In-Situ Recycling: Applications, Guidelines, and Case Study for Local Governments

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ABSTRACT

In-situ pavement recycling has become a viable solution for pavement preservation, rehabilitation, and reconstruction. However, transportation agencies infrequently look to recycling as an option for maintenance and rehabilitation of roadways because of lack of experience or knowledge about the various available treatments. This thesis investigates the application of In-Situ pavement recycling, provides guidelines for localities to aid in the selection of recycling methods, and documents a local agency's experience with Cold In-Place Recycling. The recycling methods discussed in this study include Cold In-Place Recycling (CIR), Hot In-Place Recycling (HIR), and Full Depth Reclamation (FDR).

The In-Situ Recycling guidelines synthesize available information on in-situ pavement recycling treatments and section practices. It provides suggestions on how to select treatment and on what pavement to apply them, based on: traffic characteristics, existing road condition, distress types and depths, road access, local climate, road geometry, and other road characteristics. The guidelines are based on information from sources including NCHRP Synthesis 421, American Recycling and Reclamation Association (ARRA), FHWA, and state agencies with recycling experience.

The case study documents a local agency's first experience with applying Cold In-place pavement recycling, the obstacles that the agency faced during the design and construction, and the benefits of using this technology. The study highlights the importance of conducting a detailed pavement and site investigation (preferably using non-destructive evaluation equipment, such as Ground Penetrating Radar). Additionally, it shows the potential advantages of having the guidelines, proposes alternate designs, and provides a cost comparison with a conventional design.

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CHAPTER 1. INTRODUCTION AND OBJECTIVE

INTRODUCTION

Road rehabilitation and replacement can be an expensive and time-consuming processes. Pavement recycling is an alternative process to conventional pavement rehabilitation methods. This technique re-uses existing road materials, often without removing from the construction site, thereby reducing project cost, time, and greenhouse gas (GHG) emissions.

The benefits of in-situ recycling (recycling materials on-site) include reductions in virgin materials, lane closure time, fuel consumption, and emissions. By reusing existing materials, recycling cuts landfill contributions. Although recycling methods perform best with a surface course (HMA overlay, microsurfacing, chip seal, etc.), the overall recycling cost is usually less than conventional alternatives. For example, cost savings for Hot In-Place Recycling (HIR) versus conventional construction methods (i.e. HMA overlay or reconstruction) amount anywhere between 17 and 50%. Cold In-Place Recycling (CIR) cost savings can amount to as much as 87%. This technique has the highest GHG potential reduction of 80%, followed by almost 50% for Cold Central Plant Recycling (CCPR) and 45% for Hot In-Place Recycling (Schvallinger, 2011). Although there are many benefits to recycling, as mentioned above, this method of pavement maintenance and rehabilitation is not common practice. Barriers to a wider spread of in-situ pavement recycling for an area may include a lack of contractor experience, agency experience, engineering design, specifications, mix design, and project selection criteria (Stroup-Gardiner, 2011). These barriers are especially prevalent for local governments trying to maintain their pavement condition. Local agencies may not have the resources necessary for properly selecting and designing pavement recycling projects.

The selection guidelines developed as part of this thesis attempt to promote local agency knowledge of recycling and confidence in recycling as a maintenance and rehabilitation alternative. These guidelines include three in-situ recycling methods: Hot In-Place Recycling, Cold In-Place Recycling and Cold Central Plan Recycling, and Full Depth Reclamation. These guideless are complemented by an in-situ recycling case study.

PROBLEM STATEMENT

In-situ pavement recycling has become a viable solution for pavement preservation, rehabilitation, and reconstruction. However, transportation agencies infrequently look to recycling as an option for maintenance and rehabilitation of roadways. This is particularly true for local agencies, where recycling implementation is limited in local government agencies due to lack of information and experience with the methods. The hypothesis behind this thesis is that more awareness of the advantages of the techniques, coupled with selection guidelines, a synthesis of practice and case studies could facilitate the adoption of in-situ pavement recycling methods among local agencies.

OBJECTIVES

The main objective of this thesis was to develop selection guidelines, to be used by local governments, for in-situ pavement recycling methods. In-situ pavement recycling is a potentially more sustainable alternative to traditional pavement rehabilitation and reconstruction techniques, which can help reduce material waste and environmental pollution, cut costs and non-renewable resource utilization, and encourage sustainability. A secondary objective of this study was to understand a local agency's experience and challenges with in-situ pavement recycling by documenting a case study on road sections recycled in Christiansburg, VA in June 2013.

The main purpose of the effort is to facilitate the adoption and utilization of in-situ recycling practices by developing guidelines for in-situ pavement recycling treatment selection and a case study on in-situ pavement recycling. The guidelines cover Full-Depth Reclamation (FDR), Hot In-Place Recycling (HIR), and Cold Recycling (CR). Cold recycling includes the cold in-place recycling (CIR) and cold central-plant recycling (CCPR) technologies.

SCOPE

After conducting an extensive literature review for in-situ recycling methods (Appendix A and Chapter 2), guidelines for recycling were created (Chapter 2). The in-situ pavement recycling methods considered in this report were: FDR, HIR, and CR. The guidelines provide a background to each recycling method and then provide parameters to help local agencies choose the appropriate method for their road. Agencies will thus be able to make better-informed decisions in their pavement management and maintenance activities regarding in-situ recycling.

A case study (Chapter 3) of recycling for a locality (Christiansburg, VA) was conducted. The case study focused on CIR, as it was the first recycling method used by the Town of Christiansburg. Their experience was recorded and investigated. The initial plan was to apply the guidelines developed and determine if they may have changed the decision. As these guidelines were not available at the time of recycling, the investigations Christiansburg performed on the sections did not provide all of the information, such as distress depth, preferred for application of the guidelines. Although there was not enough information on the prior condition of the recycled sections, the guidelines were applied to one of the sections to the best ability. Additionally, the case study documents the experience, illustrates additional tests that could have been conducted, and provides designs that could be more effective.

THESIS OVERVIEW

This thesis is organized following a manuscript format and contains two papers, which can be found in chapters 2 and 3. Chapters 1 and 4 tie the papers together and provide a detailed introduction and conclusion summarizing the two papers.

Chapter 1 – Introduction: This chapter introduces the intent of the thesis and the two papers contained within the document.

Chapter 2 –Guidelines for the Selection of In-Situ Recycling Methods for Local Governments: This first paper presents a set of selection guidelines developed based on a synthesis of available literature. The guidelines introduce the main types of in-situ pavement recycling and how to select the most promising one based on: pavement condition, type of distresses present, depth of distresses, traffic on the roadway, road geometry, and climate/weather.

Chapter 3 – Lessons Learned from a Locality In-Situ Recycling Case Study: The second paper documents the in-situ recycling experiences of a local agency were documented as well as analyzed. The Town of Christiansburg, VA had CIR performed on 4 different streets in June

2013. The “lessons learned” from the agency were documented to help other local agencies manage or avoid those barriers. Additional post-construction tests were conducted to analyze the construction of the CIR sections versus the pavement design, as well as analyze how appropriate the pavement designs were for each section. Alternate CIR designs were determined based on available boring logs, samples taken from the sections, and the additional tests conducted. For some of the sections, the analysis suggested that FDR could have a better fit. Finally, cost compared conventional design for one of the sections.

Chapter 4 – Summary, Conclusions, and Recommendations: This chapter summarizes the main finding and presents conclusions of the thesis and recommendations for future research.

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CHAPTER 2. GUIDELINES FOR THE SELECTION OF IN-SITU RECYCLING METHODS FOR LOCAL GOVERNMENTS

ABSTRACT

The objective of this study was to develop selection guidelines, to be used by local governments, for in-situ recycling methods. In-situ recycling, also referred to as in-place recycling by the ARRA (2001), is an alternative to pavement rehabilitation and reconstruction for reducing virgin material waste, cutting cost, and encouraging sustainability.

Recycling implementation is limited for local government agencies due to limited information and experience with the methods. This thesis describes the in-situ recycling options of Full-Depth Reclamation (FDR), Hot In-Place Recycling (HIR), and Cold Recycling and aims to provide selection guidelines for these methods. These guidelines are aimed at increasing locality awareness of recycling as well as confidence in the in-situ recycling methods selected by a contractor.

The study resulted in selection suggestions based on traffic characteristics, existing road condition, distress types, road access, local climate, road geometry, and other project characteristics. The study also resulted in more clearly understanding the obstacles localities face for in-situ recycling projects as well as the impact of limited experience with recycling, for both agencies and contractors.

INTRODUCTION

Road rehabilitation and replacement can be expensive and processes that requires virgin materials, such as aggregate an asphalt. An alternative process to conventional methods is in-situ pavement recycling, which re-uses existing road materials, thereby reducing project cost and process emissions. Schvallinger (2011) found that Cold In-Place Recycling (CIR) has the highest Greenhouse Gas (GHG) reduction potential of 80%, followed by almost 50% for Cold Central Plant Recycling (CCPR) and 45% for Hot In-Place Recycling (HIR). In addition, CIR with a double chip seal can replace a conventional mill and overlay and reduce the cost/mile by up to 56% (Bemanian, 2009).

As estimated by the FHWA, about 100 million tons of reclaimed asphalt pavement (RAP) are produced each year (Venner, 2008). By recycling as little as 30 million tons of RAP with hot mix asphalt (HMA), up to $300 million per year can be saved (Venner, 2008). Furthermore, instead of placing the milled material into stockpiles for later use, one can recycle in-situ and reduce energy consumption, transportation, raw materials, and cost. For example, AASHTO mentions that one recycling process, CIR, can be as little as “...one-third to one-half of the total cost incurred for conventional reconstruction” (Venner, 2008)

Local governments may lack the funds and resources to plan for pavement recycling in their locality. Christiansburg, VA followed the state’s pavement design criteria regarding material choice but did no further investigation to the extent of traffic growth factors, structural indices, soil testing and classification, material testing, and so on. This may also be the case for other agencies at the local level. Additionally, localities may be forced to rely on local contractor experience with recycling or have to reach out to recycling contractors out-of-state. By having the selection guidelines, agencies can understand in-situ recycling methods and understand method(s) is (are) appropriate for a project and make informed pavement management and maintenance decisions.

There are existing local government guidelines for recycling, such as the Federal Highway Administration's (FHWA) "Pavement Recycling Guidelines for State and Local Governments," but this document does not reflect the most current recycling practices, as the document is from 1997 (FHWA, 1997). To create these guidelines, more recent sources, such as the American Recycling and Reclaiming Association (ARRA) Basic Asphalt Recycling Manual (BARM) and the National Cooperative Highway Research Program (NCHRP) Synthesis 421, were investigated.

PURPOSE AND SCOPE

The purpose of this study is to support the practice of in-situ recycling for local governments by providing a selection tool for the available processes using the following methods:

- Collecting central concepts from various literature and projects
- Evaluating methods of recycling proposed in the literature
- Developing a recycling selection process that best suits road condition and characteristics

This document aims to identify the properties of in-situ recycling processes nationwide by first outlining in-situ recycling methods, including: Full Depth Reclamation (FDR), Hot-In-Place Recycling (HIR), Cold-In-Place Recycling (CIR), and Cold Central Plant Recycling (CCPR). Method requirements, characteristics, and limitations are considered to suggest the best solution to address pavement distress. The selection guidelines created from this study will provide suggestions for localities trying to select the most appropriate recycling method for a project. The focus of this report is on in-situ recycling, in which a road will be preserved, rehabilitated, or reconstructed using its own recycled layers, including Cold Central Plant Recycling (CCPR). This report does not focus on RAP stockpiles, in which the milled material, which may be collected from a combination of milled pavements, is heated in addition to the asphalt binder.

BACKGROUND

A literature review was performed to gain knowledge pertaining to recycling methods and characteristics. Sources investigated include the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), Asphalt Reclaiming and Recycling Association (ARRA), National Cooperative Highway Program (NCHRP), various Department of Transportation agencies, and presenters from recycling conferences.

Reclaimed Asphalt Pavement (RAP) versus In-Situ Recycling

Reclaimed asphalt pavement (RAP) is defined as "…salvaged, milled, pulverized, broken, or crushed asphalt pavement" that is created during the resurfacing or reconstruction of a road (Venner, 2008). The scope of this thesis is solely in-situ recycling, also referred to as in-place recycling by the ARRA (2001), which occurs on-site and does not require transport to an asphalt plant. RAP stockpiles are not included in the scope (milling, removal, transportation to asphalt plant, and placed in stockpiles); all recycled material will come from the existing layers of the pavement being recycled.

