	Old M-76		8/20/1998	1.01	3.21	Multi -Head	13A	13A	11A	Yes	Yes	Yes		1/8
74073	33937	M-25		7/2/1998	0.48	4.94	RMI	13A	13A	13A	Yes	Yes	Yes		
64555	39385	Third Street		8/30/1998	0.13	0.44	RMI	13A-MOD	13A-MOD						
82400	44388	Larned St.		6/1/1998	0.00	1.49	Multi -Head	1500 T	31 A	1100 L	Yes	Yes	Yes		
09042	28163	M-25	EB	8/24/1990	0.06	1.27	RMI	1500-20AAA	1500-20AAA	700-MOD		Yes	Yes		
09101	28163	US-10	EB	11/1/1989	0.92	7.36	RMI	1500-20AAA	1500-20AAA	700-MOD		Yes	Yes		
09101	28163	US-10	EB	9/8/1990	9.12	11.36	RMI	1500-20AAA	1500-20AAA	700-MOD		Yes	Yes		

Table 3.7 List of rubblized pavement projects in Michigan (continued)

Control section	Job number	Route	Dir.[1]	Completion Date	POB	END	Rubblizer	Asphalt Mix			Distresses				
								Top	Level	Base	TTDC[2]	LTDC[3]	SG[4]	Raveling	Rut depth (in)
13081	24112	I-94	EB	6/8/1988	2.47	5.65	RMI	1500-20AAA	1500-20AAA	900 MOD-20C					
13081	24112	I-94	WB	6/8/1988	2.47	5.65	RMI	1500-20AAA	1500-20AAA	900 MOD-20C					
41131	21089	US-131	NB	6/12/1990	6.47	10.14	RMI	1500-20AAA	1500-20AAA	700 Mod-20C					1/2
41131	21089	US-131	SB	6/12/1990	6.47	10.32	RMI	1500-20AAA	1500-20AAA	700 Mod-20C					1/2
47555	29902	Old US-16		10/29/1990	0.00	1.41	RMI	1500-20AAA	1500-20AAA	700-20C		Yes	Yes		3/4
47013	29768	US-23	NB	10/15/1992	5.49	6.95	RMI	1500-20AAA	1500-20AAA		Yes	Yes	Yes	Yes	
47013	29768	US-23	SB	10/15/1992	5.49	6.95	RMI	1500-20AAA	1500-20AAA		Yes	Yes	Yes	Yes	
47014	29768	US-23	NB	10/15/1992	0.00	7.17	RMI	1500-20AAA	1500-20AAA		Yes	Yes	Yes	Yes	
47014	29768	US-23	SB	10/15/1992	0.00	7.17	RMI	1500-20AAA	1500-20AAA		Yes	Yes	Yes	Yes	
82400	44388	Lafayette St.		7/10/1998	0.00	1.03	RMI	1501 T	32	1101 L	Yes	Yes	Yes		
41013	31067	M-44	EB	8/13/1993	0.70	2.67	RMI	3B	3B	2B		Yes	Yes	Yes	1/4
41013	31067	M-44	WB	8/13/1993	0.70	2.67	RMI	3B	3B	2B		Yes	Yes	Yes	1/4
41033	31068	M-37	NB	9/13/1995	7.93	10.61	RMI	3B	3B	2B			Yes		
41033	31068	M-37	NB	9/13/1995	10.76	15.82	RMI	3B	3B	2B			Yes		
41033	31068	M-37	SB	9/13/1995	7.97	10.61	RMI	3B	3B	2B			Yes		
41033	31068	M-37	SB	9/13/1995	10.76	15.81	RMI	3B	3B	2B			Yes		
01052	31045	US-23		10/29/1996	0.49	2.47	RMI	4B	3B	3B		Yes	Yes		
03555	35605	Blue Star Hwy		5/30/1997	3.54	3.93	RMI	4B	3B	N/A		Yes			
03555	35605	Blue Star Hwy		5/30/1997	3.98	4.01	RMI	4B	3B	N/A		Yes			
13033	29670	I-194/M-66		6/4/1993	0.49	1.68	RMI	4B	3B	3B	Yes	Yes	Yes		1/8

Table 3.7 List of rubblized pavement projects in Michigan (continued)

Control section	Job number	Route	Dir.[1]	Completion Date	POB	END	Rubblizer	Asphalt Mix			Distresses				
								Top	Level	Base	TTDC[2]	LTDC[3]	SG[4]	Raveling	Rut depth (in)
13033	37138	M-66/I-194	NB	8/22/1997	0.06	0.49	RMI	4B	3B	3B		Yes			
13033	37138	M-66/I-194	SB	8/22/1997	0.02	0.49	RMI	4B	3B	3B		Yes			
25092	29727	M-15		9/22/1994	8.61	8.90	RMI	4B	3B	2B					
28091	34060	US-131		9/25/1997	0.00	0.13	Multi -Head	4B	3B	3B	Yes	Yes	Yes	Yes	1/2
33555	35233	Grand River		9/9/1998	0.10	1.06	RMI	4B	3B	3B		Yes	Yes	Few	
37013	28116	US-27	NB	10/14/1993	8.95	11.72	RMI	4B	3B	2B	Yes				1/5
37013	28116	US-27	SB	10/14/1993	8.95	11.36	RMI	4B	3B	2B	Yes				1/5
37013	28116	US-27	SB	10/14/1993	11.45	11.72	RMI	4B	3B	2B	Yes				1/5
37014	38206	US-27	NB	10/7/1997	7.15	14.43	RMI	4B	3B	2B	Yes	Yes	Yes		1/8
37014	38206	US-27	NB	7/31/1998	1.54	7.71	RMI	4B	3B	2B	Yes	Yes	Yes		1/8
37014	38206	US-27	SB	10/7/1997	7.21	14.51	RMI	4B	3B	3B	Yes	Yes	Yes		1/8
37014	38206	US-27	SB	7/31/1998	1.57	7.14	RMI	4B	3B	3B	Yes	Yes	Yes		1/8
41401	37494	Chicago Dr		10/16/1995	0.01	0.37	RMI	4B	3B	3B	Yes	Yes	Yes	Yes	1/8
46082	32388	M-50		9/29/1997	3.94	4.37	Multi -Head	4B	3B	3B	Yes	Yes	Yes	Yes	1/8
46082	32388	M-50		9/29/1997	0.11	1.82	Multi -Head	4B	3B	3B	Yes	Yes	Yes	Yes	1/8
46082	32388	M-50		9/29/1997	4.59	7.13	Multi -Head	4B	3B	3B	Yes	Yes	Yes	Yes	1/4
46082	32388	M-50		7/15/1998	9.58	12.38	Multi -Head	4B	3B	3B	Yes	Yes	Yes	Yes	1/8
56021	35139	M-20	WB	10/22/1994	6.05	10.59	RMI	4B	3B	2B	Yes	Yes	Yes		3/4
58041	32388	M-50		7/15/1998	0.00	5.02	Multi -Head	4B	3B	3B	Yes	Yes	Yes	Yes	1/8
58111	34596	M-50		6/15/1996	1.86	2.25	RMI	4B	3B	2B		Yes			
61407	56926	Airline Dr.		10/1/2000	0.00	0.64	RMI	4B	3B	3B					
70024	35989	I-196	EB	8/20/1997	6.58	10.58	RMI	4B	3B	3B	Yes	Yes	Yes	Yes	1/8
74012	29729	M-53		8/25/1995	9.00	13.00	RMI	4B	3B	3B	Yes	Yes	Yes	Yes	1/4
81063	26796	US-12	EB	11/9/1996	3.61	4.09	Whip Hammer	4B	3B	3B	Yes	Yes	Yes	Yes	

Table 3.7 List of rubblized pavement projects in Michigan (continued)

Control section	Job number	Route	Dir.[1]	Completion Date	POB	END	Rubblizer	Asphalt Mix			Distresses				
								Top	Level	Base	TTDC[2]	LTDC[3]	SG[4]	Raveling	Rut depth (in)
81063	26796	US-12	EB	11/9/1996	4.20	5.12	Whip Hammer	4B	3B	3B	Yes	Yes	Yes	Yes	
81063	26796	US-12	EB	11/9/1996	5.29	5.85	Whip Hammer	4B	3B	3B	Yes	Yes	Yes	Yes	
81063	26796	US-12	WB	11/9/1996	3.98	4.73	Whip Hammer	4B	3B	3B	Yes	Yes	Yes	Yes	
81063	26796	US-12	WB	11/9/1996	4.84	5.08	Whip Hammer	4B	3B	3B	Yes	Yes	Yes	Yes	
81063	26796	US-12	WB	11/9/1996	5.36	5.51	Whip Hammer	4B	3B	3B	Yes	Yes	Yes	Yes	
81063	26796	US-12	WB	11/9/1996	5.63	5.94	Whip Hammer	4B	3B	3B	Yes	Yes	Yes	Yes	
83032	34060	US-131		9/25/1997	12.97	18.66	Multi -Head	4B	3B	3B	Yes	Yes	Yes	Yes	1/2
1052	32335	US-23		11/1/1999	16.37	16.39	RMI	4C	3C	2C		Yes	Yes		
04031	32335	US-23		11/1/1999	0.00	0.24	RMI	4C	3C	2C		Yes	Yes		
04031	44350	US-23		11/1/1999	4.22	7.89	RMI	4C	3C	2C		Yes	Yes		
04032	32336	US-23		11/1/1999	0.45	0.91	RMI	4C	3C	2C		Yes	Yes		
04033	32337	US-23		11/1/1999	1.40	2.25	RMI	4C	3C	2C		Yes	Yes		
12555	39160	Broadway St.		10/25/1997	0.01	0.04	RMI	4C	3C	N/A					
12555	39160	Broadway St.		10/25/1997	0.07	0.22	RMI	4C	3C	N/A					
23012	32386	US-27 BR	NB	10/28/1998	10.69	13.01	RMI	4C	3C	3C	Yes	Yes	Yes	Yes	
23012	32386	US-27 BR	SB	10/28/1998	10.66	13.01	RMI	4C	3C	3C					
25092	45534	M-15		10/1/1998	9.50	10.41	Multi -Head	4C	3C	2C		Yes	Yes		
33083	29581	I-96	EB	7/30/1994	2.11	3.69	RMI	4C	3C	2C					
33084	28213	I-96	EB	10/27/1993	8.98	17.49	RMI	4C	2C	1C	Yes	Yes	Yes	Yes	
33084	29581	I-96	EB	11/8/1995	0.00	1.07	RMI	4C	3C	2C					
39052	48864	E. Michigan		6/11/1999	0.00	2.41	Multi -Head	4C	3C	2C					
39060	39503	E. Michigan		10/1/1998	0.99	3.61	RMI	4C	3C	2C			Yes		
39405	46994	Portage Rd.		11/29/1998	0.00	2.14	Multi -Head	4C	3C	2C		Yes	Yes	Yes	

Table 3.7 List of rubblized pavement projects in Michigan (continued)

Control section	Job number	Route	Dir.[1]	Completion Date	POB	END	Rubblizer	Asphalt Mix			Distresses				
								Top	Level	Base	TTDC[2]	LTDC[3]	SG[4]	Raveling	Rut depth (in)
39405	49551	Portage Rd.		9/15/1999	0.00	1.13	RMI	4C	3C	2C			Yes	Yes	
39405	50708	Shaver Rd		10/30/1999	1.28	1.93	Multi -Head	4C	3C	3C			Yes		
39555	39212	E. Michigan		9/4/1996	13.89	15.17	RMI	4C	3C	2C	Yes	Yes	Yes	Yes	
41013	45797	M-44		8/22/1999	2.67	2.82	RMI	4C	3C	2B, 2C	Yes	Yes	Yes	Yes	1/4
41033	26691	M-37	NB	8/14/1992	2.48	7.92	RMI	4C	2B	2B	Yes	Yes	Yes		
41033	26691	M-37	SB	8/14/1992	2.48	7.35	RMI	4C	2B	2B	Yes	Yes	Yes		
41033	26691	M-37	SB	8/14/1992	7.44	7.92	RMI	4C	2B	2B	Yes	Yes	Yes		
41401	49321	Wolverine Blvd		8/22/1999	0.00	1.39	RMI	4C	3C	2B, 2C	Yes	Yes	Yes	Yes	1/4
58171	34113	I-275	NB	Top in 98	0.47	1.96	Multi -Head	4C	3C	2C					1/4
58171	34113	I-275	SB	Top in 98	0.00	1.98	Multi -Head	4C	3C	2C					1/4
67021	45053	US-10		10/30/1998	1.94	2.63	Multi -Head	4C	3C	2C		Yes	Yes	Yes	
67022	45053	US-10		10/30/1998	0.00	1.52	Multi -Head	4C	3C	2C		Yes	Yes	Yes	
70013	38179	US-31	NB	9/12/1997	1.23	8.28	RMI	4C	3C	2C		Yes	Yes		1/2
70013	38179	US-31	NB	9/12/1997	8.93	13.01	RMI	4C	3C	2C		Yes	Yes		1/2
41029	35990	I-196	EB (NB)	7/31/1998	1.15	4.08	RMI	4C-MOD	3C-MOD	2C-MOD			Yes		
41029	35990	I-196	WB (SB)	7/31/1998	1.12	4.11	RMI	4C-MOD	3C-MOD	2C-MOD			Yes		
41029	45068	I-196	EB (NB)	7/31/1998	4.08	6.61	RMI	4C-MOD	3C-MOD	2C-MOD			Yes		
41029	45068	I-196	WB (SB)	7/31/1998	4.11	6.66	RMI	4C-MOD	3C-MOD	2C-MOD			Yes		
70024	35987	I-196	EB	9/30/1996	12.59	15.59	RMI	4C-SHRP	3C-SHRP	2C-SHRP		Yes			
65041	45865	I-75	NB	5/17/2001	6.54	9.54	Multi -Head								
65041	45865	I-75	SB	5/17/2001	6.62	9.34	Multi -Head								
65041	50649	I-75	NB	5/17/2001	9.54	11.37	Multi -Head								
65041	50649	I-75	SB	5/17/2001	9.34	11.27	Multi -Head								

Table 3.7 List of rubblized pavement projects in Michigan (continued)

Control section	Job number	Route	Dir.[1]	Completion Date	POB	END	Rubblizer	Asphalt Mix			Distresses				
								Top	Level	Base	TTDC[2]	LTDC[3]	SG[4]	Raveling	Rut depth (in)
83-81	33614	Mackinaw Trail		9/30/1992	0.0	0.0	RMI								
33084	28213	I-96	WB	10/27/1993	17.50	8.85	RMI	SMA-A or B	2C	1C	Yes	Yes	Yes	Yes	
03111	32373	US-131	NB	6/19/1997	6.73	7.96	RMI	SMA-C	3C	2C					
03111	32373	US-131	SB	6/19/1997	6.73	7.96	RMI	SMA-C	3C	2C					
03112	32373	US-131	NB	6/19/1997	0.02	1.94	RMI	SMA-C	3C	2C					
03112	32373	US-131	NB	6/19/1997	2.08	3.10	RMI	SMA-C	3C	2C					
03112	32373	US-131	NB	6/19/1997	0.00	0.00	RMI	SMA-C	3C	2C					
03112	32373	US-131	SB	6/19/1997	0.02	0.89	RMI	SMA-C	3C	2C					
03112	32373	US-131	SB	6/19/1997	1.18	1.94	RMI	SMA-C	3C	2C					
03112	32373	US-131	SB	6/19/1997	2.08	3.10	RMI	SMA-C	3C	2C					
81076	32390	US-23	NB	11/11/1997	0.54	6.62	Multi -Head	SMA-C	3C	2C					
81076	32390	US-23	SB	11/11/1997	0.54	6.43	Multi -Head	SMA-C	3C	2C					
03112	28143	US-131	NB	11/5/1993	3.07	8.56	RMI	SMA-C, SMA-P, 4C	3C	2C	Yes		Yes		
03112	28143	US-131	SB	11/5/1993	3.07	3.52	RMI	SMA-C, SMA-P, 4C	3C	2C	Yes		Yes		
03112	28143	US-131	SB	11/5/1993	3.76	8.56	RMI	SMA-C, SMA-P, 4C	3C	2C	Yes		Yes		
18555	55091	Clare Ave		5/15/2001	4.45	6.27	Multi -Head								
41402	50251	Chicago Dr		10/31/2000	1.17	1.77	RMI	4E10	3E10	2E10			Yes		

2. The bottoms of each core (attached to some rubblized material, see figure 3.17) was trimmed off by sawing (figure 3.17).

3. The specific gravity of the entire core was then determined according to ASTM standard test procedure D-2726.

4. The AC cores were then sawn to separate the various AC courses and to produce test specimens for the ITCLT and the ITST. The ideal theoretical test specimen thickness is 3.0 in. and the absolute minimum thickness is 2.2 in. (thinner than 2.2-in test specimens are not allowed because of edge effects), (see figure 3.18). Because of the 2.2-in. minimum thickness constraint, some test specimens contained more than one AC course. For example, the test specimen representing the AC surface course contained about 1.5-in. AC surface course and a minimum of 0.7-in. leveling course. Likewise, when an AC course was less than 2.2 in. thick, a part of the adjacent course was included in the test specimen.

5. The specific gravity of each test specimen was then determined according to ASTM standard test procedure D-2726.

6. Each test specimen was subjected to ITCLT (details of the test are presented in a later section).

7. Each test specimen was subjected to ITST (details of the test are presented in a later section).

Table 3.8 provides a summary of the total number of cores extracted from each test site for 19 rubblized pavement projects that were investigated during the Phase II Study. The table also provides information regarding the number of intact and defective cores, the average total thickness of all intact cores of each test site and the average thickness of each AC course. Table 3.9 provides detailed information of all cores that were extracted during the Phase I Study. All of these cores were taken over existing cracks to verify whether or not the crack is a top-down crack. Detailed data regarding the thickness of each core are presented in Appendix F.