According to the National Asphalt Pavement Association (NAPA), in 2012 alone, over 68.3 million tons of RAP was used in new pavements, saving more than $2.2 billion dollars (Kent, 2013). Instead of removing the milled material and placing it in stockpiles, road materials can be recycled in-situ reducing energy consumption, transportation, and material use and cost. The recycling methods reviewed include: Hot-In-Place Recycling (HIR), Cold Recycling (CR), and Full Depth Reclamation (FDR).

In-Situ Recycling Agents

Different recycling agents can be used in recycling to improve the recycled mix's characteristics, including foamed asphalt, emulsified asphal, and cement stabilizers.

Asphalt emulsions are a combination of asphalt, water, and an emulsifying agent. The emulsion could also contain stabilizing agents. The emulsions allow for stability when pumping, storing, or mixing (ARRA, 2001). Foamed asphalt is created by adding cold water into hot asphalt binder, which causes an expansion of the asphalt into bubbles. Foamed asphalt works well for cold, moist materials as the foaming allows it to coat the materials (ARRA, 2001).

The right recycling agent or additive for a recycling project will depend on the materials used in recycling and the climatic conditions (cold/wet, hot/wet, cold/dry, hot/dry) (ARRA, 2005a). Depending on conditions present during construction, it may be best to wait for better weather to recycle. For example, because most agents' performance is temperature dependent, it should not be cold enough to freeze the recycled mix. Most stabilizer manufacturers recommend placing at least a month before the first predicted "hard freeze" (ARRA, 2005b). In addition to considering the time of year, one should also consider the moisture conditions. Cure time may increase based on the moisture present when paving. The recycling agent weather restrictions can be found in Table 8 on page 20.

Hot In-Place Recycling (HIR)

HIR is used for shallow distresses (no deeper than 1-2 inches from the surface) and is an alternative to mill and overlay (e.g., where 2 inches are milled and a new 2-inch HMA overlay is added). Figure 2 provides a visual of the HIR process. HIR should only be used if the underlying layers are structurally sound (Caltrans, 2008).

Most guidelines agree that HIR is not suitable for pavements with rubberized hot mix asphalt (RHMA), geosynthetic pavement interlayer (GPI), or multiple chip seals. If a road has greater than 5% alligator cracking, base or subgrade failure, or moisture related problems (poor drainage, pumping, saturated subgrade material), HIR is not a suitable solution (Maroof, 2011). There are 3 different HIR processes: surface recycling, remixing, and repaving.

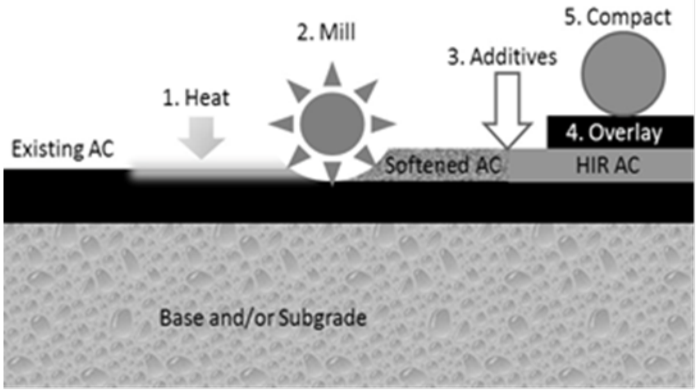

Figure 1. Hot In-Place Recycling Process (after Andrei, 2012)

Surface Recycling

Surface recycling uses a heat scarifier to remove the asphalt from 0.75 to 1.5 inches and is followed by a surface treatment or HMA layer for life extension. Untreated, the pavement will last between 2 and 4 years; treated, between 5 and 6 years (chip seal) and up to 10 years (2-inch asphalt overlay). Surface recycling is appropriate for repairing roads with potholes, raveling, rutting, corrugations, shoving, and cracking. Surface recycling also improves ride quality and corrects asphalt binder issues. Surface recycling does not resolve shoulder drop off, fatigue/alligator cracking, discontinuity cracking, inadequate pavement strength, or poor skid resistance (Venner, 2008).

Remixing

AASHTO's Center for Environmental Excellence claims remixing to be the "…hot-in-place recycling technique that provides the most options for pavement remediation" (Venner, 2008). The remixing process ranges from 1.5 to 2 inches and can be performed in single-stage (1-2 inches) or multiple-stage (1.5-3 inches) passes. A remixed pavement used as a wearing or leveling course will last 7 to 14 years (Venner, 2008). Remixing can correct rutting, raveling, potholes, bleeding, corrugations, shoving, poor ride quality, and oxidation. Remixing is not suitable for roads with shoulder drop off, discontinuity cracking, or inadequate pavement strength. Because the maximum depth of remixing is 2 inches, any distresses reaching farther than 2 inches from the surface will not be corrected, unless performed in multiple stages (Venner, 2008).

Repaving

Repaving recycles 1-2 inches of asphalt and overlays 1-2 inches, with a combined thickness of 3 inches or less. Placement, compaction, and smoothness would be difficult for any repaving mixture greater than 3 inches. When 1 inch of the existing pavement is removed and a 1-inch overlay is added, repaving is a suitable replacement for mill and overlay.

When pavement strengthening is desired, repaving is preferred over remixing, as it adds 2 inches compared to remixing's 0.75 inches. Repaving is used to treat raveling, potholes, cracking, poor skid resistance, ride quality, bleeding, rutting, corrugations, and shoving (Venner, 2008).

Cold Recycling (CR)

Cold Recycling (CR) may be performed in-place (CIR) or in an asphalt plant (CCPR). Cold Central Plant Recycling (CCPR) involves mixing the recycled material in a central or mobile (on-site) plant and is used for projects where mix design monitoring and high production rates are required. The recycled material for CCPR must be moved from the central plant to the paving location, whereas CIR recycles and mixes material in-place, reducing or eliminating the need for transportation. CR ranges from 2-5 inches in depth (although multiple layers from the CCPR process can be used) and may be opened to traffic at the end of the work day depending on the stabilizing agent and environmental conditions (ARRA, 2005a).

The Cold Recycling process does not use heat; the existing road is cold planed, possibly crushed, and additives are combined to improve the recycled mix. Although the CCPR method of CR involves transport to an asphalt plant, the recycled material is not heated; only the asphalt binder is heated. When using RAP stockpiles (as opposed to in-situ), the aggregate and RAP are heated as well as the asphalt.

CR differs from conventional mill and overlay in that conventional processes use virgin materials and heat the aggregate. Additionally, CR uses recycled materials in the construction. CIR is not suitable for deeper cracking and distresses, as the maximum milling depth of CIR is 6 inches. CR is usually followed by an overlay or surface treatment (ARRA, 2005a). Figure 3 depicts the CR process.

CR addresses: raveling, potholes, bleeding, low skid resistance, rutting, corrugation, shoving, cracking (fatigue, edge, block), slippage (longitudinal and transverse thermal cracking), reflective cracking, and poor ride quality caused by swells, bumps, sags and depressions (ARRA, 2005a).

CR is not recommended for locations where asphalt is stripped from the aggregate, high asphalt contents or fine graded aggregates have resulted in deformation, heaving or swelling in underlying soils, or wet or unstable base, subbase, and subgrade materials. ARRA suggests that if the areas unsuitable for CR rehabilitation are less than or equal to 10% of the project, localized repairs can be made before CR to address the issues (ARRA, 2005a).

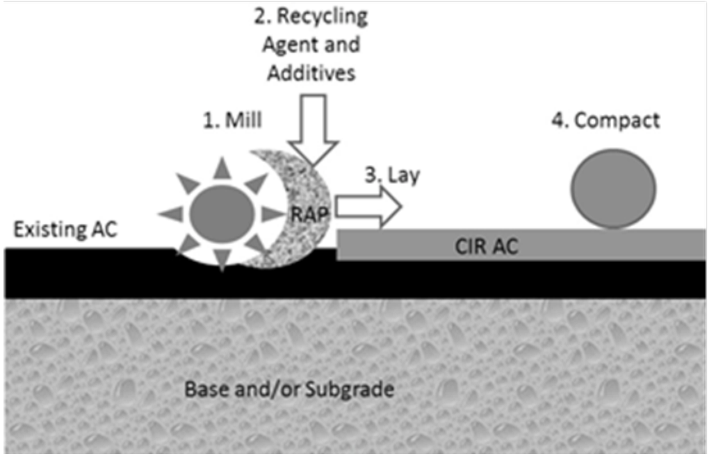

Figure 2. Cold In-Place Recycling Process (after Andrei, 2012)

Full Depth Reclamation (FDR)

FDR is typically performed as a single layer 6-9 inches deep but can extend into the underlying layers, as deep as 12 inches (ARRA, 2005b). The FDR process can include the unbound layers (such as subgrade), unlike HIR and CIR, which are restricted to asphalt layers. FDR may be considered as an alternative to roadway reconstruction.

FDR is an adequate solution for widening roads as well as strengthening bases, even those with base and subgrade issues. FDR can eliminate transverse and lateral cracking, reflective cracking, severe rutting and shoving, frost heave, and heavy pothole patching (ARRA, 2005b).

FDR is an appropriate and longer-lasting alternative to mill and overlay when many patches, potholes, and cracks exist and the extent of the deterioration includes the full depth of the pavement cross section (ARRA, 2005b). Figure 3 provides a visual description of the FDR process (Andrei, 2012).

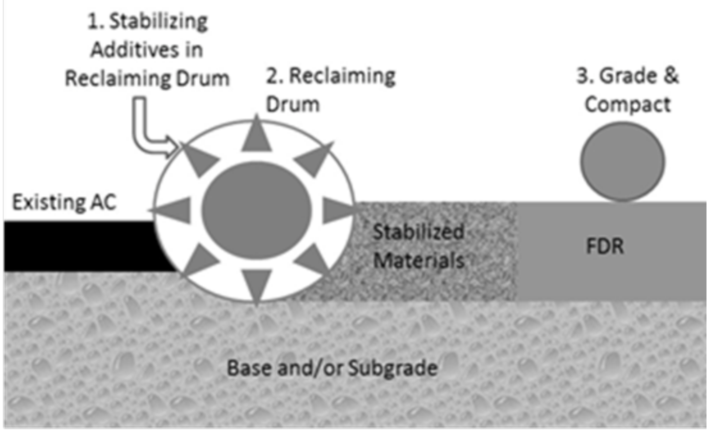

Figure 3. Full-Depth Reclamation Process (after Andrei, 2012)

Economics

Project cost and construction time may be used in the project selection process. In-Place Recycling is a quicker and less expensive alternative to conventional methods. The Florida Department of Transportation (FDOT) estimates that it has saved up to $224 million since it started recycling in 1979 (Schvallinger, 2011).

Dai et al. (2008) conducted a life cycle cost analysis (LCCA) to compare CIR and FDR with conventional alternatives (Dai e al., 2008). The functional unit was 1 centerline mile (1.61 km) on a road with 2,000,000 ESALs. The present worth method considered a 20-year period at a discount rate of 4%, while assuming that future maintenance and rehabilitation maintained the pavement's serviceability during the design period. Costs included construction, maintenance, salvage value, and user costs (Dai et al., 2008). Table 1, summarizes the compared options.

Table 1. Life Cycle Cost Analysis Comparison: Traditional Methods, FDR, and CIR

Method	Method Depth (in)	Overlay	Overlay Depth (in)	Rehabilitation year(s)	Cost/mile ($)
CIR	3	HMA and OG	2.5	12	306,000
HMA and OG	2	---	---	9 and 16	418,000
Mill	3	HMA	3	12	415,000
FDR	---	HMA and OG	4	15	382,000
Reconstruction	12 base	HMA and OG	5	12	715,000

Note: "---" denotes a non-applicable field for the situation
* Table 1 summarizes the information found in Dai et al. (2008).

As Table 1 shows, CIR was found to be the most cost-effective option ($306,000), closely followed by FDR ($382,000). The costs enumerated in the table include construction, maintenance, salvage value, and user costs. Additionally, the costs are per one centerline mile of roadway (Dai et al., 2008).