3.2 Specific Gravity Test (SG test)

As stated earlier, specific gravity of each intact core was determined after bottom of each core was trimmed. In addition, the specific gravity of each test specimen was determined after each core was cut to test specimen size. Both tests were conducted according to the ASTM standard test procedure D 2726 (1) and the specific gravities were calculated using equation 3.1.

$$G_{mb} = A / (B-C) \tag{3.1}$$

Table 3.8 A summary of the average total thickness of the cores and the average thickness of each AC course for19 rubblized pavement test sites

Test sites	Number of Cores			Average thickness (in)				
	Total	Intact	With cracks /defects	Total core	Overlay	AC surface course	AC leveling course	AC base course
10692-11	12	10	0/2	8.2		1.5	2.2	4.5
10692-12	12	9	0/3	8.0		1.6	2.3	4.1
10753-11	14	11	3/0	4.5		1.6	1.0	1.8
10753-12	15	12	3/0	4.1		1.6	1.0	1.5
11941-21	15	10	5/0	7.8	1.5	1.6	2.3	2.6
11941-22	15	8	5/2	7.4	1.5	1.4	2.1	2.4
20102-11	12	12	-	6.5		1.4	2.1	2.9
20102-12	12	12	-	6.4		1.5	2.1	2.8
20233-11	11	10	0/1	5.5		1.5	1.8	2.2
20233-12	10	7	0/3	5.5		1.3	2.4	1.7
20273-21	15	11	4/0	4.6		1.3	1.5	2.0
20273-31	12	12	-	7.0		1.8	2.5	2.6
20273-41	12	12	-	6.5		1.7	2.0	2.8
20311-11	12	12	-	6.9		1.2	1.8	3.9
30153-11	16	12	4/0	5.3		1.4	1.8	1.8
30373-51	12	12	-	6.6		1.5	1.8	3.4
30373-52	12	12	-	6.4		1.4	1.8	3.3
30373-61	18	15	2/1	5.7		1.6	2.1	2.0
30531-11	20	14	6/0	5.5		1.2	2.2	2.1

Table 3.9 Detailed information of the cores extracted from each test site during the Phase I Study to verify the type of existing distresses

Test site	Crack type	Thickness (in)				Crack depth per AC course (%)		
		Total	Surface	Leveling	Base	Surface	Leveling	Base
11942-11	TJ	4.9	1.3	1.6	2.0	100	100	100
	LC	5.0	1.5	1.6	1.9	100	100	100
	LC	5.0	1.2	1.8	2.0	100	100	100
	D	6.3	1.5	2.2	2.6	100	100	0
	LC	5.9	1.6	1.6	2.8	100	100	25
	TJ	4.7	1.4	1.4	2.0	100	100	100
	LC/TC	5.8	1.7	2.4	1.8	100	100	100
	TC	6.1	1.7	2.2	2.2	100	100	100
	LC	5.9	1.3	2.6	2.1	100	100	0
	LC	6.5	1.3	2.4	2.7	100	100	0
30371-11	TC/LC	6.1	1.8	2.2	2.2	100	20	0
	LC	6.4	1.7	2.2	2.5	100	0	0
	LC	4.8	1.3	1.6	2.0	100	100	0
	LC	5.0	1.6	1.5	2.0	100	100	0
	LC	5.0	1.6	1.5	2.0	100	10	0
30373-11	LC	5.6	1.1	1.8	2.7	100	90	0
	LC	6.0	1.3	1.9	2.9	100	10	0
	LC	6.1	1.4	1.8	3.0	100	50	0
	TC	4.4	1.2	1.6	1.6	100	100	100
10962-21	LC	6.7	1.3	1.6	3.9	100	45	0
	LC	7.2	1.2	1.6	4.4	100	50	0
	LC	6.9	1.1	1.7	4.1	100	75	0
	LC	6.5	1.1	1.7	3.7	100	30	0
	LC	6.5	1.1	1.5	3.8	100	0	0
	C	6.9	1.1	1.8	3.9	0	0	0
	C	7.0	1.2	1.7	4.1	0	0	0
10962-31	LC	6.3	1.2	1.8	3.3	100	60	0
	LC	6.5	1.2	1.6	3.7	100	75	0
	TC	6.4	1.2	2.0	3.2	100	40	0
	TC	5.7	1.2	1.7	2.8	100	100	30
	TC	6.0	1.3	1.9	2.9	100	100	100
109642	LC	7.5	1.5	1.8	4.2	100	0	0
	TC	8.0	1.3	2.0	4.6	100	0	0

C = Control (No crack), D = Diagonal crack, LC = Longitudinal crack, TC = Transverse crack, TJ = Transverse joint

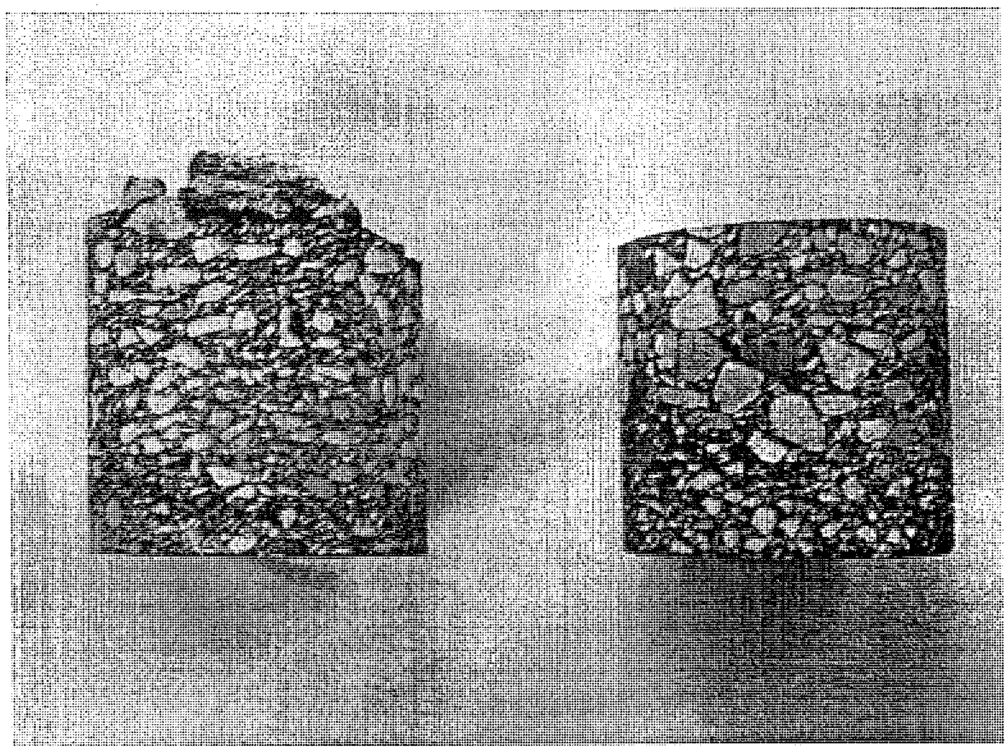


Figure 3.17 Untrimmed (left) and trimmed (right) AC cores

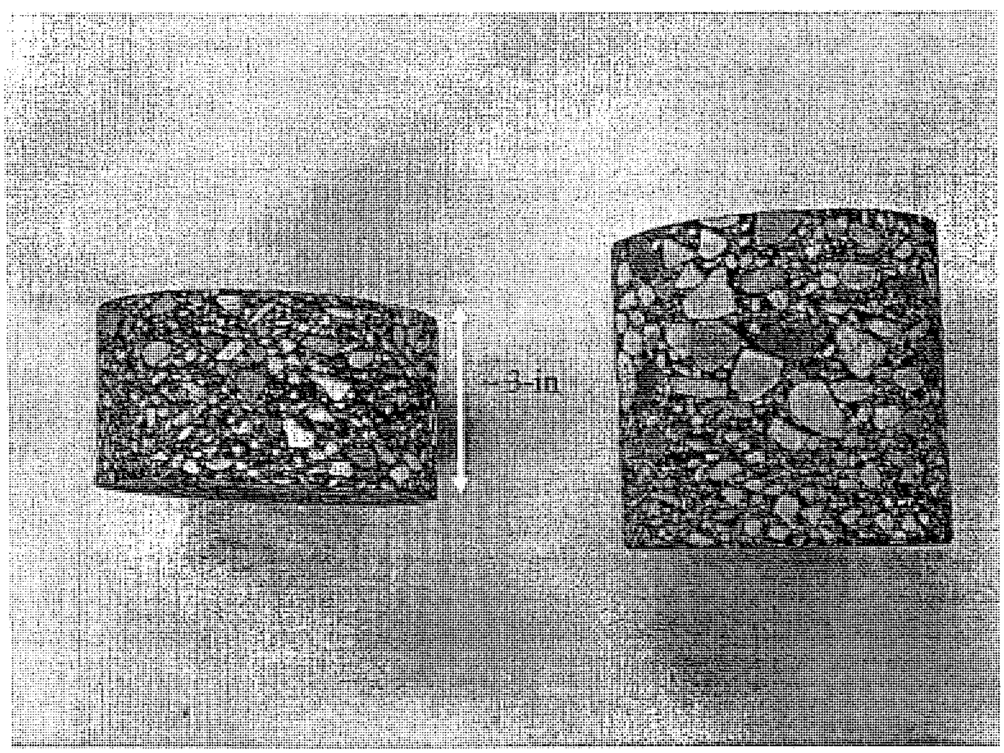


Figure 3.18 An AC test specimen (left) and a trimmed AC core (right)

where:

G_{mb} = bulk specific gravity,
A = mass of the dry test specimen in air, g,
B = mass of saturated surface-dry test specimen in air, g, and
C = mass of the test specimen in water, g.

Once the bulk specific gravities of the AC cores and the test specimens were obtained, their percent air voids were calculated using equation 3.2.

$$AV = 100*(1- G_{mb} / G_{mm}) \qquad (3.2)$$

where:

AV = percent air voids,
G_{mb} = bulk specific gravity, and
G_{mm} = maximum theoretical specific gravity

The main objective of calculating the percent air voids of the core is to assess the degree of variation in the AC mix along the project. Given this objective and the destructive nature of the G_{mm} test (ATSM standard test procedure D 2041), the G_{mm} test was not conducted. Rather a G_{mm} value of 2.5 was assumed for all AC mixes. Table 3.10 provides a summary of the averages of the bulk specific gravity, percent air voids, resilient modulus, equivalent modulus and the indirect tensile strength of all asphalt cores obtained from each test site. The bulk specific gravities and percent air voids of the individual AC cores and test specimens of the 19 rubblized test sites are presented in Appendix G..

3.3 Indirect Tensile Cyclic Load Test (ITCLT)

The objective of the indirect tensile cyclic load test is to determine the resilient modulus of each course of the asphalt mat. The ITCLT was conducted using a computer-controlled closed-loop hydraulic system (MTS) and the ITCLT loading frame shown in figures 3.19 and 3.20. To accomplish the objective, the AC core was sawn to test specimen size between 2.2 and 3.3 in. When the thickness of an asphalt course exceeded 2.2 in., the test specimen consisted of that course only. On the other hand, when the AC course thickness was less than the minimum test specimen thickness of 2.2 in., the test specimen consisted of that entire AC course and a portion of the adjacent course. After sawing the test specimen and measuring its specific gravity, the ITCL was conducted using the following steps:

1. All moving parts and the two loading strips of the ITCLT loading device were cleaned and lubricated.

2. The ITCLT loading device was placed on the MTS loading frame such that the center of the device corresponded with the center of the MTS actuator and the center of the load cell.

Table 3.10 A summary of the average physical and engineering properties of the AC cores obtained from 19 rubblized test sites

Test sites	Bulk specific gravity	Air voids (%)	Resilient modulus (ksi)		Equivalent elastic modulus (ksi)	Indirect tensile strength (psi)
			One-dimension	Three-dimensions		
10692-11	2.32	7.3	177	171	52	97
10692-12	2.31	7.4	179	173	65	107
10753-11	2.38	4.7	209	202	62	146
10753-12	2.39	4.5	196	189	73	171
11941-21	2.40	4.0	203	196	85	211
11941-22	2.40	3.9	214	206	85	241
20102-11	2.33	6.9	188	181	61	126
20102-12	2.31	7.7	207	200	62	118
20233-11	2.39	4.3	202	195	73	138
20233-12	2.38	4.8	213	205	50	120
20273-21	2.45	2.1	291	281	108	213
20273-31	2.44	2.4	217	209	44	101
20273-41	2.45	1.9	258	249	41	100
20311-11	2.46	1.4	234	226	61	123
30153-11	2.35	6.0	220	212	84	172
30373-51	2.36	5.5	186	179	66	167
30373-52	2.35	5.8	196	189	70	154
30373-61	2.45	2.1	273	263	71	143
30531-11	2.33	6.7	170	164	84	172

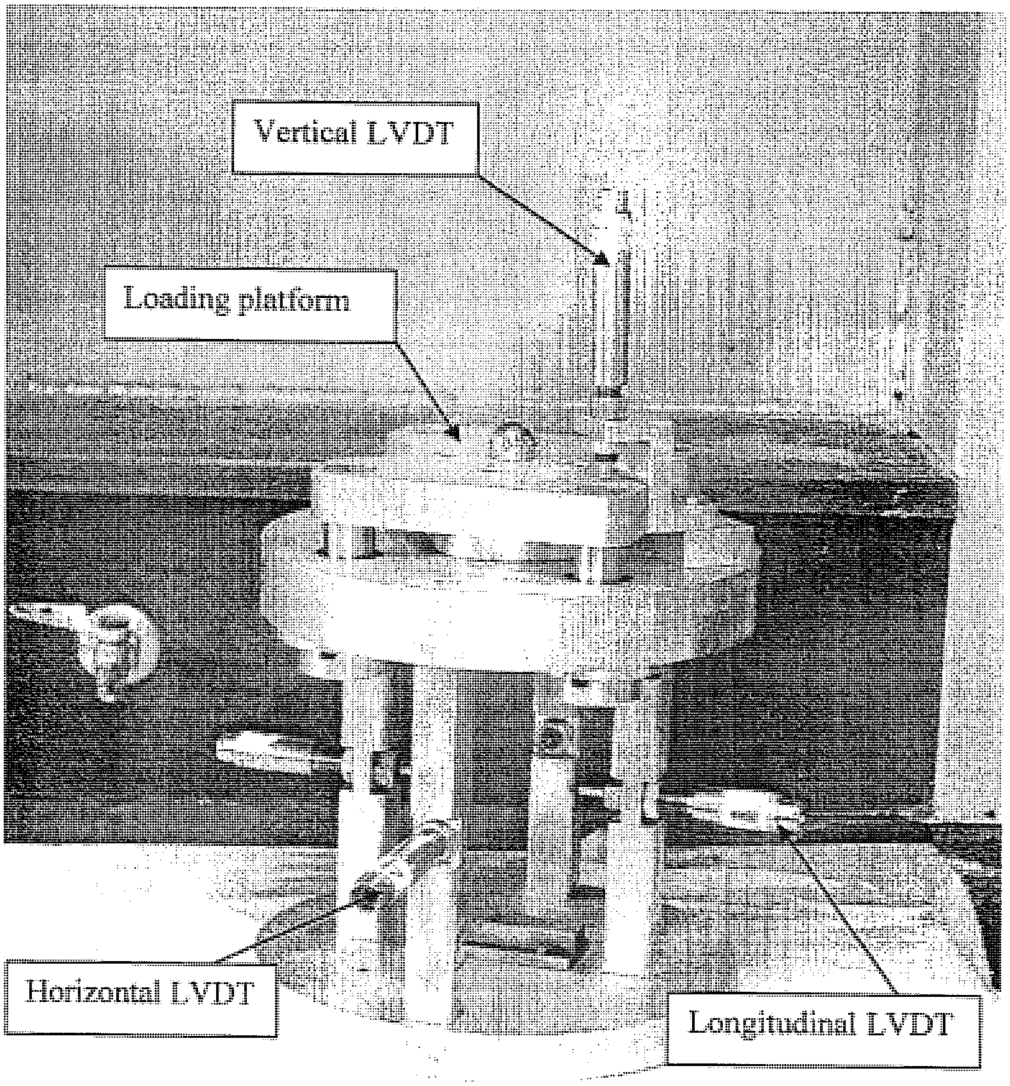


Figure 3.19 The ITCLT and ITST specimen holder device for a 6-in. diameter and 3-in. thick test specimen

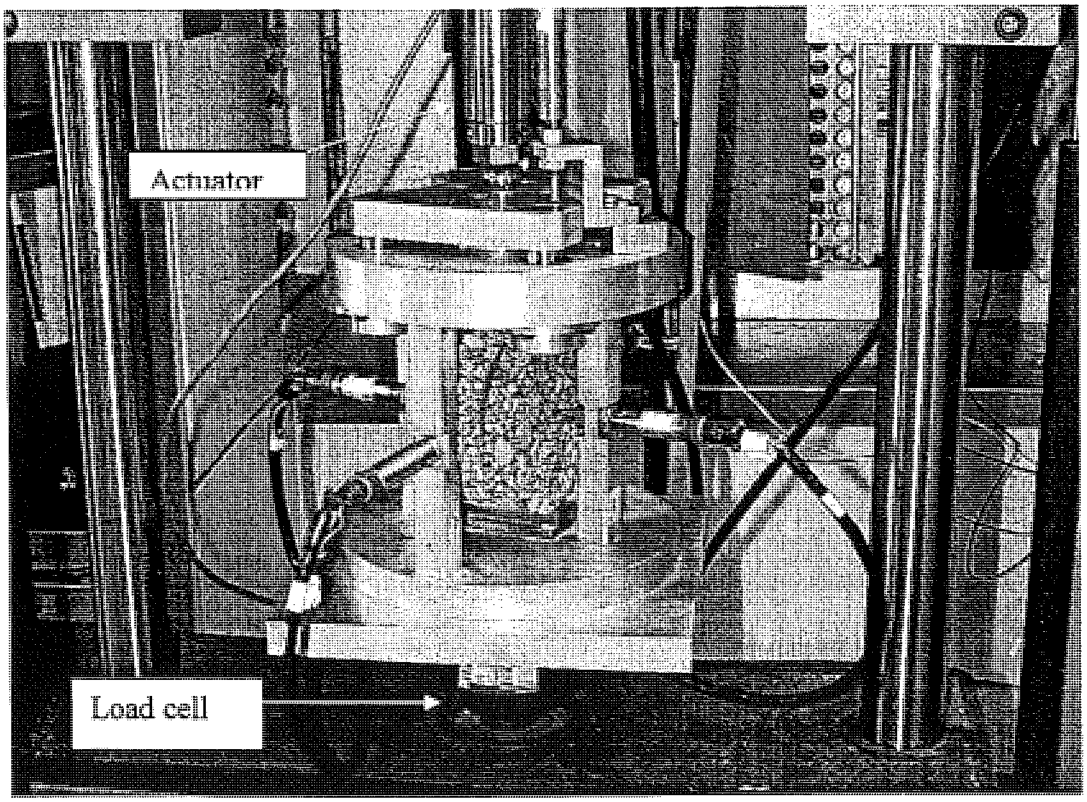


Figure 3.20 Test specimen in the specimen holding device during an ITCLT test

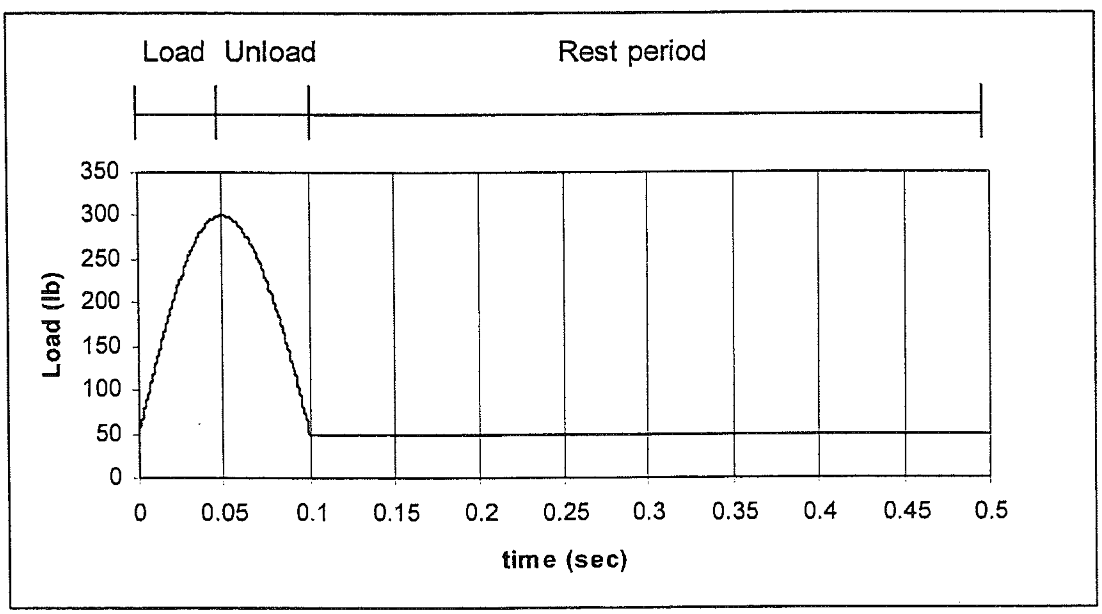


Figure 3.21 One load cycle consisting of 0.1-second load-unload period and 0.4-second relaxation period

3. The test specimen was placed on the loading frame and five linear variable differential transducers (LVDT) were placed in their respective positions as shown in figure 3.20. The accuracy and range of the LVDTs are tabulated below.

Number of LVDT	Position	Range (in)	Accuracy (in)
2	Horizontal diameter	$\pm$0.125	0.00005
2	Specimen Thickness	$\pm$0.100	0.00001
1	Vertical diameter	$\pm$0.250	0.00010

In addition, a sixth LVDT placed inside the actuator (a part of the MTS) was also used to measure the test specimen deformation along the vertical diameter.

4. The position of each LVDT on its holder was adjusted by moving the LVDT core toward or away from the test specimen using two position adjustment knots until the LVDT signal indicates that the core position would allow the use of a high percentage of the LVDT range.

5. A 50-lb sustained load was placed on the test specimen by lowering the actuator of the MTS and the resulting test specimen deformations were recorded.

6. When the rate of deformation due to the sustained load was small enough (not measurable), a 250-lb cyclic load was applied to the test specimen at a frequency of 2 Hz. Each cycle consisted of 0.1-second of load-unload period and 0.4-second relaxation period. The load-unload period simulates traffic movement at about 35 miles per hour while the rest period simulates the distance between two consequent loading (e.g., between the front and back tire and between two vehicles). Figure 3.21 illustrates a plot of one load cycle as a function of time.

7. Each test specimen was subjected to a minimum of 1000 load cycles. At certain specified cycles (e.g., the 200, 500 and 1000 cycles), the load magnitude and the test specimen deformations in three directions were recorded for three sequential cycles. The rate of data collection was set at one set of deformation readings every 0.0004-second. Hence, 250 deformation readings were collected by each LVDT during the load-unload cycle and 1,000 readings during the rest period. Note that the load data were collected using a 1000-lb capacity load cell located under the ITCLT loading frame.

8. The test was terminated and the data was downloaded for analysis.

9. The load and deformations data corresponding to load cycles 499, 500 and 501 were used to calculate the two resilient modulus of the test specimen using the deformations measured in one and three dimensions as follows: .

   a) **One-Dimensional Analysis** – The resilient modulus of the test specimen was calculated using the deformation measured along the vertical diameter of the test specimen (equation 3.3). In this calculation, since the impact of Poisson's ratio on the value of the resilient modulus is insignificant, a Poisson's ratio of 0.3 was assumed for all test specimens.

$$MR = \frac{P * (4.085950 - 0.0417333 * \upsilon)}{L * D_v} \quad (3.3)$$

b) **Three-Dimensional Analysis** - The resilient modulus and Poisson's ratio of the test specimens were calculated using the deformations measured along the vertical and horizontal diameters and along the thickness of each test specimen using equations 3.4 and 3.5.

$$MR = \frac{(0.1832585H + 4.2817159V - 0.0215089A)}{D} \quad (3.4)$$

$$D = 1.0468779(H^2 + V^2 + A^2) - (H - 0.0417333V + 0.212453A)^2 \quad (3.5)$$

Where

MR_v = Resilient modulus based on vertical deformation (psi),
P = peak load (lb),
υ = Poisson's ratio,
L = thickness of the test specimen (in.),
D_v = the deformation of the test specimen along the vertical diameter (in.),
D_h = the horizontal deformation = the sum of the displacements measured by the two LVDT along the horizontal diameter of the test specimen (in.),
DR = deformation ratio = D_v/D_h.,
H = $\frac{D_h * L}{P}$,
V = $\frac{D_v * L}{P}$,
A = $\frac{D_l}{P}$, and
D_l = the longitudinal deformation = the sum of the displacements measured by the two LVDT along the thickness of the test specimen (in.).

Note that the vertical deformation used in equations 3.3 through 3.5 was that obtained from the LVDT placed inside the MTS actuator. The reason is that the actuator and the LVDT were positioned at the center of the test specimen. The outside mounted LVDT was positioned at the corner of the top plate of the ITCLT device as shown in figure 3.20. Nevertheless, the resilient moduli obtained from equations 3.3 and 3.4 were compared. It was found that the differences between the two values are insignificant. Table 3.9 provides a summary of the average resilient moduli calculated using equations 3.3 and 3.4 of the AC cores obtained from 19 test sites. Detailed data (measured deformations in three dimensions, test specimen thickness, and the resilient moduli calculated using equations 3.3 and 3.4) for each core are tabulated in Appendix H.

3.4 Indirect Tensile Strength Test (ITST)

After all ITCLT tests were concluded, the ITST commenced. The objectives of the latter tests are to determine the indirect tensile strength and the equivalent modulus of the test specimens. The tests were conducted at 70°F using the ITCLT device and Marshall loading frame (see figure 3.22). The load was increased to failure by means of the constant rate of movement of the load jack of the Marshall apparatus of 2 in. per minute. The vertical deformation and the applied load were recorded and used in the calculation of the indirect tensile strength and the equivalent elastic modulus of the test specimen using equations 3.6 and 3.7.

$$\text{ITS} = \frac{2P}{\pi D L} \qquad (3.6)$$

$$\text{EM} = \frac{\frac{P}{2} * (4.085950 - 0.0417333 * \nu)}{1000 * L * D_{HL}} \qquad (3.7)$$

Where

ITS = indirect tensile strength (psi);
P = peak load at failure (lb);
D = test specimen diameter (in);
L = test specimen thickness (in);
EM = equivalent modulus (ksi); and
D_{HL} = vertical deformation at half the peak load (in).

The average values of the indirect tensile strength and the equivalent elastic modulus of the test specimens of each test site are reported in table 3.9. The indirect tensile strength and the equivalent elastic modulus of each test specimen obtained from 19 rubblized pavement test sites are tabulated in Appendix I.

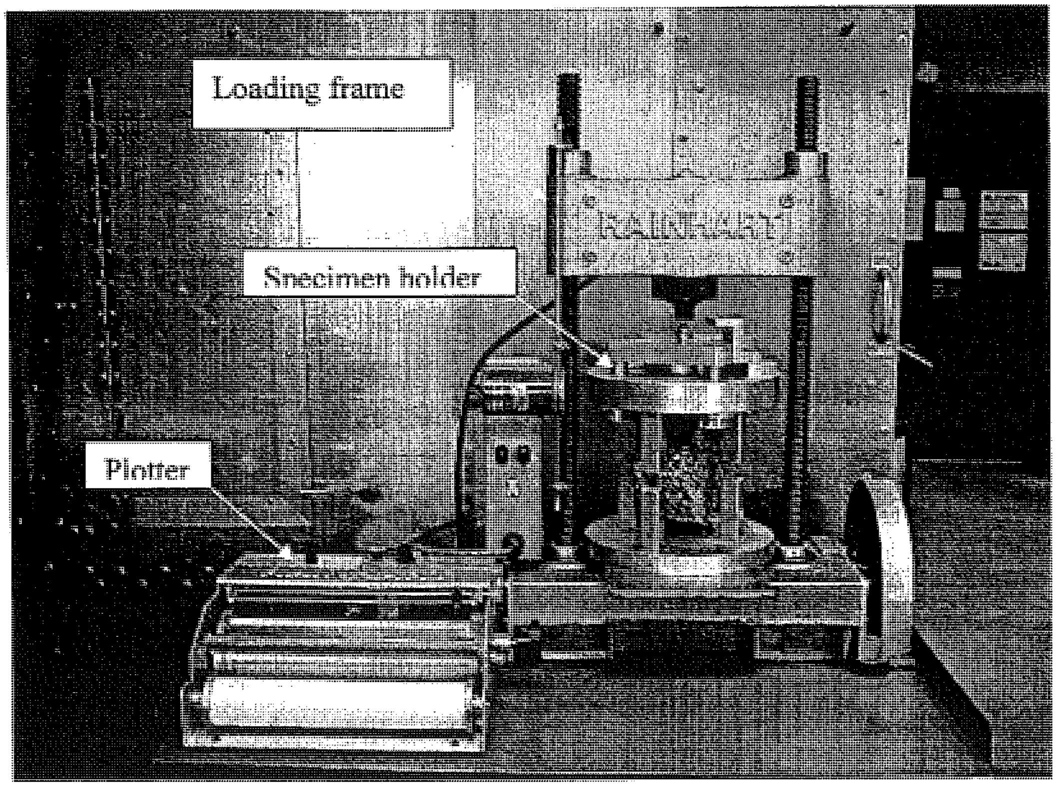


Figure 3.22 ITST loading frame and the specimen holder

REFERENCES

1. Annual Book of ASTM Standards - Section 4 - Construction, 1994, Vol. 04.03 Road and Paving Materials; Paving Management Technologies, The American Society for Testing and Materials, Philadelphia, Pennsylvania.

2. Federal Highway Administration, Integrated Material and Structural Design Method for Flexible Pavements, Vol. 1, Publication No. FHWA-RD-88-109, 1988.

CHAPTER 4
RUBBLIZATION

1.0 INTRODUCTION

With the aging of the pavement network, many techniques were developed for the rehabilitation of concrete, asphalt and composite pavements. For concrete pavements, these techniques include full and partial depth repairs with and without asphalt overlay, crack and seat with asphalt overlay and bonded and unbonded concrete overlays. Recently, the rubblization of concrete pavement with asphalt surfacing was introduced. Since the mid 1980s, considerable number of lane-miles of concrete pavements has been rubblized. Although a certain percent of the rubblized pavements have performed very well, few have under performed. The underperformance is mainly due to longitudinal and transverse cracks, segregation, raveling, block cracking and rutting. Some of these distresses were observed only few years after the completion of construction. The most dominant of these distresses are intermittent longitudinal cracks and partial- and full- width transverse cracks.

Fortunately, historical rubblized pavement performance data can be found in the pavement management databank of MDOT and other State Highway Agencies (SHAs). In Michigan, the data were and are being used to assess the performance of rubblized pavements, to develop performance prediction model; and to estimate the life cycle cost of the pavement. Analysis of the distress data and field investigation of under performing rubblized pavements indicated that the most predominant distress type is cracking, although few projects showed signs of raveling and rutting. The cracks can be divided into three categories:

1. Longitudinal cracks that initiate at the pavement surface and propagate downward and outward. Some cracks have extended through the asphalt surface and part of the asphalt leveling or the asphalt leveling and base courses. Others have propagated throughout the asphalt concrete layer. These types of cracks are referred to as "longitudinal top-down cracks (LTDC)."

2. Transverse cracks that also initiate at the pavement surface and propagate downward and outward. As is the case for LTDC, some cracks have extended through the asphalt surface course and part of the asphalt leveling or the asphalt leveling and base courses. Others have propagated throughout the asphalt concrete layer. These types of cracks are referred to as "transverse top-down cracks (TTDC)."

3. Transverse temperature cracks that extend throughout the depth of the various asphalt courses.

The underperformance of rubblized concrete pavements may be attributed to several variables including the rubblization procedure and equipment, construction procedure, the conditions of the existing concrete pavements before rubblization, the physical and engineering properties of the AC, base and subbase materials and the roadbed soils, and the aging (hardening) of the AC over time.

Unfortunately, the literature in this area is very poor to non-existent. During the course of this study, many efforts were spent searching for journal papers and other publications that address the performance of rubblized pavements; few were found, and are summarized in Appendix K of this report. This chapter addresses several topics related to the underperformance of rubblized and asphalt pavements including:

- The rubblized pavements
- The MDOT special provisions for rubblization
- The rubblization equipment and procedure
- The rubblization procedure
- The quality of rubblization
- The factors affecting the quality of rubblization
- Calibration of the rubblizing equipment
- Forensic investigation of candidate projects for rubblization

2.0 RUBBLIZED PAVEMENTS

Rubblization and AC surfacing is an alternative for the rehabilitation of distressed concrete pavements. There are three main objectives of rubblizing concrete pavements. These are:

1. Destroying the integrity of the concrete pavement joints and cracks such that reflective cracking will be eliminated.

2. Destroying the integrity of the concrete slab by debonding the temperature steel.

3. Changing the concrete slab into a particulate media whose maximum size is less than 8 in. Thus, the rubblized concrete slab would act like a base layer for the newly placed AC layer.

If the above three objectives are successfully achieved, the rubblizing alternative changes the pavement cross-section and its behavior from rigid to flexible pavements (see figure 4.1). Thus, rubblized pavement can be better explained, modeled and analyzed using the multi-layer elastic system rather than the Winkler's foundation, which is used in the analyses of rigid pavements.

If one or more of the above stated objectives are only partially achieved, then the rubblized pavement behavior will be somewhere between the behavior of flexible, composite and rigid pavements. This can be illustrated by the following examples:

Example 1 - If the integrity of the joints in the original concrete pavements is not completely destroyed, the newly surfaced pavement will behave like composite pavements and reflective joint cracking will not be eliminated as shown in figure 4.2.

Example 2 - If the temperature steel is only occasionally debonded, then the integrity of that portion of the concrete slab where the steel is not debonded remains intact and the slab will expand and contract due to temperature changes causing movements and perhaps reflective cracking in the AC layer as shown in figure 4.3.

Example 3 - If the pavement rubblization process produces fractured concrete that extends to the original pavement surface and/or large concrete pieces, the movements of these pieces will cause the asphalt layer to crack or to debond from the surface of the original concrete as shown in figure 4.4.

Note that all pictures shown in figures 4.2 through 4.4 were taken during the distress survey during May 2002.

3.0 MDOT SPECIAL PROVISION FOR RUBBLIZATION

The MDOT July 26, 2000 special provision for rubblizing concrete pavements is contained in Appendix A of this report. Note that the 2000 special provision evolved over time. Hence, many versions of the special provision affected those projects that were constructed prior to 2000 and were investigated during this study. The 2000 provision affected those projects that were constructed during the 2001 season and beyond. Hence, it might be too early to determine the impact of the new provision on pavement performance.

4.0 RUBBLIZING EQUIPMENT

As stated in the special provision (see Appendix A), MDOT allows two types of equipment for rubblizing concrete pavements; a resonant frequency pavement breaker and a multi-headed guillotine breaker, also known as a multi-head breaker. Some common characteristics and features of each machine and operational procedures are presented below.

4.1 Resonant Frequency Pavement Breaker

The resonant frequency pavement breaker was developed and became operational in 1986. From 1986 to about 1995, no other rubblizing equipment was available and therefore a large number of projects were rubblized using this type of equipment. As of 2001, more than thirty state highway agencies have used the equipment to rubblize more than 6,300 lane-miles of deteriorated concrete pavements.