In addition to this LCCA performed, others have deemed recycling to be the cost-effective alternative:

- Pappas (2012) of Delaware DOT, presenting at the 2012 Virginia Pavement Recycling conference, enumerated pavement preservation costs. FDR with an asphaltic overlay costs approximately $370,000 per centerline mile, whereas a conventional mill and asphaltic overlay costs approximately $500,000 per centerline mile.
- According to Diefenderfer and Apagyei (2011) who analyzed FDR trial sections in Virginia: VDOT, over a 50-year life cycle of using FDR, could save $10 million on primary networks and $30.5 million on secondary networks. Annually, this works out to approximately $463,000 for primary networks and $1.42 million for secondary networks.
- Slagle (2011), an Engineering and Construction Manager from Washington County, MN, listed project costs (per mile) for recycling followed by a bituminous overlay: $280,000, $270,000, and $280,000 for FDR, HIR, and CIR, respectively.

Although in-situ recycling may provide pavement preservation, rehabilitation, or reconstruction at a lower cost, engineering judgment must be used to determine the feasibility and cost-effectiveness of a specific project. For example, remote projects may not find recycling to be economical due to the costs of contractor equipment rental and transportation. Although some experts have recommended that the project length be at least 4 miles to "optimize cost savings" (Bemanian, 2012), this may not be feasible for localities, who may wish to recycle a residential/subdivision road or only part of a secondary road. This concern could be eliminated in the future with a nationwide in-situ recycling industry or with an increase in recycling practices (thus resulting in widely available and nearby recycling equipment and contractors).

Production Rate and Construction Time

HIR Production Rate and Construction Time

On average, HIR can achieve 1-2 lane miles in an 8-hour day and support user traffic one hour after paving (similar to overlay time). HIR may be performed at night, allowing for lower operational costs, although production rates may decrease (Metcalf, 2006).

CR Production Rate and Construction Time

CIR construction time depends greatly on the weather, type of recycling agent used, and depth; the time until compaction could take from 10 minutes to 2 hours. For example, rolling may be performed directly after the mix is placed if the CIR mix includes the following additives: foamed asphalt, Portland cement, or self-cementing fly ash (Type C) (ARRA, 2005a).

FDR Production Rate and Construction Time

Most contractors can cover 1 lane mile per day using FDR (Taylor, 2009). FDR may use as little as one-quarter of the construction time required by an equivalent conventional full reconstruction design (Fox, 2013).

Service Life

ARRA (2001) lists the service life of each recycling method, stressing that service life and performance depend on a variety of factors, including: local conditions, climate, traffic, technique, material quality, and workmanship quality. HIR can last 2-15 years; CR 15 years, and FDR 7-20 years, depending on the surface treatment. Scenarios of the service lives are enumerated in Table 2.

Table 2. Recycling Service Lives (ARRA, 2001; Peshkin, 2011)

Method	Service Life (years)
HIR	
Surface Recycling without surface treatment	2-4
Surface Recycling with surface treatment [a]	6-10
Remixing	7-14
Remixing with HMA overlay	7-15
Repaving	6-15
CIR	
CIR with surface treatment	6-8
CIR with HMA overlay	7-15
CCPR with surface treatment	6-8
CCPR with HMA overlay	12-15
FDR	
FDR with surface treatment	7-10
FDR with HMA overlay	up to 20 years

[a] Lifetime between 5 and 6 years with chip seal, up to 10 years with 2 in asphalt overlay

Additional examples of CR lifetime compared to alternatives include:

- NDOT concluded that the average service life for CIR projects performed between 1985 and 1992 (without the use of lime slurry) of about 10-12 years was longer than the service life of projects with an equivalent HMA overlay thickness (Dai et al., 2008). This conclusion was made after coring and surveying in 2001.
- The FHWA notes that the service life of 4in of CIR with a 1.5 in overlay is 10-15 years with little maintenance, as compared to 5-8 years for a traditional asphalt overlay thickness of 1.5 in (Gallivan, 2011).

DEVELOPMENT OF SELECTION PROCESS

Table 3 summarizes the in-situ recycling methods that will be considered in the selection process.

Table 3. Summary of In-Situ Recycling Options

Recycling Method	Process	Uses
Hot In-Place Recycling (HIR)	• Heat and soften pavement [a] • Mix, place, and compact pavement [a] • For shallow distresses (no more than 1-2 in below pavement surface) [a] • Surface Recycling: 0.75-1.5 in, Remixing: 1.5-2 in, and Repaving: 1-2 in [a]	• Correct oxidation and minor cracking[a] • Not suitable for pavements with multiple chip seals, rubberized hot mix asphalt (RHMA), Geosynthetic Pavement Interlayer (GPI), greater than 5% alligator cracking, base or subgrade failure, moisture related problems (poor drainage, pumping, saturated subgrade material) [c,d]
Cold Recycling (CR)	• Reclaims 2-5 in of the existing HMA pavement [e] • Leaves 1 in of existing reused HMA in place [a] • Does not use heat [a]	• Provides a uniform base that can be overlaid with HMA [a] • Mitigate reflective cracking problems associated with straight overlay [a] • Good for low-volume roads [a] • Addresses raveling, potholes, bleeding, low skid resistance, rutting, corrugation, shoving, cracking (fatigue, edge, block), slippage, reflective cracking, and poor ride quality [e]
Full-Depth Reclamation (FDR)	• Pulverize entire pavement structure and blend with portion of base/subbase material (HMA *and* base layers can be milled processes)[a] • Usually 6-9 in (152.4-228.6 mm), as deep as 12in[b]	• Eliminate all distress areas [a] • Eliminate potential reflective cracking[a] • Stabilize new base with emulsion, fly ash, or portland cement [a] • Base strengthening and widening [b] • Heavy pothole patching, severe rutting/shoving, frost heave, parabolic shape, and deep cracking (transverse or lateral) [b]

Table Sources: [a] (Dai et.al., 2008), [b] (ARRA, 2005b), [c] (Caltrans, 2008), [d] (Maroof, 2011), [e] (ARRA, 2005a)

Selection Criteria for In-Situ Recycling Methods

The appropriate recycling method for a project can be distinguished based on the following criteria:

- Pavement Condition
- Distress Type
- HMA Thickness
- AADT and Traffic
- Road Geometry
- Climate and Weather

Agencies should perform preconstruction investigation before using the guidelines presented in this document. This investigation can include activities such as visual inspection (pavement condition, distress type) and more in-depth techniques, such as coring or Ground Penetrating Radar (GPR). Coring or GPR would be used to analyze the layer-thickness consistency of the candidate recycling project (e.g., the depth of HMA along project may be 1” in one area and 3” in another). The thickness of existing asphalt is important for in-situ recycling, as HIR and CIR are only performed within the asphalt layers. FDR is the only recycling method of the three that extends beyond the existing asphalt into the base/subgrade materials. The preconstruction investigation will also be useful for identifying the cause for distress/deterioration in the pavement and the depth of those distresses.

Pavement Condition

The existing pavement condition is an important decision factor. The variable used to represent pavement condition in this example is Pavement Condition Index (PCI), a visual inspection rating that ranges from 0-100, 100 being excellent condition. The visual inspection is related to distresses type, extent, and severity. Other pavement condition ratings, such as IRI, PSI, and PSR can also be considered (Halsted, 2008). Figure 4 shows a graphical representation of the appropriate recycling method given a pavement condition rating.

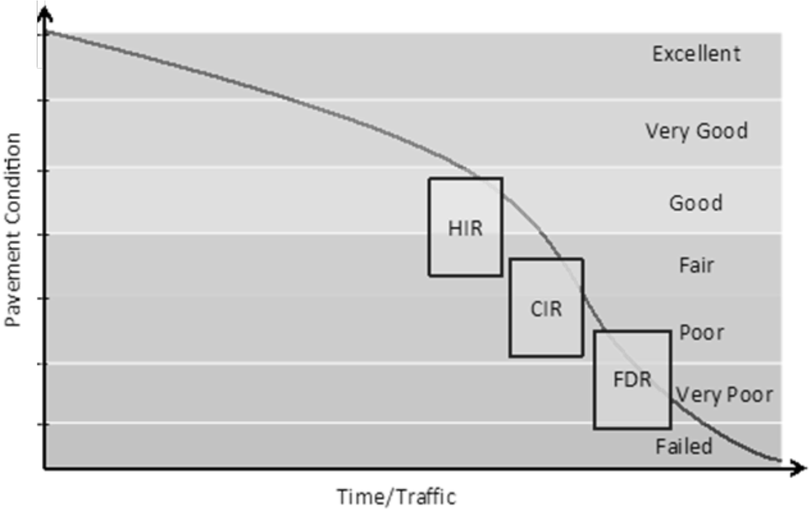

Figure 4. PCI and Recycling (after Andrei 2012; Halsted, 2008)

Figure 4 shows the condition rating of the pavement and the corresponding recycling method appropriate for a given condition. Table 4 provides the numerical PCI values for the “window of opportunity,” for a given recycling option. The values in Table 4 are provided by Peshkin (2011).

Table 4. PCI Range for In-Situ Recycling

Method Selected		**PCI Range**
HIR	**Surface Recycling**	70-85
	Remixing	60-75
	Repaving	60-75
CIR		60-75
FDR		10-30

Selecting a recycling option based on PCI or similar ratings (CCI, PSR, IRI) is acceptable for a network-level analysis, but PCI does not define the entire pavement condition, as it considers only the uppermost layer (meaning that an overlay could result in a temporarily higher PCI, while the pavement is suffering from severe fatigue cracking underneath); thus distress type and depth should be considered in the treatment selection process. For project-level analysis, more actions should be taken to discover the nature of the road’s deterioration, such as taking cores and monitoring traffic (ARRA, 2005b).

Distress Type

According to ARRA (2001), the typical “triggering factor” for roadway rehabilitation or reconstruction is roughness (smoothness). Rutting is the second-most frequent “triggering factor.” These distresses are only two of many distresses that are possible for a pavement. Other distresses and their resolving recycling methods are outlined in Table 5. Table 5 is a summary of the comprehensive literature review findings. Each method appropriate for a distress was verified with multiple sources. This crosscheck of sources can be found in Appendix A. Note that in the table, SR, REM, and REP are Surface Recycling, Remixing, and Repaving, respectively. Also note that “x” denotes that the recycling method is appropriate for the listed distress. The multiple sources of repeated information compiled in Table 5 can be found in the Appendix A.

HMA Thickness/Distress Depth

After determining what distresses are present in a pavement through inspection, such as visual inspection, automated distress evaluation, or other nondestructive techniques, an agency can coring, GPR, or other investigative techniques to determine how deep the distress extends beneath the pavement surface (or the extent of the distress) and how thick the asphalt layers are.

The depth of distress may govern what in-situ recycling method is appropriate. For example, if the distress is fatigue cracking and extends well beyond 3 inches into the pavement, the section would not be a suitable candidate for HIR, as the limit on HIR is typically 2 in. In general, HIR is only suitable for correcting deterioration that extends no deeper than 2 in into the HMA (Diefenderfer and Apeagyei, 2011).

Overall suggestions indicate that CIR ranges from 2-4 in (ARRA, 2005a; Rajendra, 2011; ARRA, 2012). The maximum researched depths reported are 5 in and 6 in, although ARRA (2005a) states that CIR should remove no more than 4 in. CCPR can be reach depths greater than 6 in if performed in multiple layers.

Because FDR can include base and subbase layers (as compared to CR and HIR, which only mill the asphalt), FDR can be performed to greater depths, ranging from 4-12 in, depending on the thickness of the asphalt and unbound layers (Diefenderfer and Apeagyei, 2011). CR and HIR should not be performed below the asphalt layers; thus, the depth of asphalt is an important factor when considering the recycling depth or method.