The resonant breaker is a self-contained and propelled machine capable of delivering to the pavement surface low amplitude energy at high frequency of 43 to 46 cycles per second (Hz). The resonant rubblizer is composed of a shoe (hammer) located at the end of a pedestal, which is attached to 12.5-ft shaft (beam) whose thickness is 6.57 in. and

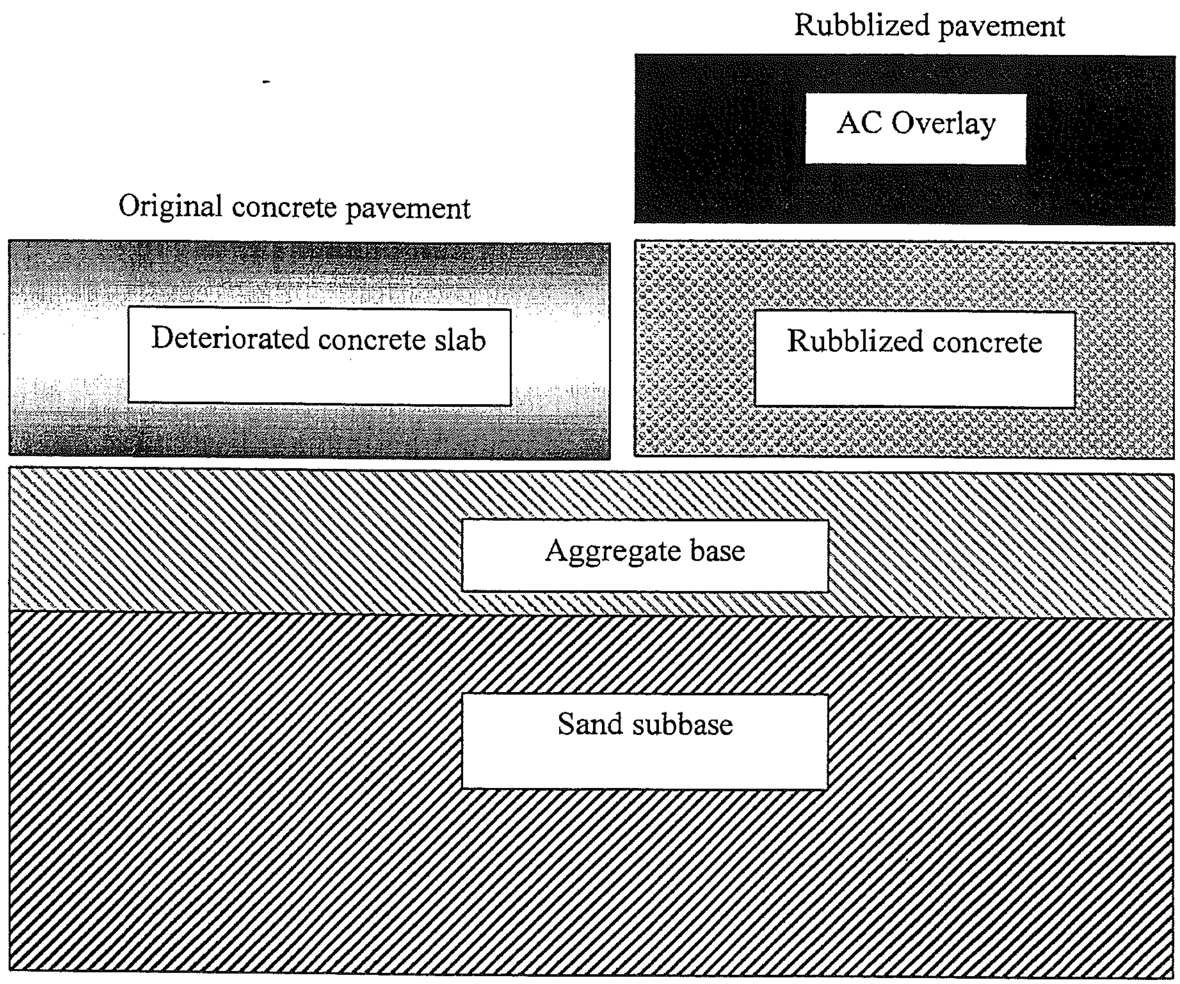
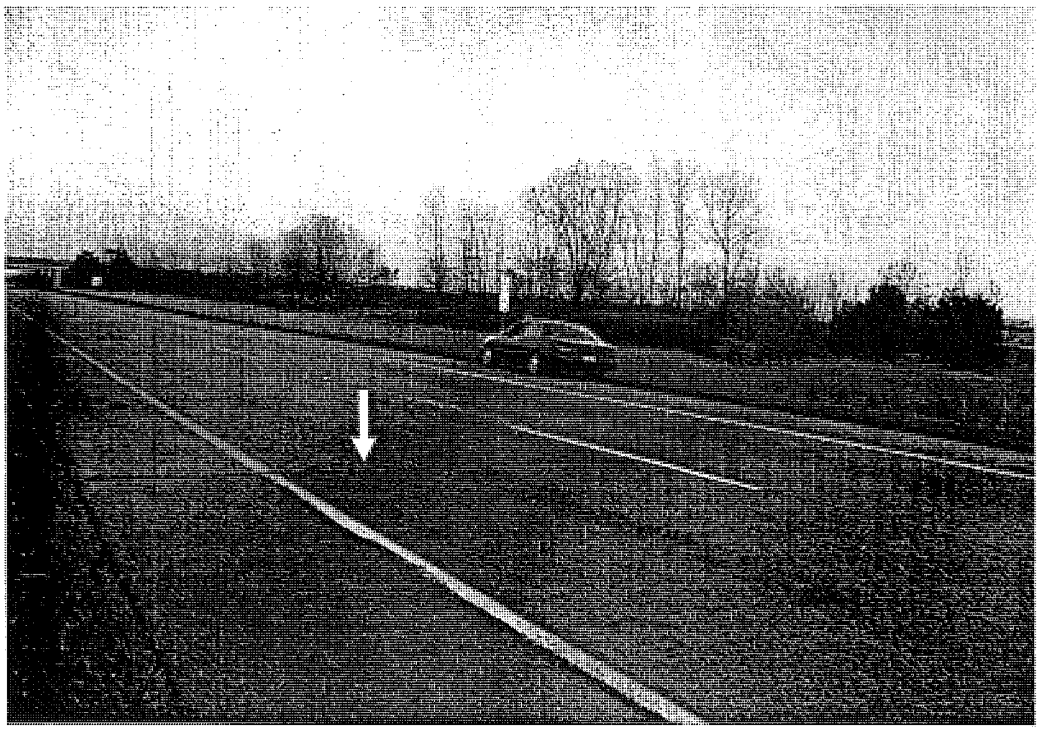
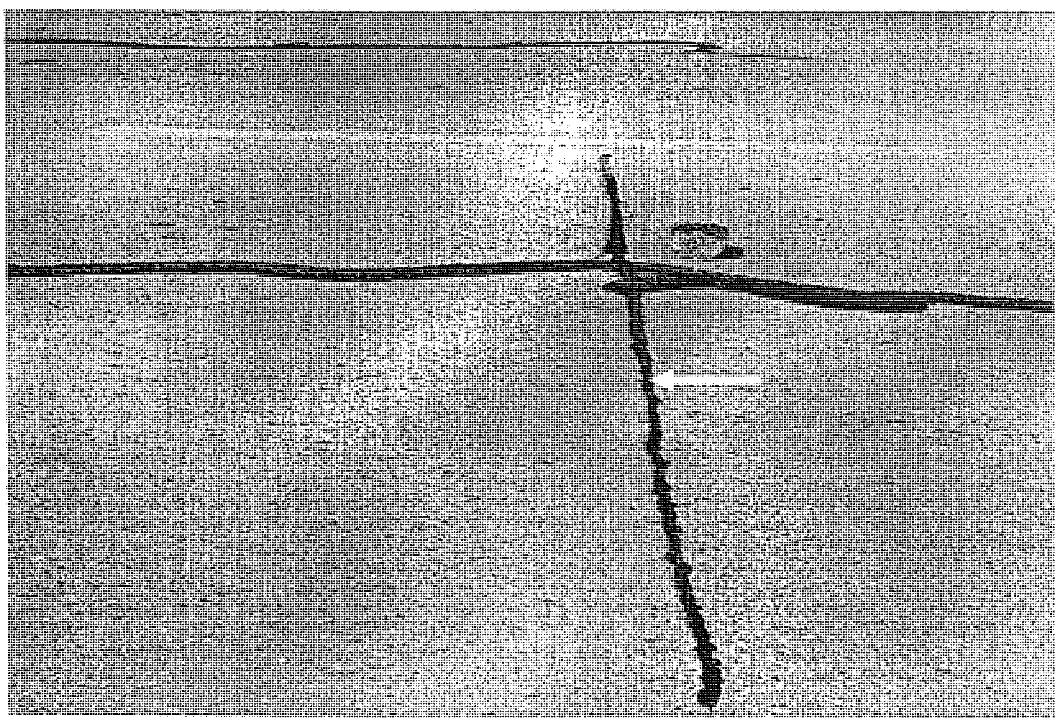


Figure 4.1 Concrete and rubblized pavement cross-sections

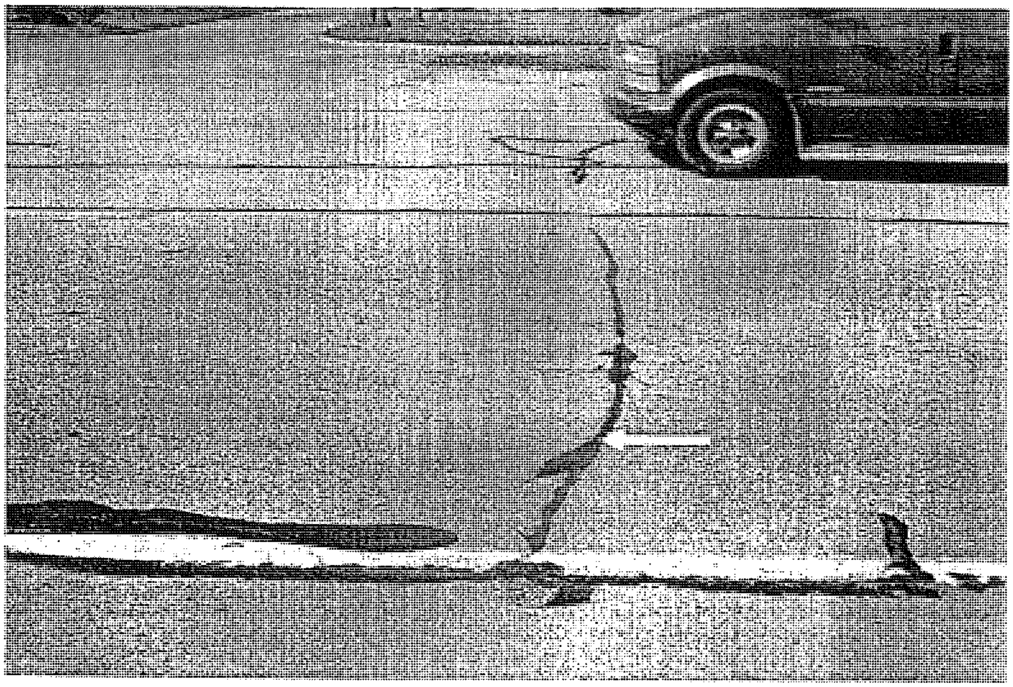


a) US 10

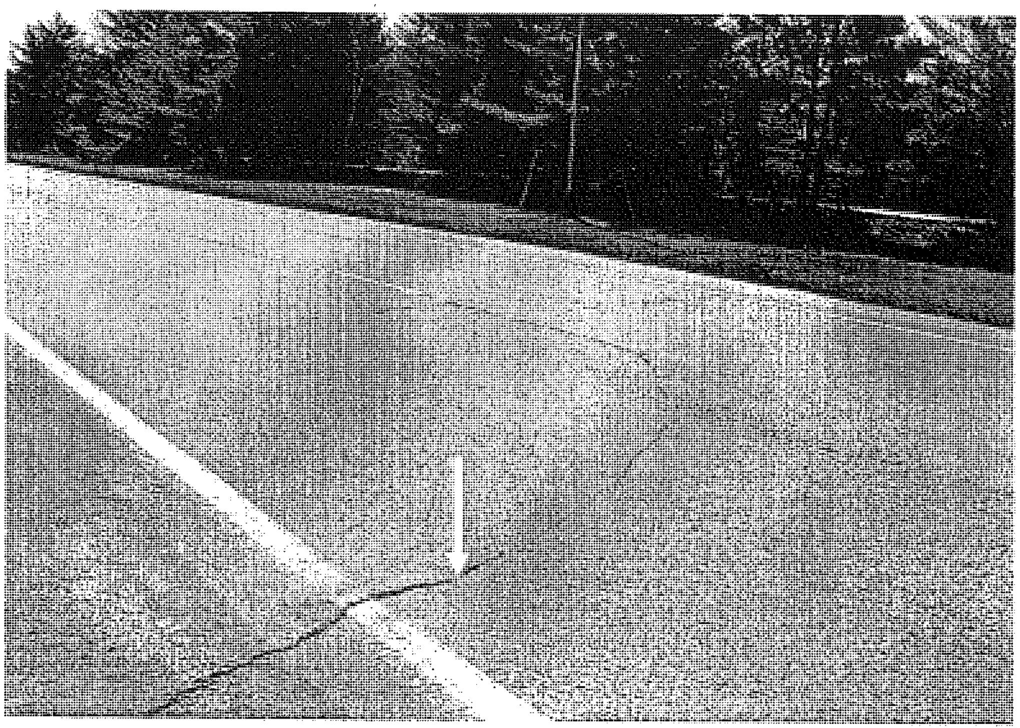


b) M-50

Figure 4.2 Reflective joint cracking in rubblized pavements



a) M-50



b) Saginaw Road

Figure 4.3 Reflective cracks in rubblized pavements

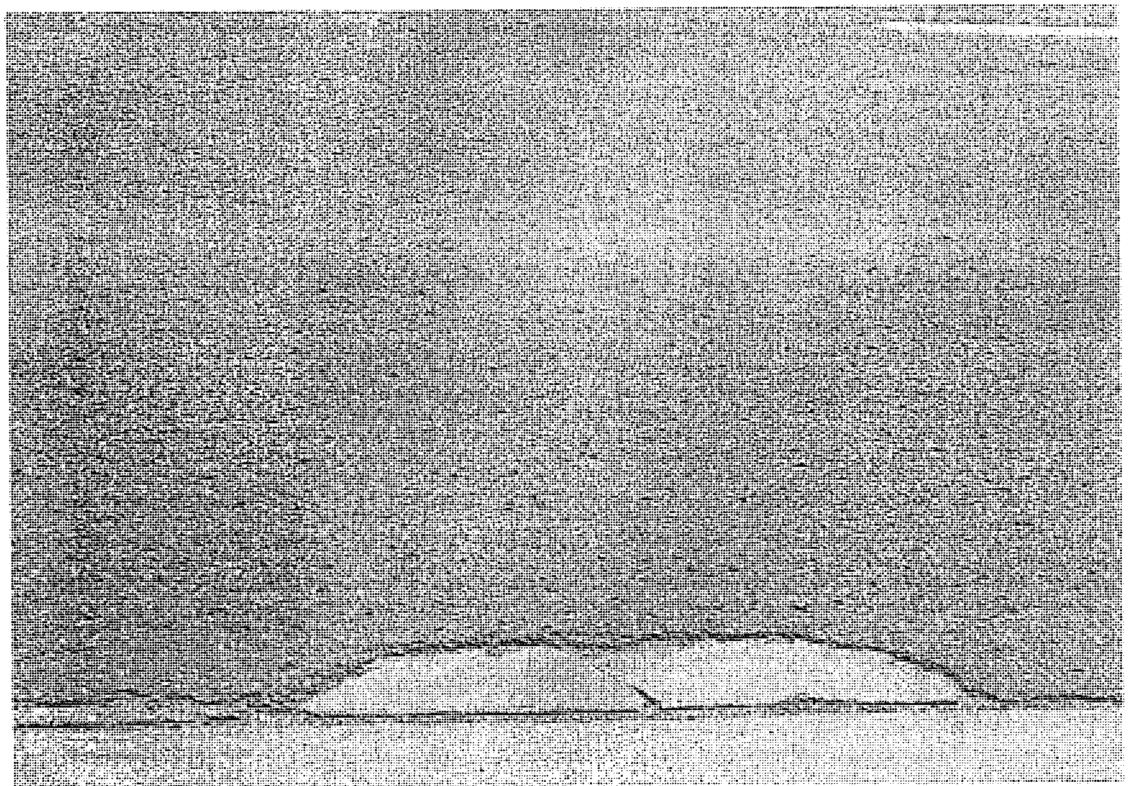


Figure 4.4 Debonding between the AC layer and the original concrete pavement where the fractured concrete extends to the original pavement surface and the integrity of the joint at that location is not destroyed – Portage Road.

loaded at the top by a 12,000-lb counter-weight. The principle on which the resonant breaker operates (figure 4.5) is that a low amplitude (0.5 in.) high frequency resonant energy is delivered to the concrete slab, which causes high tension at the top of the pavement. This causes the slab to fracture on a shear plane inclined at about 45-degrees from the pavement surface. Hence, the fractures are top-down cracking that start at the pavement surface and propagate downward. Figure 4.6 shows a schematic of the sonic shoe.

Several variables affect the rubblized products including shoe size, beam width, operating frequency, loading pressure, velocity of the rubblizer and the degree of overlapping of the various shoe passes. Typical ranges of values for the first five variables are listed below. The rate of production depends on the type of base/subbase material and is approximately 1.0 to 1.5 lane-miles per day.