Table 5. In-Place Recycling Solutions for Distresses

Distress	HIR			FDR	CR
	SR	REM	REP		
Alligator/Fatigue Cracking		x	x	x	x
Base Failure	-	-	-	x	-
Bleeding/Flushing	x[A]	x[A]	x[A]	x	x
Block Cracking (shrinkage)	x	x	x[B]	x	x
Bumps	x[H]	x[H]	x[B]	x	x[H]
Corrugations	x[B]	x	x	x	x
Delamination	-	-	-	x	x[G]
Drainage	x[A]	x[A]	x[A]	x	-
Edge Cracking	x[B]	x	x	x	x
Friction	x	x	x	x	x
Heaving	x	x[C]	x[C]	x	x
Longitudinal Cracking (joint)-- Non-Load Associated (NDR, non-wheelpath)	x[J]	x[J]	x	x	x
Longitudinal Cracking--Load Associated (LDR, wheelpath)	x[J]	x[J]	x	x	x
Minor Profile Corrections	x	x	x	x	x
Moisture Damage	x	x	x	x	x
Noise	-	-	-	-	-
Oxidation	x	x	x	x	x
Patches	x[B]	x[H]	x[H]	x	x[H]
Polishing	x[A]	x	x	x	x[A]
Potholes	-	x	x	x	x
Pumping	x[A]	-	-	-	-
Raveling	x[E]	x[E]	x[D]	x	x[E]
Reflective Cracking	-		x	x	x
Ride Quality	x	x	x	x	x
Rutting (below surface course, includes base and subgrade)	-	-	-	x	x
Rutting (limited to top 1.5-2 in)	x[B]	x	x	x	x
Sags	x[B]	x	x	x	x
Segregation	x	x[I]	x[I]	x	x[I]
Shoulder Dropoff	-	-	-	-	-
Shoving	x[B]	x	x	x	x
Slippage	x[B]	x	x	x	x
Smoothness/Roughness	x	x	x	x	x
Stripping	-	-	-	x	x[G]
Subgrade Deficiency	-	-	-	x	-
Thermal Cracking	x	x	x[E]	x	x
Transverse Cracking	x[G]	x[G]	x[E]	x	x

Table Notes: "x" denotes that the recycling method is appropriate for the given distress. Dashed, gray cells denote that the recycling method is not appropriate for the given distress

[A] Provisionally recommended

[B] Provisionally recommended for high distress
temporary solution

[C] If heaving is due to a subgrade problem, may only

[D] Suitable for HMA thicknesses 1.5 inches or less

[E] Provisionally recommended for high distress, not recommended for low distress

[F] Not recommended for severe/high distress

[G] Recommended for minor distress only be a

[H] Provisionally recommended for low distress, recommended for high distress

[I] Not recommended for low distress

[J] A "fair" solution on a scale of Poor to Very Good (P,F,G,VG)

Traffic Considerations

As with any pavement design, the volume of traffic and percentage of trucks is an important factor to consider for designing a recycling project. The amount of heavy truck traffic may dictate the structure of the pavement, such as an HMA overlay over the recycled material. Annual Average Daily Traffic (AADT) limits provided in NCHRP Synthesis 421 are suggested practice by agencies and are not set requirements (Stroup-Gardiner, 2011). These values are from agency trials and experience and should not be treated as a required standard for recycling methods.

The AADT ratings in Table 6 should be considered with engineering judgment or replaced with a pavement design method, such as the 1993 AASHTO Guide for Design of Pavement Structures (AASHTO, 1993). These ratings were based on agency and contractor experience, but may not be the only suitable volumes for each treatment.

Table 6. AADT Recommendations

Stroup-Gardiner, M. (2011). "NCHRP Synthesis 421: Recycling and Reclamation of Asphalt Pavements Using In-Place Methods," Transportation Research Board of the National Academies, Washington, D.C. Used Under Fair Use

AADT	Rating		
	HIR	CIR	FDR
< 5,000	Fair	Fair	Good
5,000-30,000	Good	Good	Good
>30,000	Good	Good	Good

The benefit of having these AADT ratings (Table 6), based on the experience of other agencies, is to understand the structural capacity for a recycling method. If the AADT is greater than the method can carry, a structural overlay may be necessary or another recycling method should be considered. For example, if CIR were used with high truck traffic, a structural overlay may be required.

Most agencies do not use CIR on roadways with an AADT higher than 30,000. HIR and FDR are considered to be adequate recycling options given an AADT > 30,000 in several states (Stroup-Gardiner, 2011). Rajendra found that CIR may ravel under high traffic volumes, although this does not mean that CIR will not work for other applications (2011). Shatnawi (California DOT) advises limiting CR to a maximum of 12,000 ADT and 11% trucks (ARRA, 2012). Gallivan suggests applying a structural overlay if traffic is greater than 300,000 ESALs (Gallivan, 2011).

Traffic is a primary concern for any pavement design and is a typical step in the pavement design process outlined by the 1993 AASHTO Guide for Design of Pavement Structures (AASHTO, 1993).

Road Geometry

Table 7, from NCHRP Synthesis 421, describes the general performance of in-situ recycling methods with respect to various geometric features (Stroup-Gardiner, 2011). These ratings are based on contractor or agency experience with recycling equipment and its performance on specific geometric features. These ratings are not an indication of success, but a documentation of states' experience. If a recycling method is rated as "P" for "Poor" for a specific geometric feature, the process should not be used for that geometry.

Table 7. Road Geometry Influence on Project Selection for Recycling

Stroup-Gardiner, M. (2011). "NCHRP Synthesis 421: Recycling and Reclamation of Asphalt Pavements Using In-Place Methods," Transportation Research Board of the National Academies, Washington, D.C. Used Under Fair Use

Geometric Features	Ranking of Acceptable Features for Recycling Projects		
	HIR	CIR	FDR
Tight Turns	P	F	VG
Steep Grades	G	G	VG
Castings	G	VG	VG
Widening	F	G	VG
Minor Profile Corrections	G	G	VG
Curbs and Gutters	G	G	VG

Table Notes:

P= Poor, less than 10% average of agency and contractor with experience

F= Fair, between 10% and 25% average of agency and contractor with experience

G= Good, between 25% and 50% average of agency and contractor with experience

VG= Very Good, greater than 50% average of agency and contractor with experience

NCHRP Synthesis 421 mentioned that CIR should not be performed on "excessively steep grades" (5% or greater) and defines tight turns as those with a radius of less than 40 ft or a switchback turn (Stroup-Gardiner, 2011).

HIR should not be used for widening, major realignments, or drainage corrections. In a single pass, HIR equipment can cover a 12-foot wide lane. For multiple passes, the overlaps should be between 2-6 in. The equipment's long train limits productivity on urban roadways, due to obstacles such as "T" intersections or utility covers (e.g. manholes and valves). The long train "…can handle moderate radius turns such as acceleration/deceleration lanes [and] turning bays" (ARRA, 2001).

CR is not suitable if the roadway requires drainage corrections, frost heave repairs, or major realignment; reconstruction is recommended for these cases. Utility covers, such as manholes and valves, should be lowered 2-4 in below the CR depth and may be excavated and raised once the wearing course is placed. CR can treat from 10-16 ft of pavement in one pass, although the width of recycling depends greatly on the machine used (ARRA, 2001).

Because of FDR's depth, realignment, widening, and drainage corrections are possible. FDR may be used with an existing granular shoulder with sufficient granular material, good subgrade conditions, and adequate HMA thickness. Utility covers, such as manholes and valves, should be at least 4 in lower than the FDR depth. After reclamation and the applying a wearing course, manholes and valves are excavated and raised to the road surface. Most FDR reclaiming machines operate in a 6-12 ft pass; overlaps should be roughly 4 in if multiple passes are necessary. FDR can also treat narrow areas such as driveways and mailbox pullouts (ARRA, 2001).

Climate and Weather

In general, weather conditions will affect any stabilizers used in recycling; these susceptibilities should be known to ensure a successful project. Asphalt binder properties are affected by temperature; colder climates may cause low temperature transverse cracking for inappropriate binder types (ARRA, 2001). HIR must be performed when the temperature is 45°F (7.2°C) and rising with minimal wind and no water is present on the surface or in the layers of the pavement (Metcalf, 2006). HIR construction processes perform “fair” in cold/wet climates, “good” in hot/wet and cold/dry climates, and “very good” in hot/dry climates (ARRA, 2005a).

Nighttime construction is possible with CIR, although the minimum pavement temperature should be 60°F (16°C) and rising and the minimum ambient temperature should be 50°F (10°C) and rising. This is true as the emulsion breaking process and foam dispersion depends on the temperature. CIR should not be performed in cold or wet (rain is forecasted or occurring) conditions. CR’s construction process is rated as “good” in cold/wet and hot/wet climates and “very good” for cold/dry and hot/dry climates (ARRA, 2005a). Lime slurry or cement may help CR’s long-term performance in harsh environments (ARRA, 2005a; Rajendra, 2011).

FDR takes time to cure and compact (which may due to bituminous or cementitous agents used); project locations that are shaded, cold, foggy, extremely humid, or damp may lengthen cure time (ARRA, 2001). The construction process for FDR is rated as “very good” for all climates (cold/wet, hot/wet, cold/dry, and hot/dry) (ARRA, 2005a). Specific times, such as “…early spring, late fall, or winter,” as well as areas with poor drainage and high moisture content, may slow FDR’s curing (ARRA, 2001). FDR performed with an asphalt emulsion should not be performed during rain or if rain is forecasted as it can “dilute” the stabilizing agent, reducing strength (ARRA, 2001). In order to combat these temperature and moisture limitations, additional stabilizing agents (lime, Portland cement, type C fly ash) can be used in addition to the emulsion or foam to help curing and strength gain (ARRA, 2001). Table 8 lists additives and appropriate climate and weather limitations (ARRA, 2005b).

Table 8. Climactic Limitation for Recycling Agents and Stabilizers

Type of Stabilizer	Climactic Limitation for Construction
Lime, Fly Ash, or Lime-Fly Ash	Do not perform work when reclaimed material can be frozen. Air temperature in the shade should be no less than 4°C (39°F) and rising. Complete stabilization at least one month before the first hard freeze. Two weeks minimum of warm to hot weather is desirable after completing the stabilization work.
Cement or Cement Fly-Ash	Do not perform work when reclaimed material can be frozen. Air temperature in the shade should be no less than 4°C (39°F) and rising. This should be at least one month before the first hard freeze.
Asphalt Emulsion or Foamed Asphalt	Do not perform work when reclaimed material can be frozen. Air temperature in the shade should be no less than 15°C (59°F) and rising. Asphalt emulsion stabilization should not be performed if foggy or when other high humidity condition (humidity >80%). Warm to hot dry weather is preferred for all types of asphalt stabilization involving cold mixtures because improved binder dispersion and curing.
Calcium Chloride	Do not perform work when reclaimed material can be frozen. Air temperature in the shade should be no less than 4°C (39°F) and rising. Complete stabilization should be at least one month before the first hard freeze.

CONCLUSION

In order to select the appropriate recycling method, one must first know the existing pavement condition and layer thicknesses, which can be determined through detailed pavement evaluation. Ideally, this evaluation should include: GPR, soil borings/pavement cores, and material characterization, as recommended by Slagle (2011). The pavement's construction history (existing materials and layer thicknesses) should be known, as well as any limiting characteristics of the roadway including shoulders, slopes, and drainage. Part of understanding the existing pavement condition is knowing the distresses that contributed to the condition rating, as well as the potential root causes for those distresses.

The distress type and its depth will have a significant influence in selecting a recycling method. Table 6 provides a detailed listing of which recycling methods are appropriate for given distresses. For example, if a road experiences severe fatigue cracking, HIR and CIR will only repair the top few inches of the pavement (not unlike a Mill & Overlay) and not address the potential further issues of base failure and poor drainage. The drainage or base of the roadway must be improved; FDR would be more appropriate. Even though HIR and CIR both correct fatigue cracking, one must look into the depth of the distress and the root cause of the fatigue cracking. Other factors to consider include traffic, geometry, and climate/weather conditions. Ultimately, if more than one in-situ recycling method is appropriate for a project, cost may govern the selection.

The main findings of the study include the following:

- There are several in-situ pavement recycling treatments, namely HIR, CIR (or CCPR), and FDR, which can help reduce project time, cost, and environmental impact.
- It is possible to follow a methodology for selecting a recycling method, similar to how one would choose conventional maintenance activities for a project.
- The recycling criteria are based on the issues each recycling method may address, as well as each method's placement limitations or requirements. The general steps of the selection process are summarized in the following flowchart (Figure 5).

Figure 5. General In-Situ Recycling Process

After considering all of these guidelines, a locality will understand which recycling method(s) may be appropriate for a project. If, after running through the selection process, all three methods are still applicable, contractor experience and equipment availability may dictate the method available to a given locality.