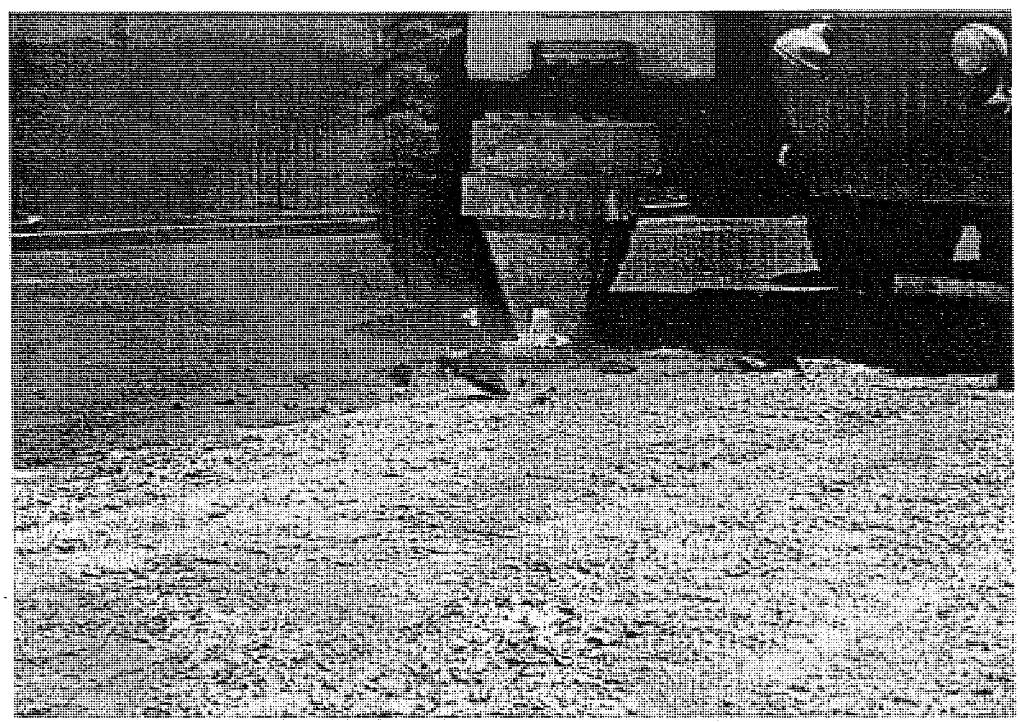
During its operation, a resonant rubblizer may encounter difficulty in the vicinity of pavement discontinuities, such as joints or cracks. At a discontinuity, the microprocessor controller automatically increases the rubblizer speed causing a decrease in the energy delivered to the concrete or a shut down. Bituminous patches or un-milled asphalt overlays present another problem. The shoe penetrates the asphalt causing a large loss in the energy delivered to the concrete. When the applied pressure is low, the shoe bounces on the concrete surface and the shoe does not transfer the needed energy to breakup the concrete. Hence, the effective depth of rubblization decreases substantially and the temperature steel may not debond from the concrete. High pressures, on the other hand, cause the shoe to penetrate into the concrete.

Resonant rubblizer characteristics	Values
Resonant shoe width	7 to 12 in.
Contact strip width	Approximately 2 in.
Beam width	18, 20 and 22 in.
Loading force	5,000 to 25,000 lbs
Loading pressure	208 to 1,800 psi
Frequency	43 to 46 Hz
Velocity	3 to 6 mile/hr

4.2 Multi-head Breaker and Vibratory Grid Roller

A multi-head breaker operation includes multiple drop hammers arranged in two rows on a self-propelled unit (figure 4.7) and a vibratory grid roller (figure 4.8). The bottom of the hammer is shaped as to strike the pavement on a 1.5-in. wide and 8-in. long loading strip. The hammers in the first row strike the pavement at an angle of 30 degrees from the transverse direction. The hammers in the second row strike the pavement parallel to the transverse direction. The hammers strike the pavement approximately every 4.5 in. along the direction of travel. Figure 4.9 shows a typical hammer

a) General view



b) Close-up of the sonic shoe

Figure 4.5 Resonant frequency pavement breaker

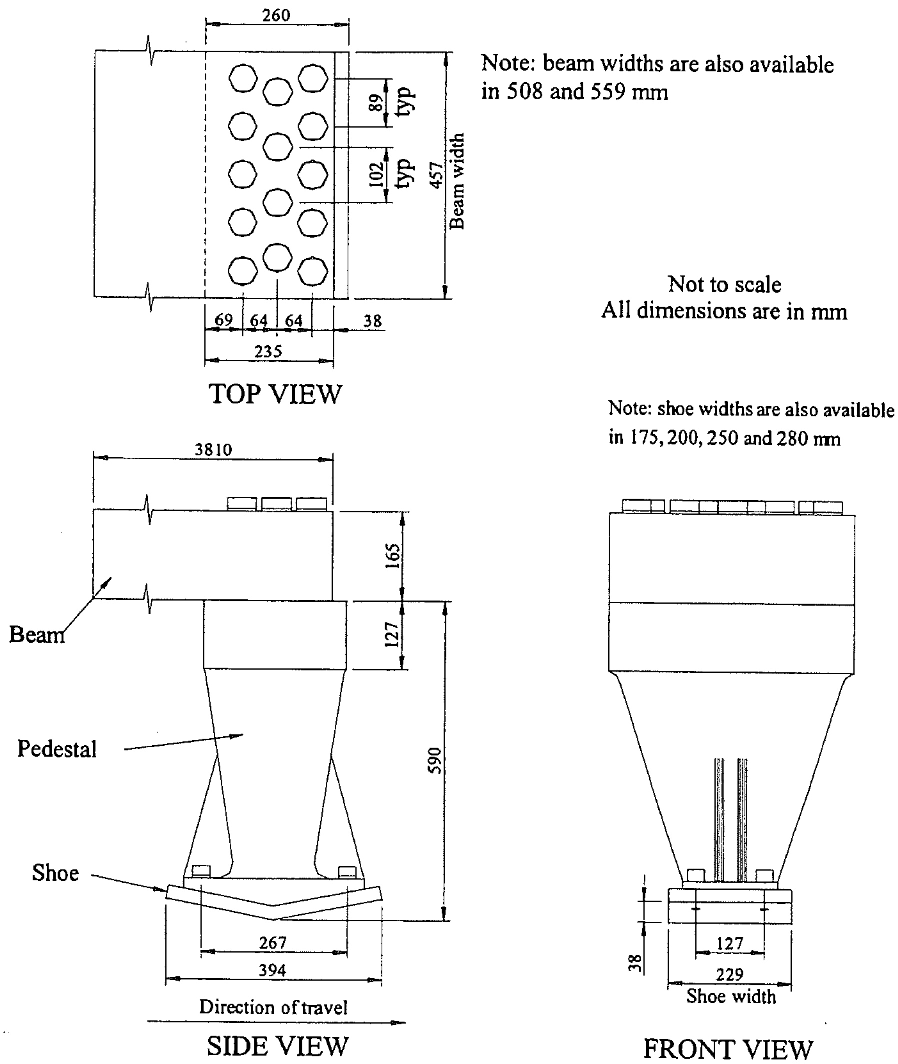


Figure 4.6 A schematic of the sonic shoe of the resonant frequency pavement breaker

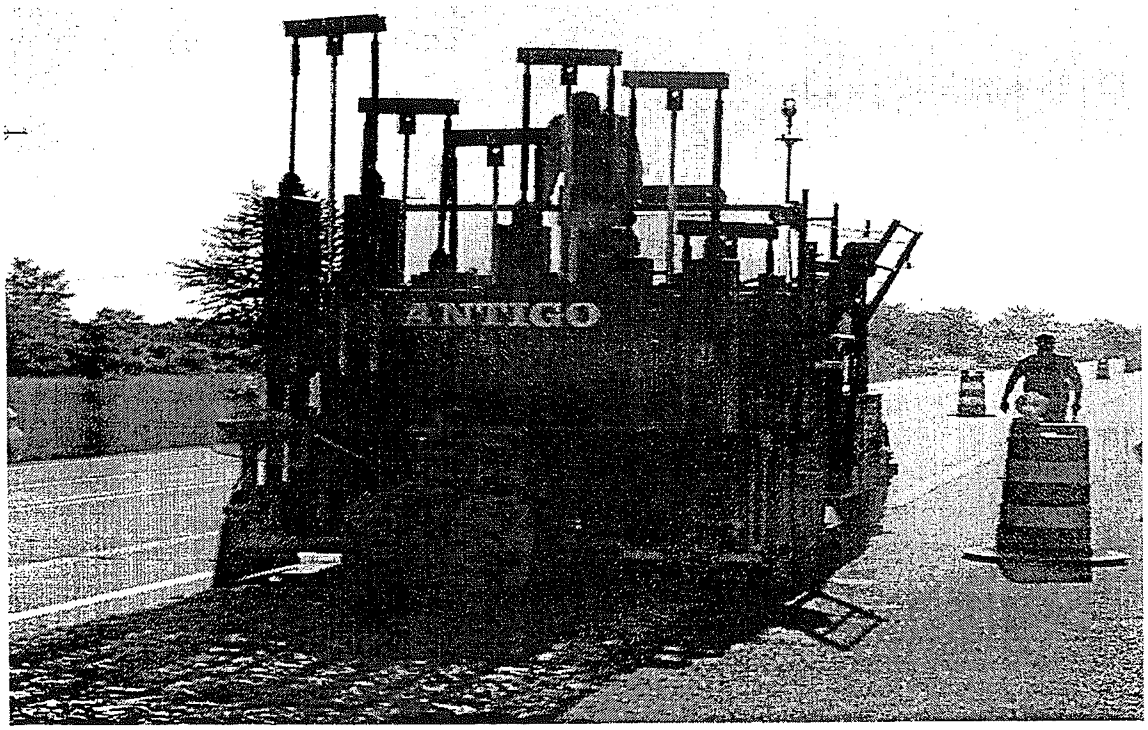


Figure 4.7 A multi-head breaker

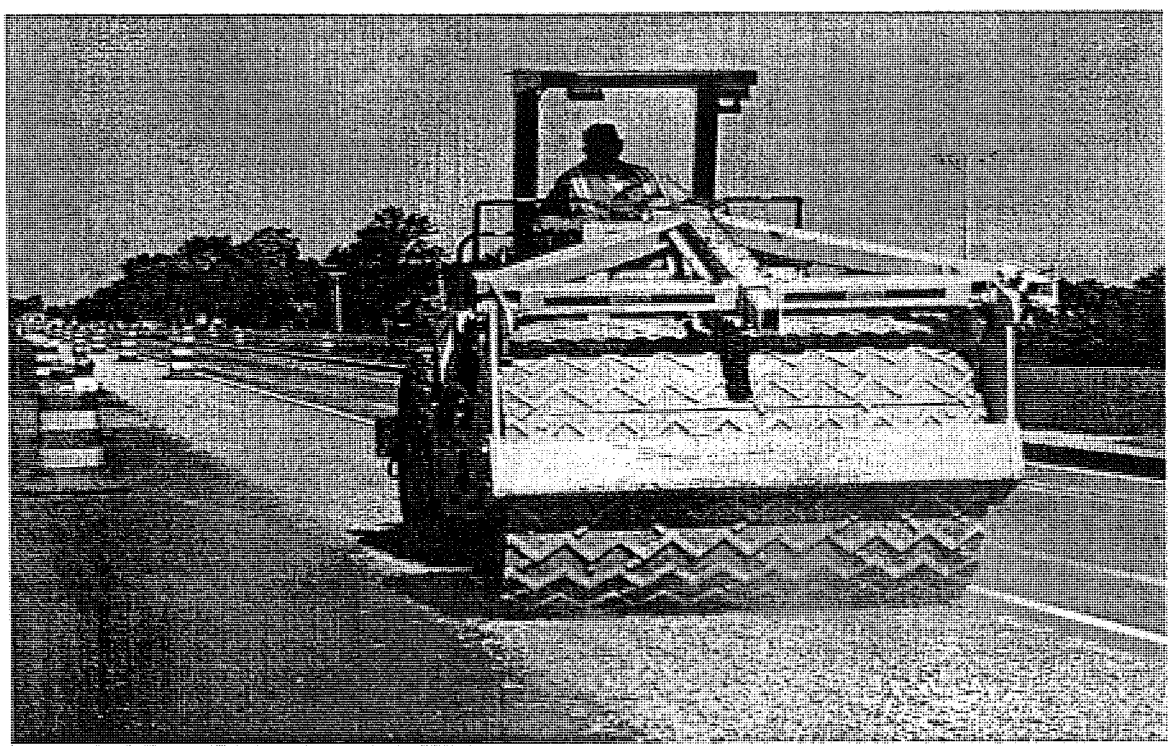


Figure 4.8 A vibratory grid roller

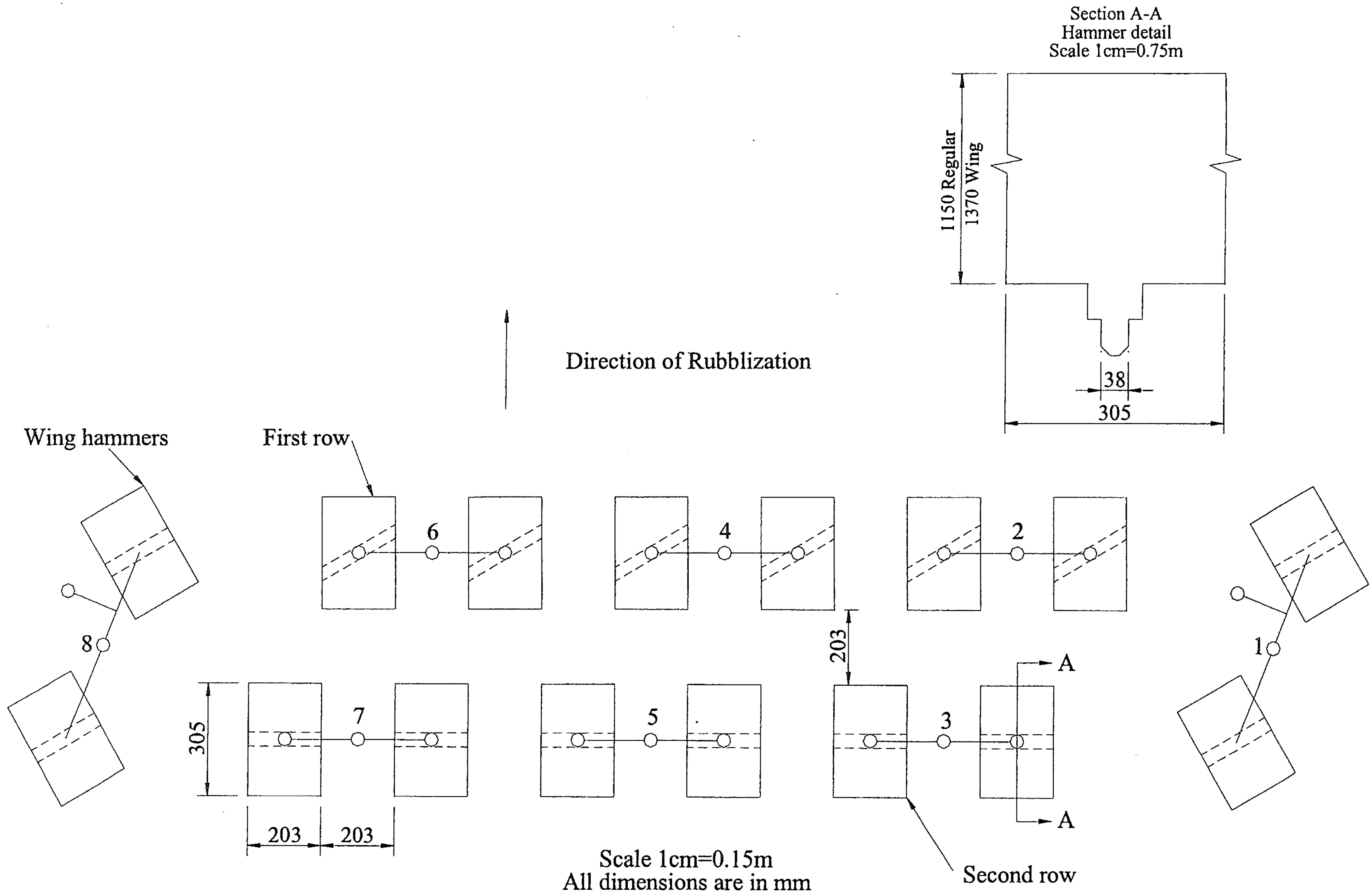


Figure 4.9 Typical hammer configuration of the multi-headed guillotine breaker (multi-head breaker)

configuration. The sequence of hammer drops is irregular because each cylinder is set on its own timer/frequency system. By disabling some cylinders, the width of the rubblized area can be varied from 2.5-ft to 12.67-ft. The 10-ton vibratory grid roller follows the multi-head breaker to reduce the size of the broken concrete. The rate of production of the multi-head breaker depends on the type of base/subbase material and is about 0.75 to 1 lane-mile/day. Some characteristics of the multi-head breaker are provided below.

Multi-head breaker characteristics	Values
Rubblization width	2.5 to 12.7 ft
Cylinders/row	4 or less
Number of rows	2
Distance between rows	20 in.
Number of hammers per cylinder	2
Hammer width	8 in.
Hammer length	12 in.
Pavement striking dimension	1.5 by 8 in.
Distance between hammers in one row	16 in.
Weight/hammer [wing hammer]	1200 to 1500 lbs
Maximum drop height [wing hammer]	48 to 60 in.
Rubblizer operating velocity	500 to 950 ft/hr

Several variables affect the quality of the rubblization operation including the speed of the rubblizer and height, weight and frequency of the drop hammers. The multi-head breaker encounters difficulties on saturated subbase and/or weak roadbed soil (less than 3000 psi modulus), which fail in shear causing large concrete pieces to rotate and/or penetrate the underlying material. Such failure would result in poor pavement performance.

5.0 RUBBLIZATION PROCEDURE STEPS

A typical rubblization procedure consists of several steps that affect the quality of the rubblization operation. Some steps are applicable to the resonant frequency breaker, others to the multi-head breaker and still others apply to both. These steps are:

1. Remove all asphalt overlays and/or asphalt materials from around deteriorated joints and in asphalt patches. Failure to do so would cause poor quality rubblization in these areas and, in the case of the resonant frequency equipment, may cause the automatic shut down of the equipment.

2. Calibrate the operational parameters (frequency, load and velocity) of the rubblizer at the start of every project as to:

   - Produce maximum size rubblized concrete of less than 8 in.

- Debond the temperature steel.
- Destroy the integrity of joints.

3. Slightly overlap the boundaries of the rubblized strips.

4. Add approved filler aggregate to areas where asphalt patches and/or concrete pieces have been removed.

5. Rubblize the same area only once.

6. Spray the rubblized materials with water to minimize dust and prevent the loss of fine materials.

7. Cut and remove all exposed temperature steel.

8. Compact the rubblized materials uniformly using vibratory roller.

6.0 QUALITY OF THE RUBBLIZATION AND PAVING OPERATIONS

There are four objectives (stated in chapter 3 and repeated here for convenience) that need to be achieved by the rubblization operation and one objective in placing the asphalt concrete. These are:

1. **Breaking the Concrete Slab** - Breaking the concrete slabs into small pieces (less than 8 in. maximum dimension). This would eliminate independent movement of large pieces and would increase the degree of interlocking between the broken concrete pieces.

2. **Steel Debonding** - Debonding the temperature steel to decrease the magnitudes of temperature expansion and contraction of the rubblized concrete slab and hence, to reduce the potential of reflective cracking.

3. **Joint Integrity** - Destroying the integrity of the concrete joints to prevent reflective joint cracking.

4. **Rubblized and Fractured Concrete Layers** - Eliminating or decreasing the potential of rubblizing the concrete slab into two distinctive layers; a rubblized material layer and a fractured concrete layer. The two layers when capped with asphalt concrete would behave like a sandwich model (a soft layer between two hard layers). Higher differential stiffness between the three layers causes increases in the load-induced tensile stress at the top of the AC layer, which may cause increases in top-down cracking potential.

5. **Segregation** - Eliminating particle and temperature segregations in the asphalt concrete. Physical or particle segregation substantially decreases the service life

of the segregated areas and decreases the tensile strength of the AC (2 and 3). Figure 4.10 shows two views of a rubblized pavement section along US 23. The construction was completed in 2000. Less than two years after the completion of construction, the segregated area along a part of the passing lane caused severe raveling. The traffic lane (outer lane) and the passing lane outside the segregated area were still in perfect condition in May 2002 (the surveying date). Likewise, figure 4.11 shows two views of an area along US 131where an end-of-load segregation was found.

Examination of rubblized concrete pavements where trenches were excavated at mid slab and transverse joints prior to the placement of the AC surface revealed that in general:

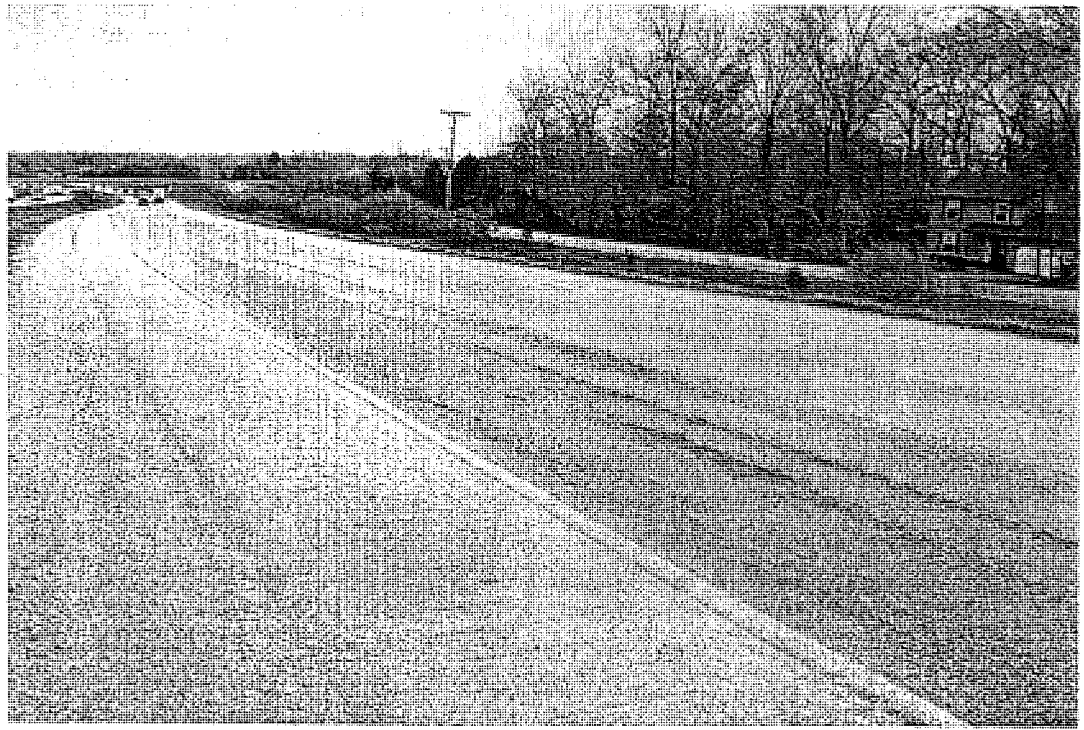
1. The rubblization procedure produced two different layers in the rubblized concrete slabs, a rubblized material layer at the top and a fractured concrete layer at the bottom as shown in figures 4.12 and 4.13. The thickness of each layer varied from one location to another. In some areas, the fractured concrete extended to the original pavement surface (see figures 4.14 and 4.15) while in other locations the rubblized material extended to the bottom of the original concrete slab. Further, the stiffnesses of the two layers were substantially different. It was estimated that the stiffness of the fractured concrete is in order of magnitude higher than that of the rubblized material layer. Such differential stiffness may cause high tensile stress at the top of the AC surface due to traffic load, which increases the potential for top-down cracking.

2. At few locations, the temperature steel was debonded from the original concrete as shown in figure 4.16. However, at most locations, the temperature steel was not debonded.

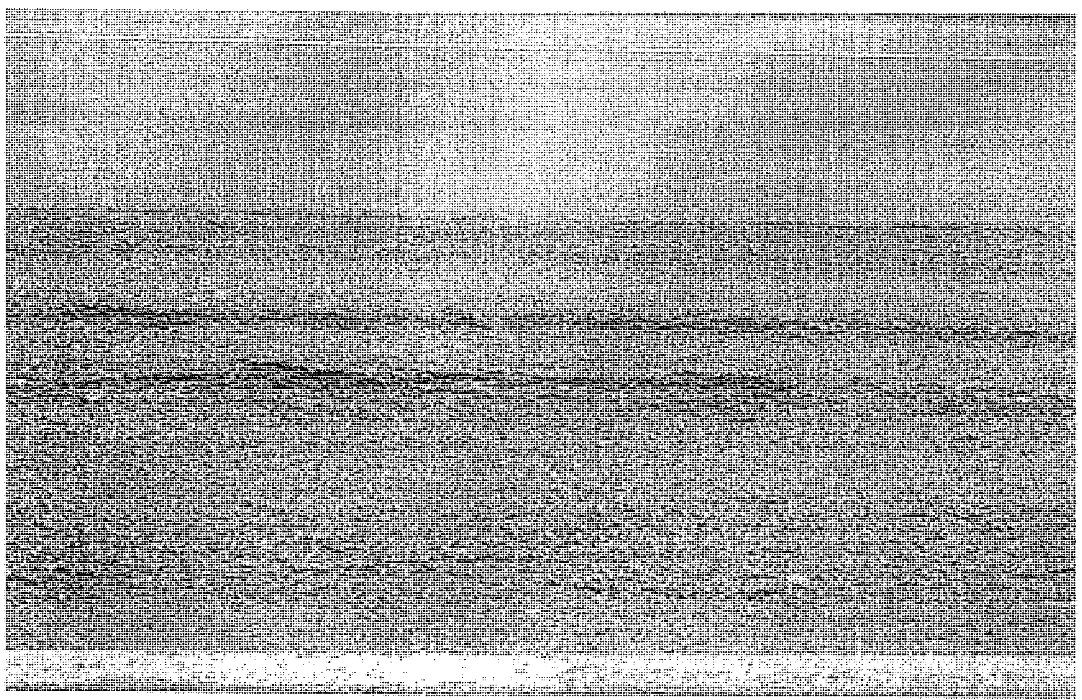
3. At some longitudinal and transverse joints, the integrity of the joints in the original slabs was not completely destroyed (see figure 4.17). Some dowel bars were found embedded in the concrete on both sides of the joint. This may cause the development of reflective joint cracking.

4. On some projects, the drainability of the fractured concrete layer was poor (see figure 4.18). The layer would trap water that infiltrates through cracks in the asphalt layer. The trapped water under the asphalt layer would increase the stripping potential of the asphalt layer.

5. At some locations, the rubblization procedure caused some large concrete pieces (more than 8 in.) to rotate and/or penetrate the underlying base or roadbed material. This implies that the base and/or the roadbed soil have failed in shear action (bearing capacity). This failure is mainly caused by saturated base and/or weak roadbed soil. If the shear failure in the base and/or subbase is not corrected, the finished pavement will experience shear failures in these locations as shown in figures 4.19 through 4.21.

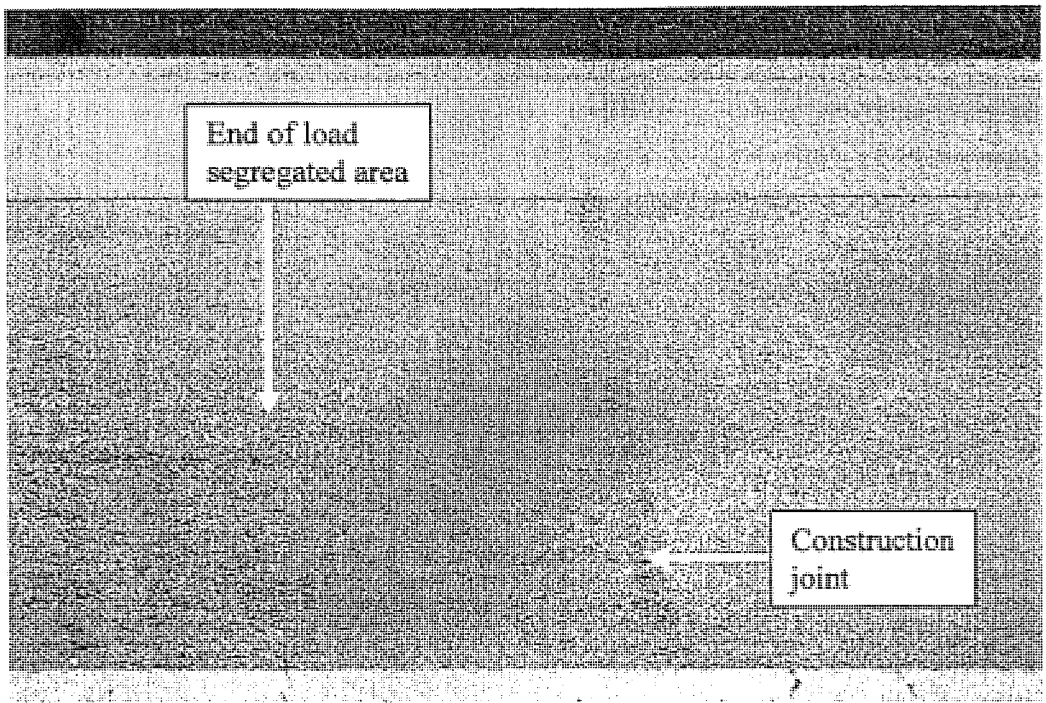


a) General view of a segregated area in the passing lane

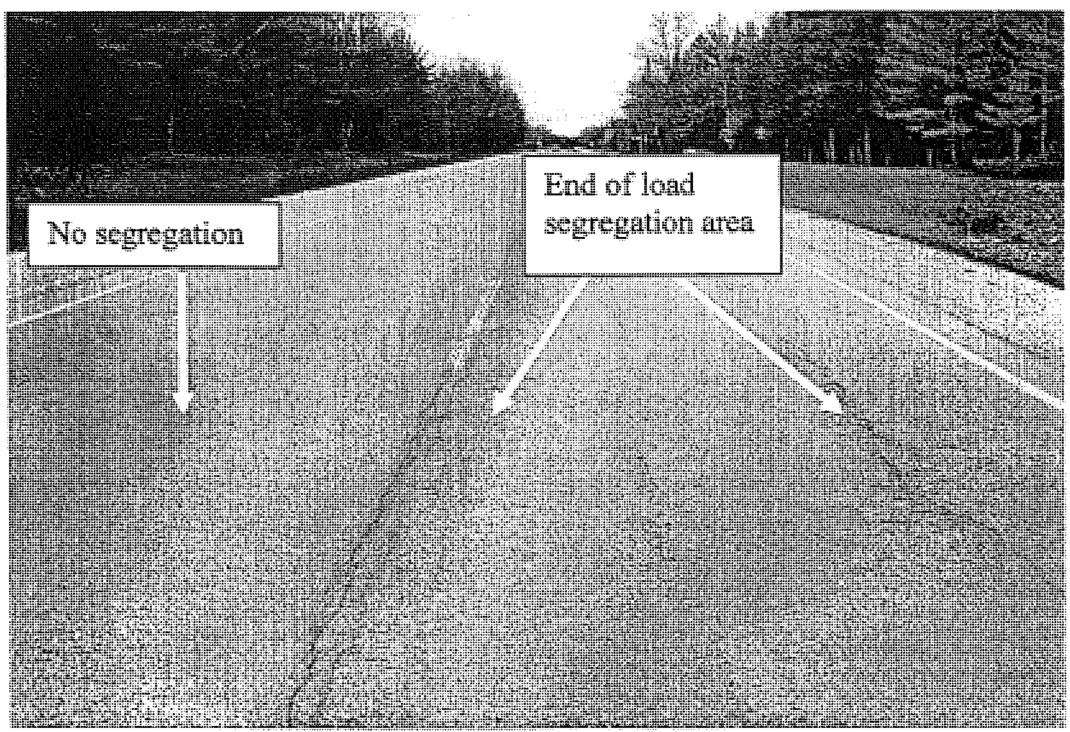


b) A close-up vies of the segregated area in the passing lane

Figure 4.10 Pavement condition in segregated and non-segregated areas along US 23 in May 2002, 2 years after construction,



a) End of load segregated area



b) General pavement condition of segregated and not segregated areas

Figure 4.11 Pavement condition in segregated and not segregated areas along US-131 in May 2002, 5 years after construction

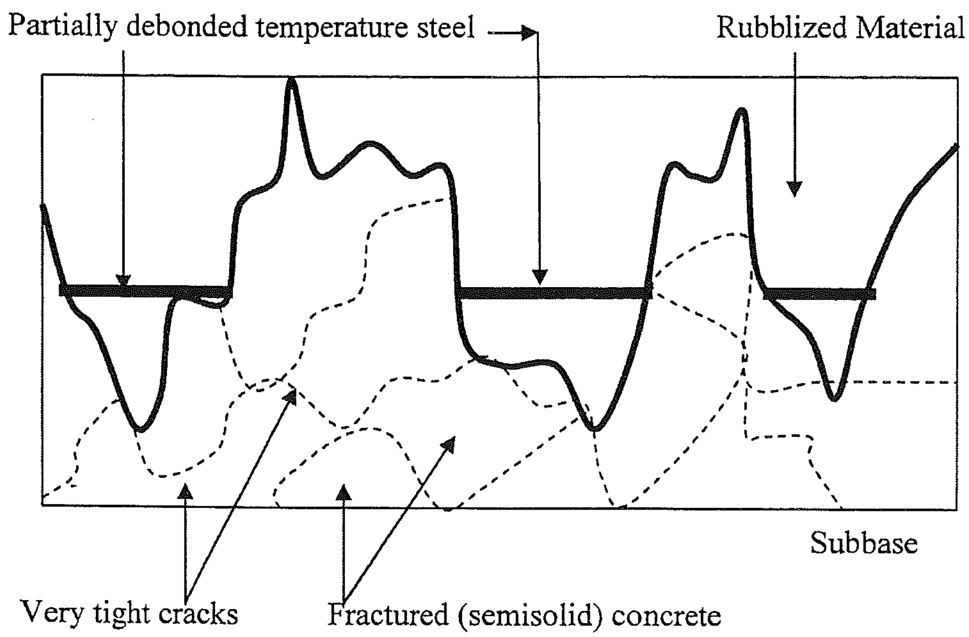


Figure 4.12 Schematic of rubblized concrete slab showing rubblized and fractured layers