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CHAPTER 3. LESSONS LEARNED FROM A LOCALITY IN-SITU RECYCLING CASE

ABSTRACT

This paper documents a local government's experience and challenges with using in-situ pavement recycling for the first time and proposes additional steps to mitigate some of the challenges. The case study is based on four road sections (South Franklin Street, George Edward Via, Independence Boulevard, and Miller Street) cold in-place recycled in Christiansburg, VA in June 2013. In addition, this paper documents testing performed to evaluate the recycled sections' construction and characteristics as well as to create alternative recycled and conventional designs.

This paper also discusses the in-situ recycling selection process (Bartku, et al., 2014) to select an appropriate in-situ method for one of the sections. The in-situ recycling guidelines, which typically require pre-construction investigation, are based on the following parameters: distresses, traffic, road geometry, and climate. This application of the selection process concluded that CIR was an adequate design for all of the streets except Independence Boulevard and that both Full-Depth Reclamation (FDR) and (CIR) were adequate methods for Independence Boulevard.

The study resulted in documenting obstacles that localities may face when in-situ recycling, as well as the impact of limited experience with recycling, for both agencies and contractors.

The study also evaluated the performance of the cold in-situ recycled pavement sections, in Christiansburg, VA, using Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR). This data was used to determine the resilient modulus of the subgrade (M_R) (found to be 24,700 psi and multiplied by a correction factor of 0.33, resulting in a design M_R of 8,154 psi) and the structural layer coefficient for CIR (found to be 0.39). Additionally, the in-place depths of CIR were gathered from GPR data and used to determine the structural adequacy of the placed designs. Independence Boulevard was not structurally adequate; it had a required Structural Number (SN) of 2.35 and an effective (in-place) SN of 2.15. The three remaining designs were determined to be structurally adequate.

Alternate recycled designs were created for the four sections (CIR and FDR for all but Miller Street, where it was decided that CIR was not appropriate) and the potential cost savings for South Franklin Street were calculated comparing the CIR to conventional methods for Christiansburg, VA.

INTRODUCTION

The Town of Christiansburg, VA awarded a contract to Lanford Brothers, Inc. for four CIR projects in May 2013 as part of the town's pavement maintenance plan. The contractor completed all projects by June 30, 2013. This was the Town's first experience with this technology. The roads recycled include: George Edward Via, Independence Boulevard, South Franklin Street, and a portion of Miller Street.

The Town of Christiansburg was interviewed about its recent recycling projects in order to understand the challenges that localities may experience when considering in-situ recycling.

The cold in-place recycled (CIR) construction was compared with alternate recycled designs. The recycling methods chosen for the alternate designs were initially intended to follow the Guidelines for the Selection of In-Situ Recycling Methods (Bartku, et.al., 2014).

Unfortunately, the characteristics of the recycled sections in Christiansburg were not fully documented prior to recycling. The information required to apply the guidelines, such as pavement distress extent and depth, was not fully documented. Some of the distresses could be identified from photos of the project, such as map or fatigue cracking on Independence Boulevard, but the quantity and depth of the distresses were unknown. Ideally, one would know the depth of distress and depth of asphalt before going through the selection process, although a theoretical application of the guidelines for Independence Boulevard was provided using the distress photo. Photos were not provided for the pre-recycling condition of the other three sections, so the in-situ recycling guidelines could not be applied. General knowledge from literature review provided the basis for the alternate design suggestions.

These in-situ selection guidelines suggest agencies perform more preconstruction investigation to determine parameters such as distress depth, in order to select the appropriate recycling method (Bartku et. al., 2014). Following these guidelines may have led to choosing a different recycling method, such as FDR for some sections versus CIR.

After the CIR projects were compared with alternate recycled designs, the potential cost savings were calculated for South Franklin Street for Christiansburg's CIR design versus conventional methods.

PURPOSE AND SCOPE

The purpose of this paper is to document a local government experience and challenges with using in-situ pavement recycling for the first time and illustrate how the availability of simple guidelines can support the practice of in-situ recycling at the local governments. It is based on a case study on in-situ pavement recycling in Christiansburg, VA. The effort included the following activities:

- Interviewing the Town of Christiansburg Engineers
- Documenting Christiansburg's experience with recycling
- Reviewing the construction process (June 2013) and documenting the difficulties encountered
- Evaluating the condition of sections recycled after approximately one year (May 2014)
- Creating alternate in-situ recycled designs for comparison with the selected CIR method
- Compare the sections constructed with alternate conventional designs to quantify potential cost savings

BACKGROUND

In-Situ Recycling

In-situ recycling is the recycling of pavement layers in-place. The equipment used in this process is one train of equipment that mills the existing pavement layers, crushes/breaks up the material into aggregate-sized pieces, mixes the material with asphalt and stabilizers, and places the material. This is one continuous process and does not require transport of milled material to a central asphalt plant for mixing or transport from the asphalt plant for placement and compaction; all work is performed on-site and in-place. The in-situ recycling methods considered in this study are summarized in Table 9 (Bartku, et.al., 2014).

Table 9. Summary of In-Situ Recycling Options

Recycling Method	Process	Uses
Hot In-Place Recycling (HIR)	• Heat and soften pavement • Mix, place, and compact pavement • For shallow distresses (no more than 1-2 in below pavement surface) • Surface Recycling: 0.75-1.5 in, Remixing: 1.5-2 in, and Repaving: 1-2 in recycled [a]	• Correct oxidation and minor cracking • Not suitable for pavements with multiple chip seals, rubberized hot mix asphalt (RHMA), Geosynthetic Pavement Interlayer (GPI), greater than 5% alligator cracking, base or subgrade failure, moisture related problems (poor drainage, pumping, saturated subgrade material)
Cold Recycling (CR)	• Reclaims 2-5 in of the existing HMA pavement • Leaves 1 in of existing reused HMA in place • Mixes recycled material with new AC • Additional material can be obtained from RAP or virgin aggregate	• Provides a uniform base that can be overlaid with HMA • Mitigate reflective cracking problems associated with straight overlay • Good for low-volume roads • Addresses raveling, potholes, bleeding, low skid resistance, rutting, corrugation, shoving, cracking (fatigue, edge, block), slippage, reflective cracking, and poor ride quality
Full-Depth Reclamation (FDR)	• Pulverize entire pavement structure and blend with portion of base/subbase material (HMA *and* base layers can be milled processes) • Usually 6-9 in (152.4-228.6 mm), as deep as 12in	• Eliminate all distress areas • Eliminate potential reflective cracking • Stabilize new base with emulsion, fly ash, or portland cement • Base strengthening and widening • Heavy pothole patching, severe rutting/shoving, frost heave, parabolic shape, and deep cracking (transverse or lateral)

Treatment Selection

The FHWA provides Pavement Recycling Guidelines for State and Local Governments (FHWA, 1997). More information relevant to in-situ recycling has been presented since then, such as the American Recycling and Reclaiming Association (ARRA) Basic Asphalt Recycling Manual (BARM) and the National Cooperative Highway Research Program (NCHRP) Synthesis 421 (ARRA, 2001; Stroup-Gardiner, 2011).

After extensive literature review of documents such as those mentioned above, a set of selection guidelines for local governments was created, titled: “Guidelines for the Selection of In-Situ Recycling Methods” (Bartku et.al., 2014). These guidelines consider the pavement distress, distress depth (to determine treatment depth), pavement thickness, traffic, roadway geometry, and climate/weather. These guidelines require some preconstruction investigation to select the appropriate in-situ recycling method for a project.

Required Information

The information required to select an in-situ recycling treatment for a pavement includes the type of distress, distress depth, pavement thickness, traffic, roadway geometry, climate/weather, and economic considerations. The pavement thickness, if construction history is unknown, can be determined using technology such as the non-destructive Ground Penetrating Radar (GPR; see Appendix B). After the pavement thickness is determined from the GPR data, any inconsistencies identified in the pavement profile can be further investigated with activities such as coring. Coring is also useful for determining the depth of distresses present in the pavement. After the necessary treatment depth is determined from the construction history, GPR data, and/or coring, the pavement design should also consider traffic levels. The traffic loading on the project is essential to any pavement design, as the new structure should be constructed to structurally accommodate future traffic volumes. Additionally, it is useful to know the strength of the existing layers that the in-situ recycling will cover. The strength of the existing layers can be determined using Falling Weight Deflectometer (FWD) testing if funds and time are available. This information will not only provide the strength of layers, but also the strength of the subgrade for pavement design. Additionally, the strength of the in-situ recycled mix depends on the additives or stabilizers used. Depending on the stabilizer or additive chosen for the recycling process, there may be climate/weather constraints on construction time or practices (Bartku, et.al., 2014).

CASE STUDY

The Town of Christiansburg, VA constructed four cold in-place recycling projects in June 2013. The information presented in this study was gathered through personal interviews with Mr. Wayne Nelson, Director of Engineering and Special Projects for the Town of Christiansburg, VA and Mr. Todd Walters, Assistant Director of Engineering. Mr. John Boyer, Assistant Director of Public Works for the Town of Blacksburg, VA, was also interviewed about his opinion regarding possible obstacles for pavement recycling at the local level.

Introduction

The roads recycled include: George Edward Via, Independence Boulevard, South Franklin Street, and a portion of Miller Street. The longest stretch of pavement recycled was 6,400 feet (South Franklin Street). Figure 6 depicts the locations of the newly recycled roads. Additional figures, denoting the exact start and end of each recycled section, are provided in Appendix C.

Figure 6. CIR Project Locations, Map by Google Maps at https://maps.google.com/

Existing Condition

The existing condition of the streets was provided by Wayne Nelson from the Town of Christiansburg and is summarized in the following sections. As part of pre-construction investigation, the Town took cores along the sections that were planned for in-situ recycling. This information is summarized in Table 10.

Table 10. CIR Section Cores, Table by Todd Walters, 2014, Used with Permission

Sample ID	Asphalt Thickness (in)	Granular Thickness (in)	Comments
GE – 1	5	8	In front of 1160 George Edward Via
GE – 2	3.5	7	In front of 1130 George Edward Via Big Rock found under the stone
GE – 3	1.5	7	In front of 1100 George Edward Via Big Rock was found 4.5" from top of asphalt
GE – 4	2	6	In front of 1040 George Edward Via Big Rock was found 6" from top of asphalt
GE – 5	4	7	In front of 975 George Edward Via
GE – 6	5	6	In front of 890 George Edward Via
I -1	6	12	Near the lower property corner of 355 Independence Blvd
I – 2	5	12	In front of 465 Independence Blvd
I – 3	4	3	In front of 510 Independence Blvd
I – 4	3	3.5	In front of 660 Independence Blvd
M – 1	3	1	In front of 311 Miller St
M – 2	4	0	In front of 405 Miller St Shell material under the asphalt
M – 3	3.5	0	In front of 411 Miller St Shell material under the asphalt
SF – 1	6	5+	In front of the north entrance of the power station
SF – 2	6.5	5+	In front of 1485 S. Franklin St
SF - 3	6.5	6	In front of 1805 S. Franklin St

Note: GE, I, M, and SF refer to George Edward Via, Independence Boulevard, Miller Street, and South Franklin Street, respectively.

South Franklin Street

South Franklin Street is a collector road with approximately 5,900 cars per day. The last time maintenance on this section had been performed on South Franklin Street. was 21 years prior to the recycling. As provided in the preconstruction investigation (See Appendix C, Christiansburg Boring Summary), South Franklin had approximately 6.5 inches of asphalt (Table 10). Figure 7 contains images of South Franklin St. before recycling. As Figure 7 shows, South Franklin Street had various types of cracking, including fatigue cracking, and some patching.