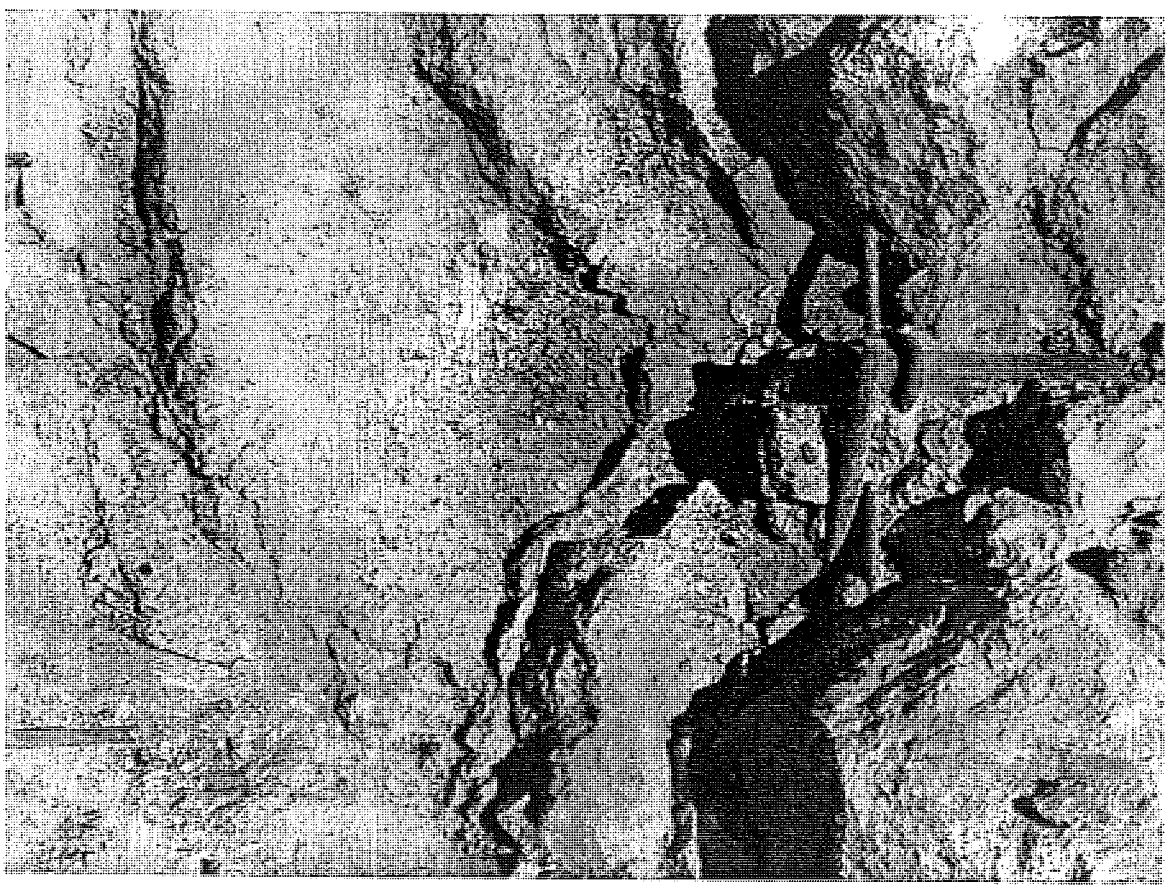


Figure 4.13 Close-up of the fractured concrete in a trench (M-50)

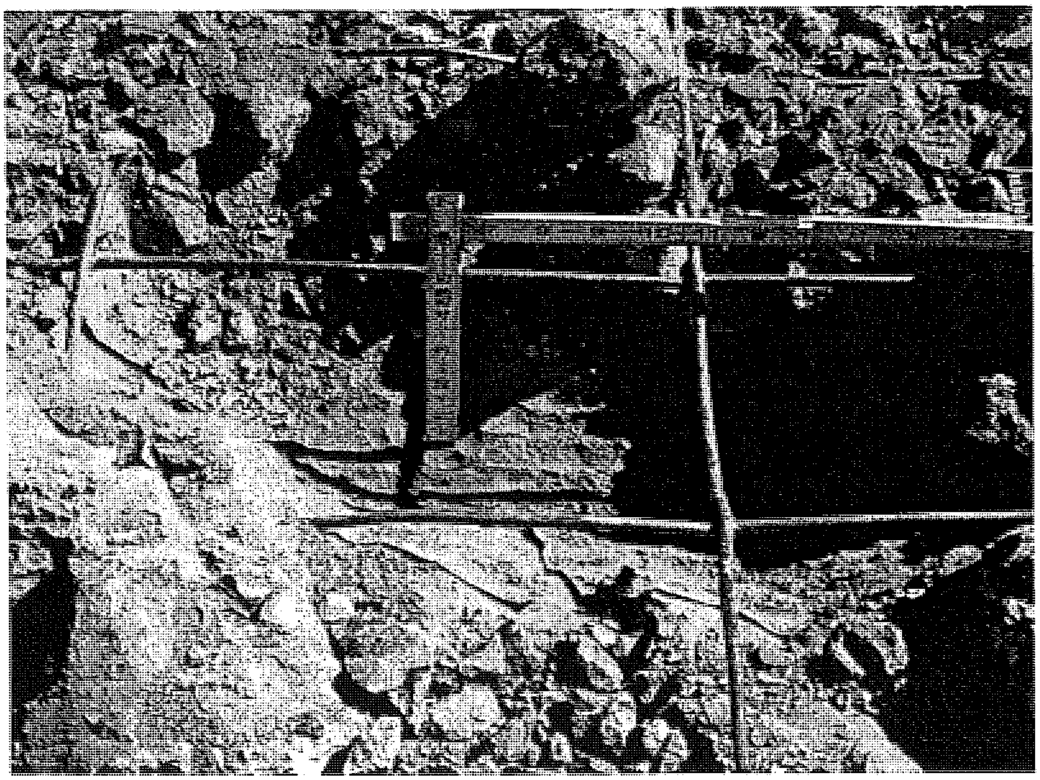


Figure 4.14 Excavated trench in a rubblized concrete slab showing the sand subbase and the fractured concrete

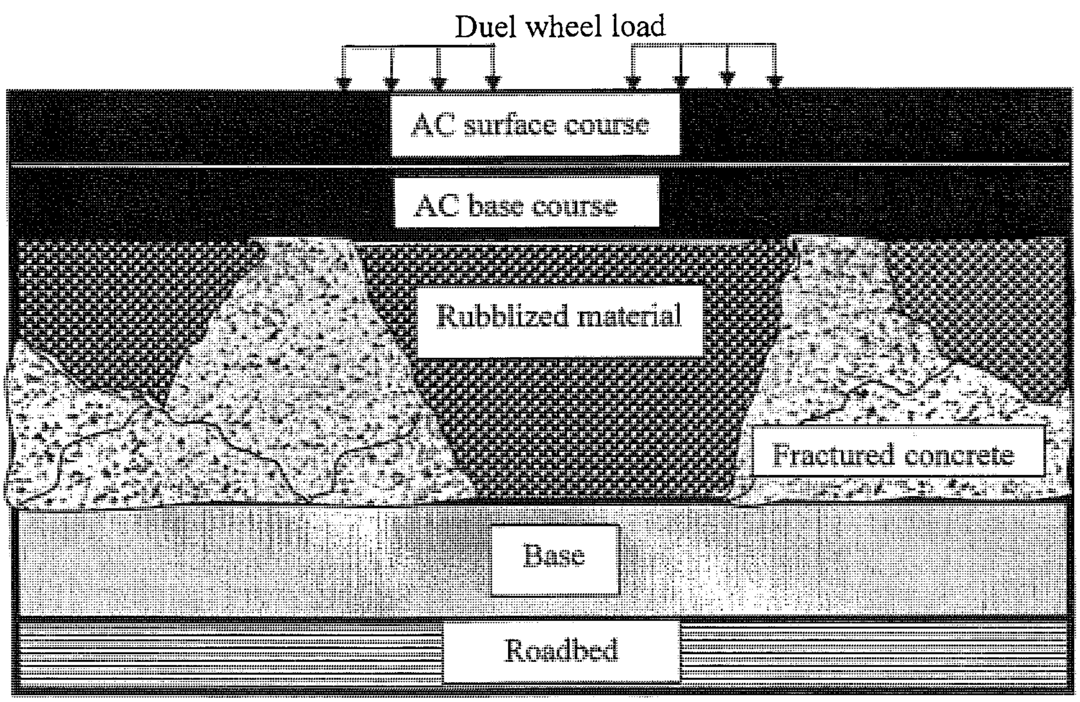


Figure 4.15 Schematic representation of the trench area of figure 4.13 after construction

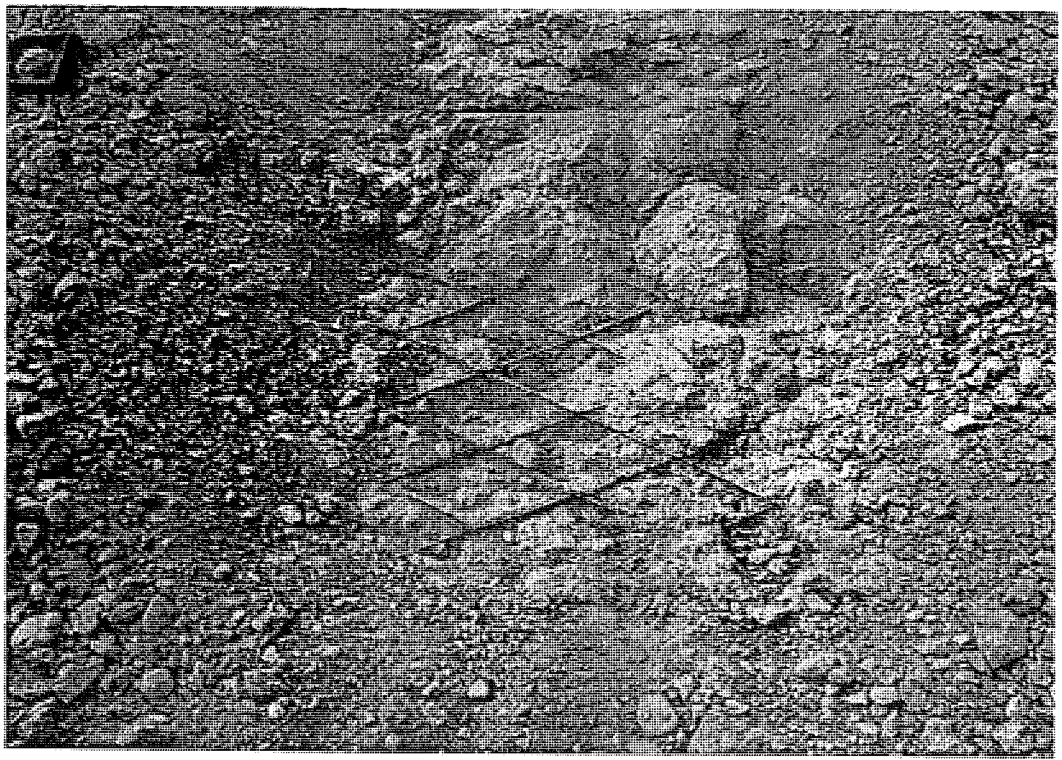


Figure 4.16 Partial debonding of the temperature steel (M-21)

Figure 4.17 Partial destruction of the joint integrity (US-131)

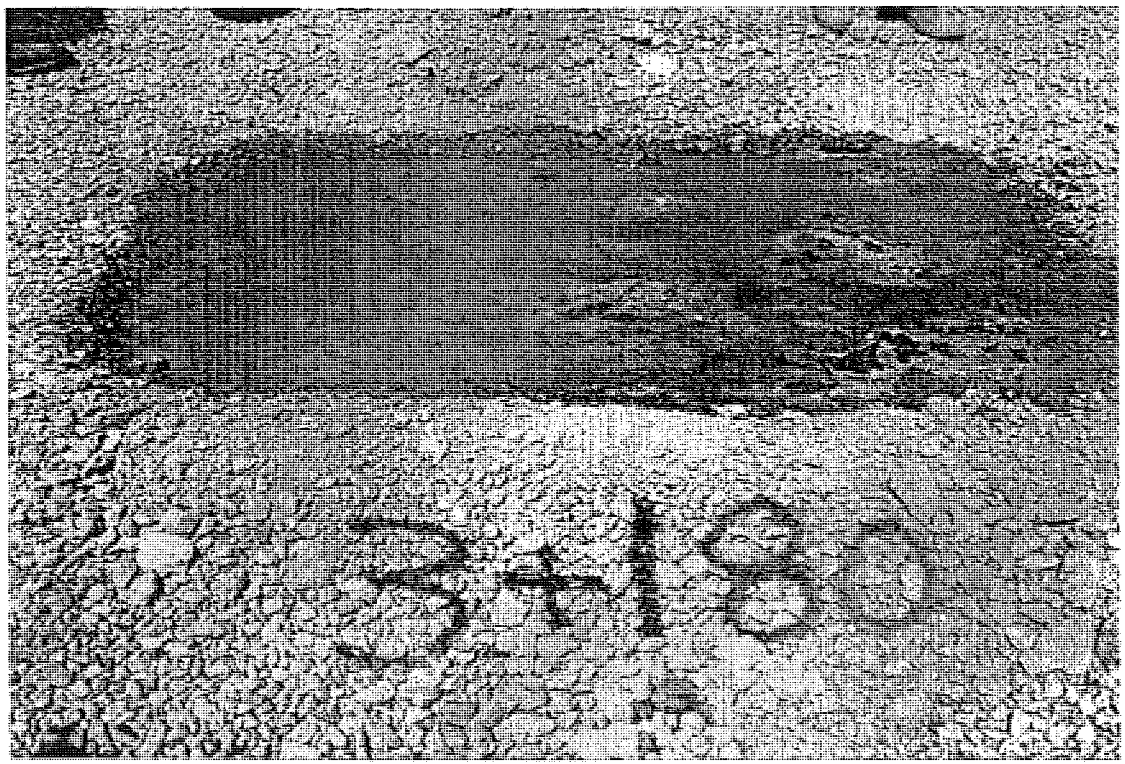


Figure 4.18 Trapped water above the fractured concrete in a trench along M-18

Figure 4.19 Shear failures in the rubblized pavement along NB I-196, August 2001

Figure 4.20 A shear failure along the rubblized pavement on NB I-196, May 2002

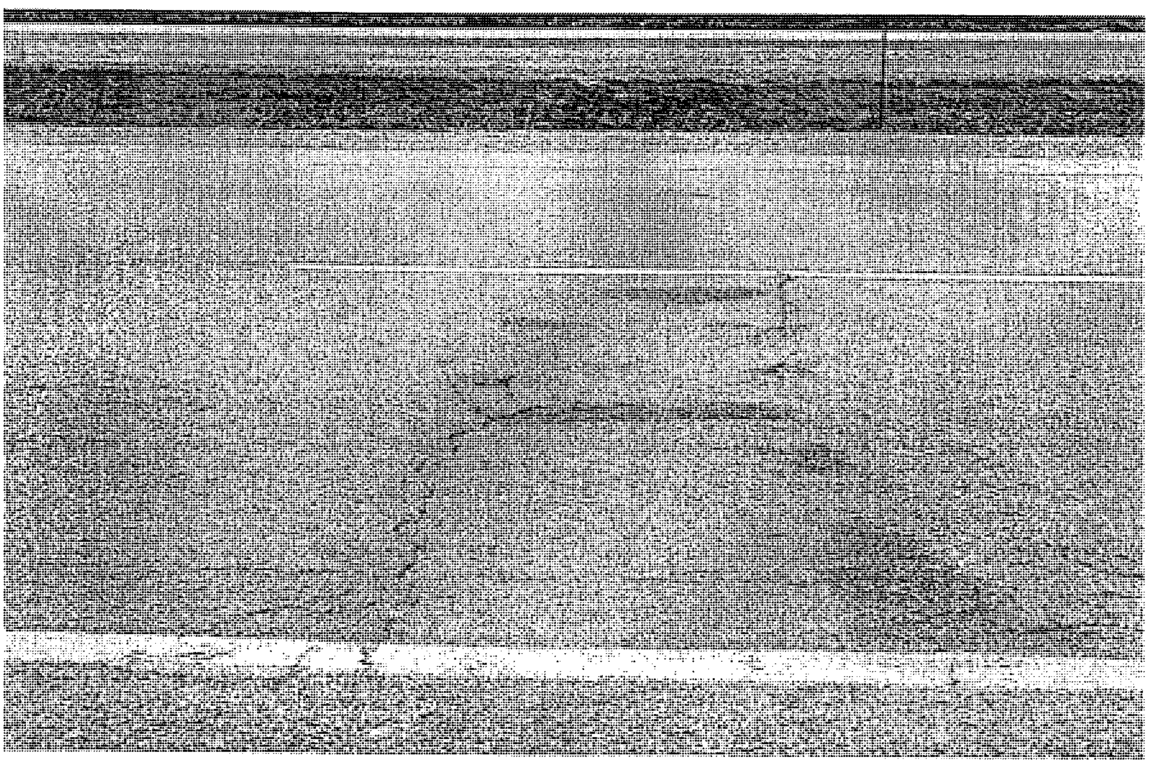


Figure 4.21 The initiation of a shear failure on rubblized project on NB I-196, May 2002