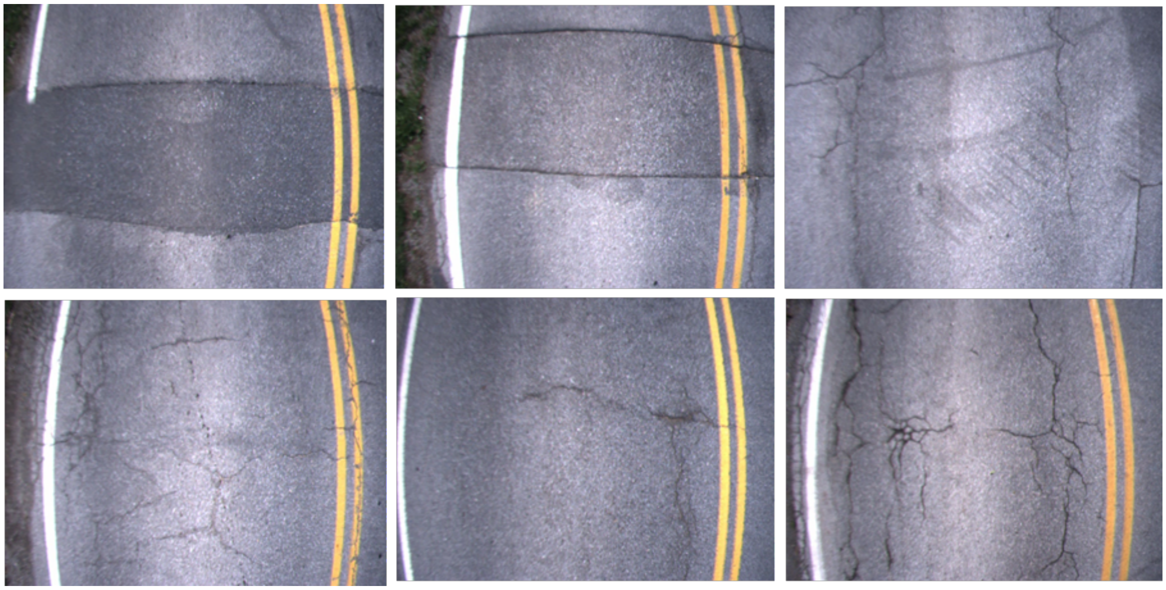


Figure 7. South Franklin Street, Previous Condition, Photo by James Bryce, 2012, Used with Permission

George Edward Via

George Edward Via is a dead-end collector road with approximately 1,600 cars per day. The existing pavement consisted of two different sections: surfaced with asphalt over VDOT No. 1 ballast stone base, "choked off with" crusher run stone, and the newer section built via Christiansburg's current standard practice, VDOT 21-A stone base and asphalt surface. The depth of asphalt was variable (2-5"), but the stone depth was approximately 7" (Table 10).

Independence Boulevard

Independence Boulevard is a collector road with approximately 4,700 vehicles per day. Figure 8 shows that Independence Boulevard was in poor condition before recycling, with map or alligator cracking and patching.

Figure 8. Independence Boulevard, Previous Condition, Photo by Todd Walters, 2013, Used with Permission

Independence Boulevard exhibited areas of “significant pavement failure,” including extensive fatigue cracking (Christiansburg Interview). Independence Boulevard was comprised of Christiansburg’s older construction cross-section (Asphalt surface, VDOT No. 1 ballast stone base, choked off with crusher run stone). The asphalt surface was approximately 4” thick, on top of approximately 3” stone (Table 10).

Miller Street

Miller Street is a collector road with approximately 220 cars per day and has a total width of 18 feet. Miller Street had 3-4” of asphalt over 0-1” of granular material (Table 10).

Recycled Pavement Design

The pavement design was performed by the contractor, but information regarding the design process and assumptions were unavailable. The Town of Christiansburg provided data on the depth of CIR on the four sections and the types of seals used. The work conducted on the four sections included 3-4 inches of CIR, stabilized with 2% of asphalt. The CIR mix was covered with a Modified Cape Seal (1 layer of chip seal (#8 chips) followed by a microsurfacing layer, using a modified latex emulsion with fine aggregate. The recycling projects used a total of approximately 163 tons of foamed liquid asphalt. All information provided by the Town of Christiansburg can be found in Appendix C, including Boring Logs, Bid Documents, Equipment Listing, Mix Designs, Nuclear Compaction Tests, Bitumen Checks, and Cement Checks.

The CIR process included milling 3-4” of the existing pavement; remixing the material in-place with the stabilizer, and laying it again. The recycler was a 2012 Wirtgen 3800 Cold Recycler. Figure 9 shows pictures of the equipment during the recycling of Independence Boulevard

(a) (b)

Figure 9. Recycling Equipment, (a) Front View, and (b) Back View, Photos by Todd Walters, 2013, Used with Permission

<u>Construction</u>

Approximately 16,000 SY of 3-inch CIR were performed on Independence Boulevard, George Edward Via, and Miller Street. Approximately 25,000 SY of 4-inch CIR were performed on South Franklin St.

The Total bid price for all four projects amounted to roughly $990,000. The most costly item on the bid list was foamed liquid asphalt, at approximately $700/ton. The average price of the CIR process was \$8.84/SY (\$9.35/SY for 3" CIR and \$8.32/SY for 4" CIR. The modified cape seal included in the pavement design cost approximately \$6/SY.

South Franklin Street

South Franklin Street was recycled from just before the I-81 overpass to just past Jones St. SE--ending before Route 615 (See Figure 8). This section of road was chosen for recycling because of its pavement age, distress present, and existing asphalt thickness. The design for South Franklin St. consisted of 4" of CIR. This section had the most recycled pavement of the four projects (25,000 SY). The finished product on South Franklin Street (August 2013) is pictured in Figure 10.

Figure 10. South Franklin Street, Finished Product

South Franklin Street was multiple-pass cold recycled (6,400 feet per direction, totaling almost 13,000 feet) in the span of two days. Compaction, with 3 rollers, was performed approximately 15 minutes after the material was recycled. The road was fog sealed and opened to traffic the same day.

As of March 20, 2014, the street has started to develop local premature cracking and potholes right before the I-81 overpass (Figure 11). The town felt that this distress is most likely a result of insufficient compaction near the overpass, as compaction can be difficult near bridge abutments. Before recycling, drivers had mentioned the "bump up" to the bridge from the pavement. Fill was placed in this area, so another issue could be inadequate compaction of the fill. Slowing traffic at the pavement-overpass transition may have also contributed to the distress.

Figure 11. South Franklin Street Local Premature Cracking (May 2014)

George Edward Via

George Edward Via was recycled from its cul-de-sac to the intersection with Independence Boulevard, shown in Figure 16. The design for George Edward Via was 3” of CIR. The section recycled on George Edward Via was approximately 0.70 miles long. The cul-de-sac at the end of George Edward via was actually not recycled, but milled and surfaced with HMA, as the large recycling train could not maneuver the tight radius. The non-recycled portion (cul-de-sac) was topped with the cape seal, as with the recycling.

According to Boring Logs 1, 2, and 3 for George Edward Via (See Appendix C, Figure C1-C3) the deepest amount of asphalt found was 2.25”. Each asphalt layer was above 4-8” of crushed stone (the crushed stone was assumed to be VDOT 21A/21B graded aggregate). If this were the case, the CIR would go beyond the asphalt (which, at most, was documented as 2.25”) and into the crushed stone. CIR should remain within the asphalt layer. Only FDR extends into the layers below the asphalt.

Independence Boulevard

Independence Boulevard was recycled from the entrance to Christiansburg High School to the second intersection with Gold Leaf Dr. The in-situ pavement recycling design for Independence Boulevard was 3” of CIR. Figure 12 contains pictures taken of the recycling performed on Independence Boulevard

Figure 12. Independence Boulevard Recycling, in progress, Photo by Todd Walters, 2013, Used with Permission

The initial design for Independence Boulevard had less asphalt content than the designs for Miller Street, South Franklin Street, and George Edward Via, although the roads had similar characteristics (materials and age). After discussion with the contractor, the Town and Lanford Brothers, Inc. were agreed on a mix design consistent with the other three projects.

Upon visual inspection, most of Independence Blvd appears to be performing well as of August 2013 (Figure 13a below). There is one portion, at the top of the hill that experienced cracking (seen in Figure 13b). The Town of Christiansburg speculated that the cracking may be due to poor subgrade condition and decided that samples were necessary to determine the problem. Samples were removed from the recycled pavement and were patched with HMA and covered with the modified cape seal (Figure 13c). The samples revealed that the subgrade was in good condition but that there was moisture in the pavement.


(a) (b) (c)

Figure 13. Independence Boulevard Recycling (August 2013): (a) overall section, (b) pavement cracking, and (c) sample patching,

The only difference in construction between the section with pavement cracking and the rest of the recycled project was operation of the machinery. On the last day of paving, the recycling train operator had to leave and was substituted with an employee who typically ran milling equipment. The recycling train started at the top of the hill on Independence Boulevard, and as it started down the hill, the asphalt truck in the train was not pumping any asphalt into the mix. This was most likely due to the hill, tilting the liquid in the truck so that it would not flow out of the nozzle. The train stopped recycling at this point, moved forward to the level area of Independence Blvd, and then recycled up the hill instead. This could have caused the moisture and cracking because of the train running over the recently-paved area.

Miller Street

Miller Street was recycled from about halfway between the intersecting streets of Miller Court and Harmon Circle to its dead-end, reaching approximately 600 ft in length. The design for Miller Street consisted of 3” of CIR, approximately 16,000 SY. Although Miller Street had the lowest traffic of the four streets recycled, traffic was still an obstacle. The width of the recycling machinery temporarily blocked all traffic flow on the street because of Miller Street’s 18-foot total width.

The recycling on Miller Street was less successful than the other sections; there was what appears to be “loose gravel” on the surface of Miller Street (see Figure 14). When recycling, sections of the asphalt were not as thick as expected and the underlying clay (subgrade) was combined into the mix. Once this was observed, construction was stopped on Miller Street. Miller Street had to be overlaid with HMA not long after the recycling was performed.

Figure 14. Miller Street (August 2013): After Recycling, before HMA Overla

One concern regarding the design of Miller Street, after reviewing the boring logs (Table 10), is the depth of CIR (3”) versus the depth (approximately 3-4”) of asphalt over stone (0-1”).

Out of the three cores taken, two have 0” of stone. The lowest thickness of asphalt (3”) is on top of stone (1”), but the variability of stone depth beneath the asphalt is a concern where sections of the asphalt could be as low as 3”. If the asphalt is slightly less than 3” on top of 0” of stone, the subgrade will be directly beneath and may get into the recycled mix. This is assumed to be the cause of the clay that got into the CIR mix on Miller Street

Initially, the Town planned on leaving Miller Street in its gravel-like recycled state to monitor its performance. After consideration, Christiansburg decided to rebuild the failed sections and surface the project with HMA in October 2013. The Town agreed that the previous activities of heavy utility patching, in addition to the recycling project, were enough stress on the residents and that it was only fair to bring the road back into good condition.

Lessons Learned

Christiansburg’s comments on the CIR process were documented to reveal the pros and cons of their recycling experience. By providing the Town’s results with in-situ recycling, other localities may weigh this experience of recycling for their specific needs, as well as learn from the challenges Christiansburg faced and avoid or mitigate those issues before they occur.

Advanced Planning for the Long and Heavy Equipment

The size of the recycling train, in addition to its weight (154,000 lb) was an obstacle in itself. Not only did the Town have to negotiate crossing the I-81 overpass (not owned by the Town), but the Town also had to plan for the size of equipment on their residential roads that were recycled.

Christiansburg had to cross the I-81 overpass bridge with the heavy recycling equipment, which exceeded the allowable weight limit. The Town had 3 options: find an alternate route, purchase a permit to cross the bridge from the Department of Motor Vehicles (DMV), or disassemble the equipment to cross the bridge. Finding an alternate route would result in extra transport costs as well as wear-and-tear on other roads in Christiansburg's pavement network and acquiring a permit would add additional cost to the project. The Town decided to disassemble the equipment to cross the overpass and then reassemble the equipment once on-site, taking more time than expected to resume.

Additionally, when performing any paving operation on local networks, other obstacles must be considered that differ from those of a highway. Manholes and valve boxes are typical obstacles that may be considered when repaving. In Christiansburg, manhole frames and covers were removed and replaced with circular plates to cover the manhole during construction. The manholes, after recycling, were backfilled with stone or HMA; this mixture was cut and manhole covers were replaced before the chip seal and microsurfacing operations. Valve boxes were lowered to protect them from the equipment. In addition to these more familiar obstacles, some other obstacles were present due to residences.