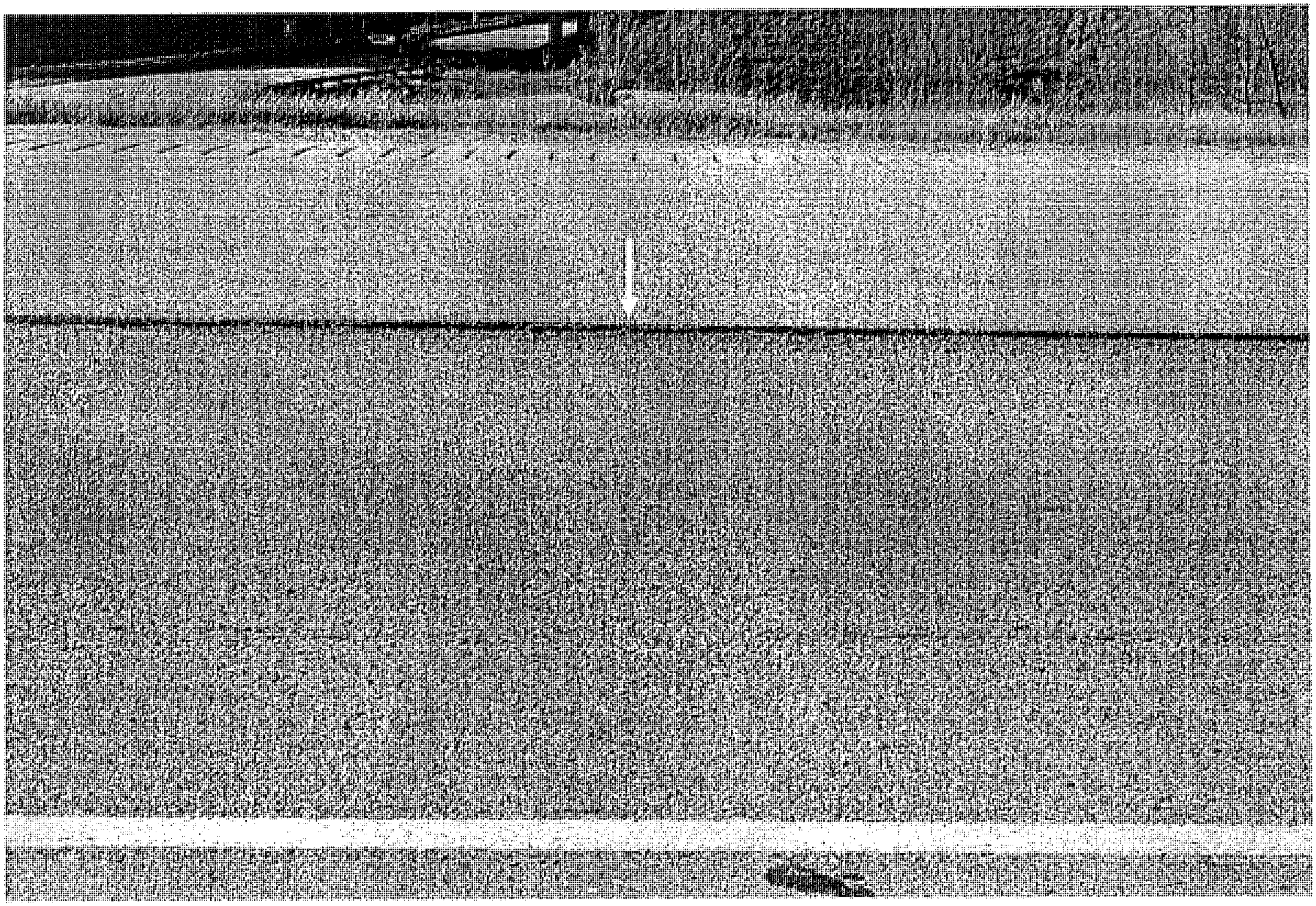


Figure 4.22 Differential settlements between the two lanes along NB I-196, May 2002

On some projects, the rubblization procedure produced rubblized material in one lane and mainly fractured concrete in the other lane along the longitudinal joint. This could mainly due to substantial difference in the concrete strength between the two lanes. The problem could be resolved by recalibration of the rubblizer parameters. If the situation is not corrected, it may cause differential settlement between the two lanes as shown in figure 4.22.

The significance of the above observations is that, in general, the objectives of rubblizing concrete pavements are not completely accomplished and that the rubblization procedure may adversely affect the pavement performance. Hence, the quality of rubblization could be defined in terms of the four objectives stated above and in terms of any variable that adversely affect the expected pavement service life of 20 years. Table 4.1 provides definition of the quality of rubblization along with a proposed method to assign a numerical value to the quality of rubblization:

The quality of the rubblization procedure could be substantially improved by implementing an equipment calibration procedure and by conducting adequate investigation during the project scoping process and prior to the selection of rubblization option. These issues are presented below.

6.1 Equipment Calibration

The quality of the rubblization procedure could be improved by calibrating the rubblizing equipment prior to the commencement of full-scale rubblization. Such calibration should be conducted at one end of the project using the following steps:

2. Divide the slab along one lane into twelve adjacent sections such that each section is 6-ft wide (across the slab) and 6-ft long (along the slab) as shown in figures 4.23 and 4.24 for the multi-hammer and the resonant frequency breakers, respectively.

3. Rubblize each section using different setting of the rubblizer parameters as follows:

Resonant Frequency Breaker		Multi-head breaker	
Frequency	43, and 45 Hz	Drop heights	48 and 60 in.
Velocity	2 and 3 mile per hour	Hammer weight	1200 and 1500 lb
Pressure	700, 800 and 1000 psi {pressure = force/(2*shoe width)}	Velocity	600, 700 and 800 ft/hr

4. Excavate two trenches along the slab as shown in figures 4.13 and 4.14 and examine the quality of rubblization as stated in the earlier section. That is,

Table 4.1 Definition, objectives and score of the quality of the rubblization operation

Definition, objectives and rating of rubblization

Rubblization Definition and Objectives

The quality of rubblization is a measure of the degree of success to which the rubblization procedure satisfies the following objectives.

1. Breaking the concrete slabs to pieces smaller than 6 in. (152 mm)
2. Completely debonding the temperature Steel
3. Destroying joint integrity
4. Producing full-depth rubblization

The rating of the quality of rubblization can be calculated using the following equation:

$$\mathbf{QR = Max\ (S_i)}$$

Where QR = quality of rubblization and S_i is a score relative to the i^{th} objective.

Lower QR values imply better rubblization quality. A QR value of 50 is the threshold value above which the quality of rubblization is not acceptable. The proposed values of S_i are listed below.

Score of each objective of the rubblization operation

Objective	Measurements within a 3-ft wide and 6-ft long trench	Best score	Maximum acceptable score
1	50*the number of loose pieces larger than 6 in.	0	50
2	100* the area of the trench where steel is not debonded/the total area of the trench (%)	0	50
3	25* the number of dowel bars that cannot be easily extracted from the trench.	0	50
4	100* the thickness of the fractured concrete in the trench/the total slab thickness (%)	0	50

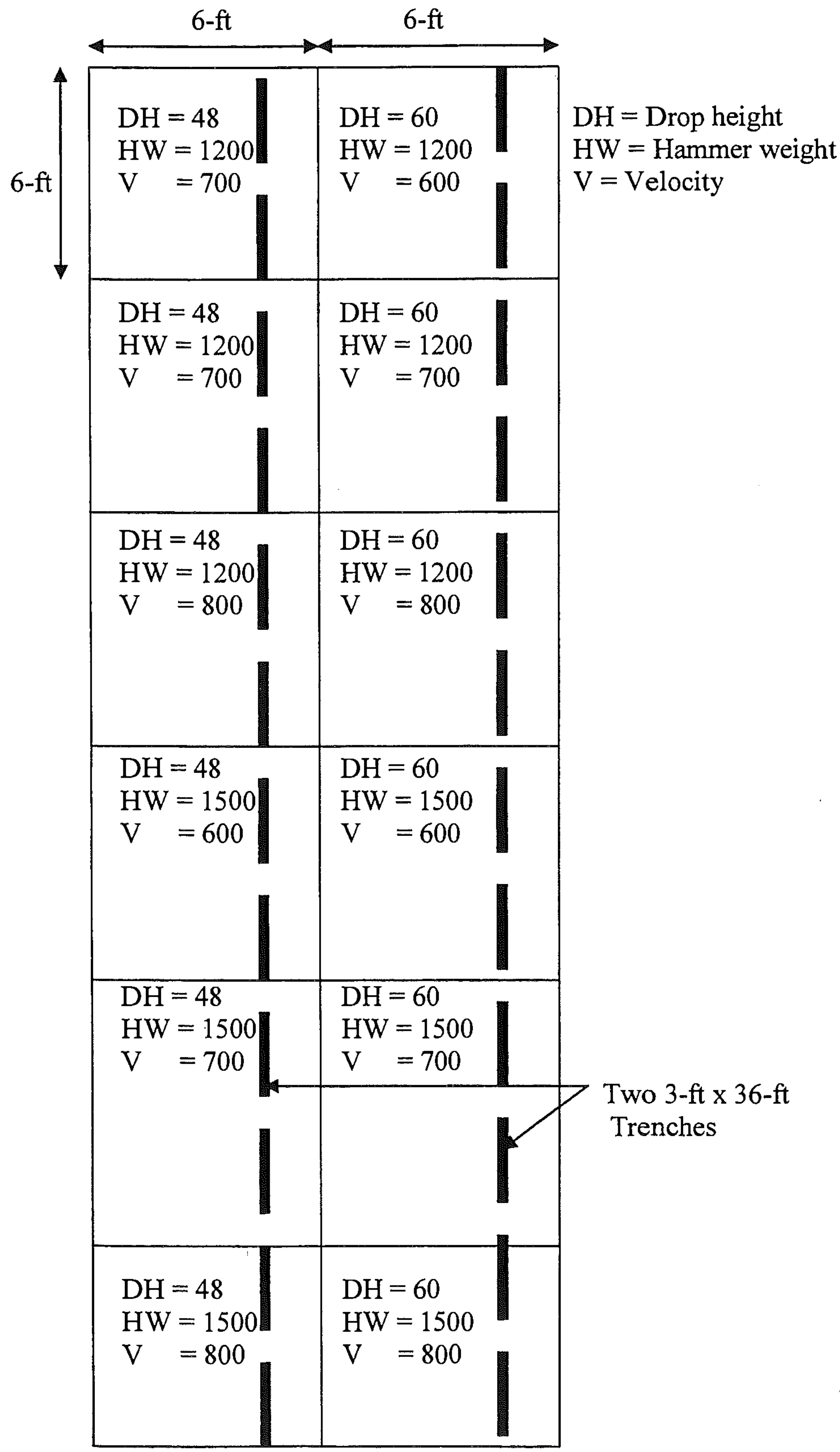


Figure 4.23 Calibration layouts for the multi hammer rubblizer

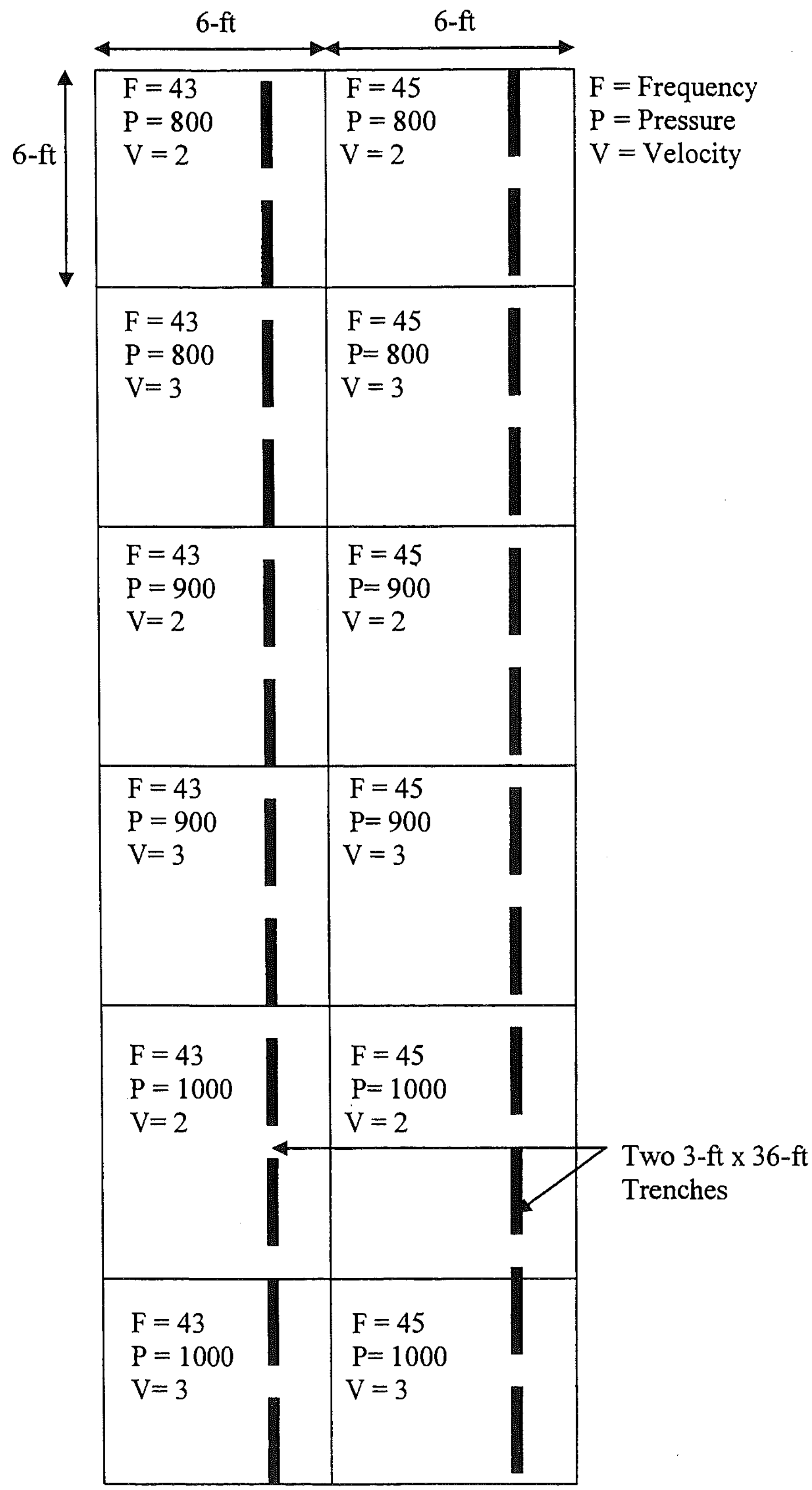


Figure 4.22 Calibration layouts for the resonant frequency breaker

investigate the degree of steel debonding, the depth of the rubblized material, and the thickness of the fractured concrete. The settings that yield the best results should be used to rubblize the rest of the concrete slabs.

4. Repeat the calibration when the unconfined compressive strength of the concrete along or across the pavement changes by more than 50 percent (the contractor can obtain the compressive strength data from MDOT, the data should be obtained by MDOT during the forensic investigation of the pavement). For example when a widening concrete strip exists, it is likely that the strength of the newer concrete is different than that of the original concrete. In such a scenario, the calibration should be conducted along the old concrete and the widening strip.

5. Excavate the rest of the rubblized material and fractured concrete and replace with approved filler aggregate. This section of the project will be later used by MDOT as a control section. Historical distress data collected along this section will be compared to those collected along the rubblized section, which would help MDOT to compare the performance of both sections.

6.2 Project scoping

Although the AASHTO 1993 Pavement Design Guide (1) states that rubblization can be used as a rehabilitation option for any distressed concrete pavement condition, field data do not support such statement. On the contrary, based on field observations that were conducted during the Phase I Study of this research project, rubblization is not an appropriate rehabilitation option for some distressed concrete pavements. Hence, prior to the selection of concrete pavement projects for rubblization, engineering forensic investigation should be conducted. The investigation should consist of the following items:

1. **History** – Obtain all available information regarding the original construction of the candidate pavement and its rehabilitation history. These include: temperature steel, dowel and tie bars, thickness, pavement type (JRCP, JPCP or CRCP), joint spacing, widening strip, full or partial depth patches, overlays and so forth.

2. **Distress** - Obtain the PMS distress data and conduct distress survey to determine the extent of longitudinal and transverse cracks and other discontinuities such as asphalt patches in the concrete pavement.

3. **Nondestructive Deflection Test (NDT)** – Conduct FWD test at 500-ft interval along the project. Use the deflection data to backcalculate the stiffness or modulus of subgrade reaction of the roadbed soil.

4. **Coring** – Obtain one concrete core for each 500-ft interval along the project. Examine the cores for delamination type cracks and record the width of the cracks. Determine the compressive strength of each core. If asphalt overlay is

present; determine the thickness of the overlay (for backcalculation and for milling purposes). If widening strips exist, obtain cores from the widening strip to determine the compressive strength of the concrete.

5. **Soil boring** - At two to three core locations, drill through the base, subbase and at least 2 ft through the roadbed soil. The objectives of the drilling are to document the type of base, subbase and roadbed materials and to determine whether or not the roadbed soil is saturated.

Based on the analysis of the above data, the following pavements should not be selected for rubblization:

1. Composite or concrete pavements that have extensive discontinuities. The rubblization energy will dissipate in the gaps at discontinuities instead of breaking the concrete slab. Such discontinuities include:

    a) Extensive longitudinal and transverse cracks as defined in MDOT distress manual.
    b) Concrete pavements that were previously rehabilitated using crack and seat method.
    c) Concrete pavements with frequent delamination type cracks.

2. Concrete pavements that are supported on soft or saturated subbase and/or roadbed soil. The term "soft subbase" refers to any subbase material having resilient modulus of less than 7000 psi. The term "soft roadbed soil" refers to any roadbed soil having a resilient modulus of less than 3000 psi.

3. Concrete pavements supported on a considerable soft subbase relative to the stiffness of the roadbed soil. The rubblization energy causes shear failure and lateral displacement of the subbase. For example, if a concrete pavement is supported on a base material with 10,000-psi modulus and a roadbed soil with 20,000-psi modulus, the rubblization energy may cause the softer subbase to fail in shear or be displaced laterally. This scenario is analogous to a sandwich model where a soft material is housed between two harder layers; the concrete and the roadbed soil.

In addition, the timing of the rubblization operation is very crucial to its success. For example, the operation should not commence immediately after a period of sustained rain (few days). The deteriorated and cracked concrete pavements would allow considerable water infiltration causing softening of the subbase material and roadbed soil. Likewise, commencing the rubblization operation shortly after the end of the thaw period is not desirable because of the high probability of roadbed saturation.

REFRENCES

1. The American Association of State Highway and Transportation Officials, "AASHTO Guide for Design of Pavement Structures", pp. 106-112, Washington D.C., 1993

2. Chang, Chieh-Min, Baladi, GY and Wolff, TF, "Using Pavement Distress Data to Assess the Impact of Construction on Pavement Performance", Journal of the Transportation Research Board no. 1761, 2001.

3. Chang, Chieh-Min, Baladi, GY and Wolff, TF, "Detecting Segregation in Bituminous Pavements", accepted for publication by the Transportation Research Board, paper no. 02-2634, January 2002.