A locality's network usually contains residential roads, where different obstacles may be present than on primary roads. Lane width in residential areas may be less than a primary or secondary, such as Miller Street totaling an 18 foot-width for both directions. Mailboxes must be avoided by the machinery or removed (if overhanging the road) and replaced. Driveway entrances must also be recognized, not only for the driveway-road interface, but also for residents' access to homes. The Town had to be cognizant of the post office deliveries as well as garbage collection schedules, as these operations could hinder recycling (or vice versa). This access (or, if paving, lack of access) would need to be organized prior to construction and locals would be alerted. Christiansburg kept its constituents aware of any lane closures or construction occurring in the future via their website, http://www.christiansburg.org/index.aspx?nid=777 (Wayne Nelson, Personal Communication).

These obstacles lead to the lesson that municipalities must take enough time to plan each step of the construction process; otherwise, extra time and money will be expended on a project.

Preconstruction Investigation and Available Funds

The Town engineers also learned that careful pre-design investigation is necessary. Frequent sampling/coring may be necessary, as one cannot assume that the entire project has the same pavement characteristics. This is especially true in residential areas where different "pockets" of the neighborhood may have been created at different times. Depending on the time of construction, one road may have multiple pavement types based on the paving practice of the locality at that time.

If possible, GPR should be used first to identify the "problem areas" or areas that are not similar to the rest of the profile; then coring should be done in those areas to identify the anomalies.

Wayne Nelson considers this experience as one of the most important "Lessons Learned;" He notes that Christiansburg, in the future, will conduct extensive field investigations and borings, as the original pavement construction, despite best intentions, may not "…result in a consistent street cross-section." By finding these problem areas and addressing them prior to construction, the locality can reduce unforeseen problems and delays.

Interaction with the Public

Constituent interaction is necessary for any public agency. Although Christiansburg alerted citizens of the upcoming and ongoing construction via digital signs and their website, there was still public complaint about the construction. First, there was the pressure to perform the recycling quickly, both because of the timespan available for the project, as well as awareness of traffic congestion related to the construction (i.e. lane or shoulder closures).

Because not every citizen is familiar with paving operations or what is involved in the construction process, concerns arose with construction activities, such as the dust created during the placement of the double chip seal. After the chip seal cured, Christiansburg cleaned up the dust and performed the microsurfacing.

Some public complaint was experienced as to the appearance of the road (i.e. before the chip seal, or the appearance of the microsurfacing) because the roads were open to traffic at different intervals during their construction.

Christiansburg: Learning from Others' Experiences

Christiansburg officials met with representatives from Fairfield, CT to discuss Fairfield's experience with recycling. Christiansburg gained insight on recycling operations and a general idea on the challenges and benefits of recycling. In fact, Christiansburg added an addendum to South Franklin St.'s bid to align specifications with CT. Christiansburg saw that CT's design was successful and decided to implement a similar design with the chip seal on foamed asphalt, topped with microsurfacing as a wearing course.

After visiting with Henrico County in Richmond, VA, Christiansburg was introduced to the Cape Seal, which was a more cost effective option than plant mix (for traffic less than 10,000 vehicles/day).

Christiansburg: Others Learning from Their Experience

John Boyer, the Assistant Director of Public Works in Blacksburg, VA was interviewed regarding his opinion on Christiansburg's experiences. Boyer first mentioned Christiansburg's website for ongoing projects and noted that it would help with public outreach and awareness of the ongoing projects and construction schedules.

Some of the lessons recorded were considered important; for example, Blacksburg would have to transport recycling equipment over 2 bridges and had not considered the permitting or disassembly required to cross them. The investigation should also include identifying surface indicators of distress (such as drainage issues) and testing that area and the areas around it.

Post-Construction Investigation

In May 2014, FWD and GPR data were collected for some of the recycled pavements. The raw GPR images can be found in Appendix D and the related calculations are in Appendix E. This data allow for a more accurate pavement design. The recycled sections were tested to determine if the projects are constructed and performing as expected. The testing data was also used to determine the characteristics relevant to pavement design. FWD and GPR data were also used to calculate the resilient modulus of the subgrade and the structural coefficient of the Christiansburg's CIR mix.

FWD and GPR Results

The equipment used for the testing was a KUAB FWD trailer (behind vehicle) and a GSSI 2.0 GHz air-coupled horn antenna (mounted on front of vehicle). The GPR was mounted to the front of a VDOT van and the FWD equipment was towed behind the van with a trailer hitch. The equipment, totaling about 40-45 feet in length, is pictured in Figure 15.

Figure 15. FWD and GPR Testing Equipment

GPR data was collected for all 4 projects. Due to equipment difficulties, FWD data was only gathered for a portion of South Franklin St.

FWD and GPR Results

The GPR was evaluated using RADAN 7.0 software. The GPR data was used to evaluate the consistency of the depth of the recycled layer as well as to determine the existence of underlying layers, as the pavement designs were unavailable.

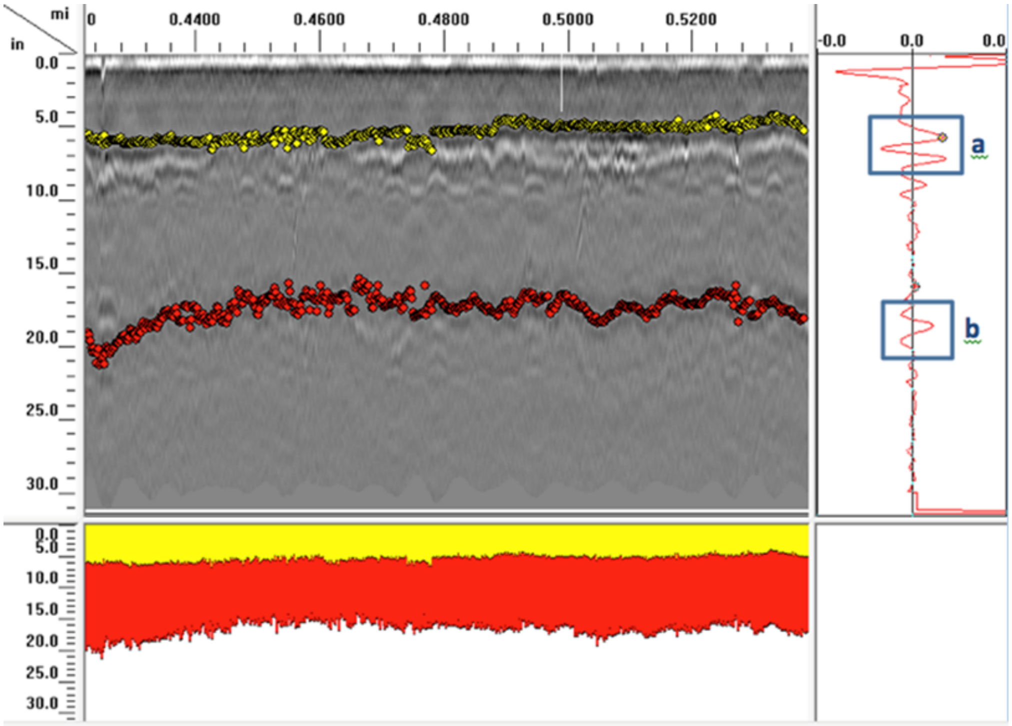


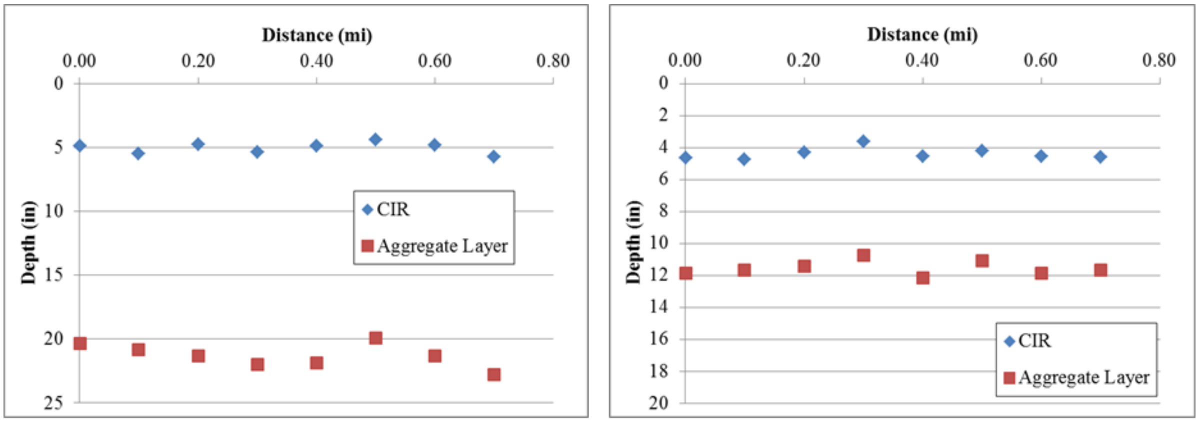
Figure 16. South Franklin Street RADAN 7.0 Profile

In Figure 16 above, the gray profile on the left is the imagery shown by the GPR. This is a profile of the pavement, where the pavement surface is at depth 0.0 inches (measurements on left-hand side). The darker/lighter horizontal lines indicate a change in dielectric constant. Each material has a unique dielectric constant, so a change in this constant indicates a change in material. The plot of the right of this profile, called a “wiggle” or “scope” plot, can also be used to clarify material changes. When the amplitude of the waves increases from left to right (box “b”), there is an increase in the dielectric constant value. If the amplitude wave increases from right to left (box “a”), there is a decrease in the dielectric constant value.

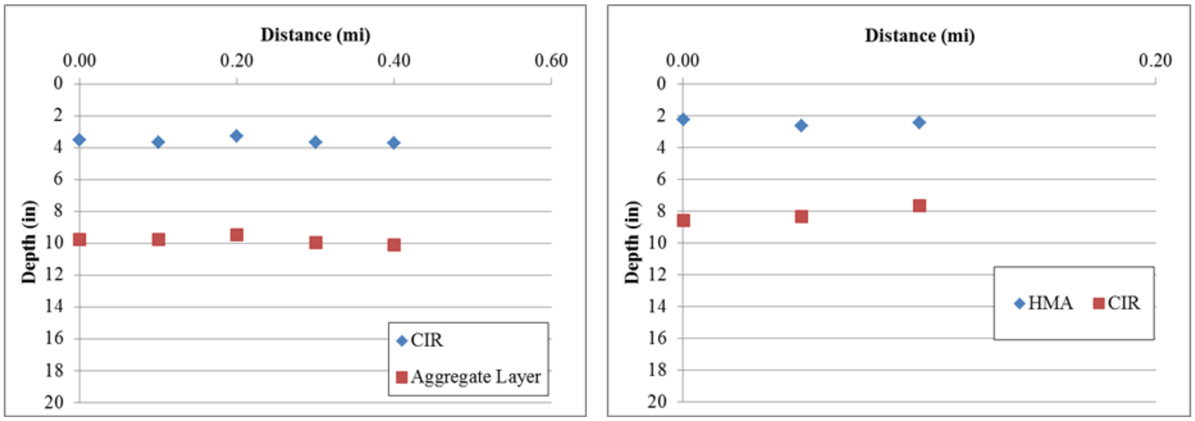
These dielectric changes allow for RADAN users to identify the interfaces between the layers and to manually select points along the layer that will be used to measure layer depths. These depths can be output into an Excel .csv file for further analysis.

After marking the layer interfaces in RADAN software, the data can be output into excel. This data was analyzed using a running average for every 0.1 miles.

Figure 17 contains plots of layer depths (inches) vs. distance (miles). The average layer depths determined from GPR analysis are presented in Table 11. The pavement surface is at Depth 0” and the bottom of each layer is denoted by the points on the plots.



(a) South Franklin Street (b) George Edward Via



(c) Independence Boulevard (d) Miller Street

Figure 17. Recycled Pavement Profiles

Table 11. Layer Thickness from GPR Analysis

Street	Layer	Thickness (in)
South Franklin Street	CIR	5.7
	Graded Aggregate Base	14
George Edward Via	CIR	4.4
	Graded Aggregate Base	7.2
Independence Boulevard	CIR	3.6
	Graded Aggregate Base	6.2
Miller Street	HMA	2.4
	CIR	5.8

One important note regarding the GPR results for South Franklin Street is the depth of the CIR (4.6”) and the distance to the next layer (the aggregate layer bottom is 14” from the CIR bottom). According to the 3 samples taken on South Franklin Street (See Table 10), there should have been 6-6.5” of asphalt over 5+” of stone, meaning that GPR equipment would have detected another layer bottom at 6-6.5” below the pavement surface (Table 10). Because the CIR layer extends to 5.7” and the next layer identified is 20” below the pavement surface, the GPR data does not appear to agree with the samples (missing the layer 6-6.5” below the pavement surface). The depth of recycling varied across the length of South Franklin Street, and the cores were taken in the pre-construction phase were from the opposite end of South Franklin Street from the end that was FWD tested.

The FWD data, collected on May 8, 2014, was analyzed using the program ModTag and the layer depth information was derived from GPR data. The FWD data was used to determine the subgrade resilient modulus as well as structural number of the CIR layer in the pavement structure. Note that the FWD analysis was only taken for a portion of South Franklin Street as technical issues prevented further testing. Outputs from ModTag software were later used to calculate the structural coefficient for the CIR in Christiansburg. The assumptions input to ModTag are presented below (Table 12).

Table 12. ModTag Assumptions for Calculations of Resilient Moduli

Inputs			
Layer	**Material**	**Thickness (in)**	**Coefficient**
Surface	Asphalt Concrete	4.6[a]	0.42[a]
Base	Graded Aggregate Base	14[a]	0.12
Subgrade	Unbound Layer	222.4	0.45
HB	Hard Bottom	0	0.2

[a] These values are respective of the area where the FWD data was taken and not reflective of the entire section recycled on South Franklin Street

The FWD data was corrected for temperature and brought to the standard 68°F. This was done inputting the average temperature for the previous day, which was 66°F. Table 13 summarizes the computed subgrade resilient modulus and effective Structural Number.
The resilient modulus of the subgrade and elastic modulus of the CIR were used in the pavement design. First, the structural coefficient of the CIR was determined using the elastic modulus output from ModTag as well as the depth of recycling on South Franklin Street

The deflection data from the 4 drops of the FWD equipment were analyzed with ModTag software and the layer depths (determined and/or assumed using GPR data). The output values for the subgrade resilient modulus are shown in Table 13.

Table 13. ModTag M_R Output

Station (mi)	Deflection with 9000-lb load (mils)	M_R (psi)	SN_{eff}	CIR Coefficient (with 16" base, D_2)
0.14	16.24	16552	3.77	0.37
0.16	10.48	30724	4.28	0.46
0.18	11.14	26923	4.23	0.46
0.20	16.65	18935	3.65	0.35
0.21	12.22	25875	4.06	0.42
0.23	16.36	17102	3.74	0.37
0.24	36.37	10942	2.69	0.18
0.30	18.20	21908	3.44	0.31
0.32	10.95	30460	4.19	0.45
0.34	11.41	30887	4.09	0.43
0.36	12.04	32890	3.95	0.41
0.38	14.04	25932	3.79	0.38
0.40	13.84	19512	3.96	0.41
0.42	12.03	23511	4.12	0.43
	AVERAGE	**24709**	**4**	**0.39**

The M_R values were averaged to find the average M_R of the subgrade along the area tested, which was calculated as approximately 24,700 psi. Note that one point (in red font at 0.24 mi) was removed from this average because of uncharacteristic results; this location was the pavement section tested that was just before the I-81 overpass bridge. The area tested at 0.24 mi had much higher deflections than the rest of the recycled pavement (deflection of 36 mils versus 10-16 mils). This area was not considered representative of the recycled section as a whole (totaling about 1.27 miles) and was removed.

When the resilient modulus is backcalculated from FWD data, it must be multiplied by a correction factor of 0.33. The Design M_R was calculated to be 0.33*24709 = 8,154 psi.

Structural coefficient of CIR

Literature Review found that the CIR coefficient ranges from 0.20-0.44 (Lee, 2003). Using the FWD data collected, supplemented by layer depths determined from the GPR imagery, a structural coefficient was calculated for the CIR performed in Christiansburg, VA.

After reviewing the GPR data, it was determined that there was approximately 5.7” of CIR placed and that there was a 14” semi-homogenous layer beneath the CIR; this material was assumed to be a graded aggregate base (VDOT 21A/21B). Note that these assumptions greatly affect the value of the structural coefficient determined for CIR.

The effective structural number for the pavement was found to be 4.0. This value is higher than expected. This high SN could be the reason that the structural coefficient of CIR was high (0.39).

The effective Structural Number is defined as the effective Structural Number of the existing pavement, and thus characterizes the current in-place structure (in the case of this study, the recycled pavement). In order to determine the individual structural coefficient (a_1) for the

CIR layer, the layer depths of both layers must be known, as well as the structural coefficient (a_2) of the layer beneath the CIR (Layer 2). The depth of each layer, which is determined using GPR data, is represented as (D) in the following equation (AASHTO, 1993):

$$\mathbf{SN_{eff} = a_1D_1 + a_2D_2m_2} \tag{1}$$

Where: a = Structural Layer coefficient
D = Depth of Layer
m = Drainage coefficient of layer

This equation can be rearranged to solve for a_1:

$$\mathbf{a_1 = [SN_{eff} - (a_2D_2m_2)] / D_1} \tag{2}$$

The coefficients of drainage (m) for the layers was assumed to be 1.0, as recommended by the VDOT "Guidelines for AASHTO 1993 Pavement Design Guide" (VDOT, 2003). The remaining values and assumptions are presented in the equation below:

For 0.14 miles:

$$\mathbf{a_1 = [3.77 - (0.12*14*1)]/5.7 = 0.37}$$

This process was repeated for all stations and the calculated a1 was averaged to find a structural coefficient of 0.39 for the CIR. These calculations for the varying SN_{eff} values along the section are in Table 13.

The structural coefficient of the second layer (a_1) was 0.12, as provided by the VDOT "Guidelines for AASHTO 1993 Pavement Design" for 21A/21B graded aggregate (VDOT, 2003). From GPR analysis, it was assumed that the layer depths were 4.6" and 16" for D_1 and D_2, respectively. This assumption of the material underlying the CIR does make a difference in the structural coefficient (a_1) of the CIR.

As seen in Table 13, the average structural coefficient (a_1) for the CIR on South Franklin Street was 0.39. This value is on the higher end of the CIR coefficient range, which is 0.20-0.44, according to the ARRA BARM (ARRA, 2001; Lee, 2003). If the aggregate layer, which was assumed to be an untreated aggregate base, were actually a 14" treated aggregate base (Cement-treated, $a_2 = 0.20$) the structural coefficient of the CIR would be 0.19. This variability of the structural coefficient of CIR based on composition of the underlying layer(s) makes analysis of the CIR structure difficult when the construction history or composition of a pavement structure is unknown. Therefore, more investigation, such as cores, should be performed in order to attain an accurate composition and depth for the layers beneath the CIR, as well as depth of CIR, for calculation of the CIR layer's structural coefficient.

Recycled Pavement Designs

The 1993 AASHTO Pavement Design process was used to analyze the CIR designs constructed in Christiansburg, VA (AASHTO, 1993). Additionally, the CIR constructed was compared with alternate CIR and FDR designs. This comparison is intended to understand the CIR designs and to potentially determine the structural capacity provided by the recycled layer. The value of a_1 (0.39) found for the CIR projects in Christiansburg, VA was used to evaluate the CIR sections constructed. Because this coefficient was higher than expected, a more common structural coefficient of 0.30 was assumed for the CIR in the alternate designs (ARRA, 2001; Bemanian, 2012; Babish, 2012).

Pavement Design Process

The 1993 "AASHTO Guide for Design of Pavement Structures" and VDOT "Guidelines for AASHTO 1993 Pavement Design" were used to create the comparable recycled designs (AASHTO, 1993 and VDOT, 2003).

The first step in the pavement design is to calculate the Equivalent Single Axle Load (ESAL) expected on the pavements over the design. The ESALs depend on the Truck Factor (T_f) and Percent Trucks (T) on each road. Because the percent trucks and truck factors were unknown for George Edward Via and Miller, assumptions were made as to the truck traffic on the roads. Additionally, a design period of 20 years was considered. The yearly growth rate, g, was found to be approximately 2.5% in a report developed for Franklin and Cambria Street in Christiansburg, VA (Blacksburg, 2010). The results are summarized in Table 14.

Table 14. Traffic Analysis Variables

Inputs				
Variables	**South Franklin Street**	**George Edward Via**	**Independence Boulevard**	**Miller Street**
ADT	5900[a]	1600[b]	4700[b]	220[b]
T	2%[a]	0.3%[c]	2%[b]	2%[c]
Tf	0.42[c]	0.56[c]	0.495[c]	0.56[c]
D	0.5[d]	0.5[d]	0.5[d]	0.5[d]
L	1[d]	1[d]	1[d]	1[d]
g	2.5%[e]	2.5%[e]	2.5%[e]	2.5%[e]
Y	20[d]	20[d]	20[d]	20[d]
(G)(Y)	25.54	25.54	25.54	25.54
Outputs				
EASLs	2.31E+05	1.12E+03	2.17E+05	1.10E+04

(a) VDOT, 2012 (b) Provided by Town of Christiansburg (c) Assumed
(d) VDOT, 2003 (e) Blacksburg, 2010

Because the volume of truck traffic (T) and truck factors (T_f) were unknown for George Edward Via and Miller Street, these value were calculated. It was assumed that approximately 4 School Buses (Vehicle Class 4) per day, 1 Garbage Truck (Vehicle Class 6) per week (trip in and trip out of street), and 8 Construction Trucks (Vehicle Class 6) per year, travelled on George Edward Via. The T_f was determined by the using the 1993 AASHTO guide (AASHTO, 1993). These values, calculated using an Excel spreadsheet, resulted in a T_f of 0.56 for both streets, T = 0.3% for George Edward Via, and T = 2% for Miller Street

T was known for Independence Boulevard, but T_f was assumed to be 0.495, following similar calculations to those used for George Edward Via and Miller Street The T = 2% for Independence Boulevard consisted of 1% trucks and 1% buses. A value of 1% buses seems high, but the traffic count was taken near the entrance to the High School so the daily bus traffic to and from the school would account for this percentage.

The M_R was backcalculated from FWD and GPR data and the W_{18} was taken from the traffic analysis calculated using a spreadsheet. The results are shown in Table 15. After the ESALs are calculated, a variety of parameters are determined and used to determine the required strength of the entire pavement structure, Structural Number (SNreq), based on these parameters. Once a SN is found, all that is necessary for the pavement design is the layer coefficients (in the case of these designs, a_1= 0.30 for CIR or a_1 = 0.20 for FDR (ARRA, 2001; Babish, 2012) and a_2 = 0.12 for the graded 21A/21B aggregate base). The structural coefficient bituminous FDR ranges from 0.20-0.28 and for cement FDR ranges from 0.15-0.20 (Bemanian, 2012). Therefore, the structural coefficient of FDR was assumed to be 0.20, as this is recommended by the ARRA BARM and is VDOT practice, for the purposes of including both bituminous and cement FDR options (ARRA, 2001; Babish, 2012).

Table 15. Required SN Calculations

Inputs				
Variables	**South Franklin Street**	**George Edward Via**	**Independence Boulevard**	**Miller Street**
Roadway Classification	High Volume Secondary [c]	Residential/ Subdivision [c]	Residential/ Subdivision [c]	Residential/ Subdivision [c]
R (Reliability)	90% [a]	75% [a]	75% [a]	75% [a]
Z_R	-1.282[a]	-0.674 [a]	-0.674 [a]	-0.674 [a]
S_0	0.49 [a]	0.49 [a]	0.49 [a]	0.49 [a]
TSI	2.8 [a]	2.0 [a]	2.0 [a]	2.0 [a]
PSI	4.2 [a]	4.0 [a]	4.0 [a]	4.0 [a]
ΔPSI	1.4	2.0	2.0	2.0
W_{18} (ESALs)	2.31E+05[b]	1.12E+03[b]	2.17E+05 [b]	1.10E+03 [b]
M_R	8,154[c]	8,154 [c]	8,154 [c]	8,154 [c]
Outputs				
SN_{req}	2.75	1.42	2.35	1.41

(a) VDOT, 2003 (b) Calculated in Traffic Analysis (Table 14) (c) Assumed

(d) FWD/GPR results of MR = 24,709. Following VDOT Guidelines, a correction factor is necessary to convert field testing to lab testing. Design MR = MR*0.33 = 24,709*0.33 = 8,154 (VDOT, 2003)

The SN_{req} indicates the required SN of the pavement given all of the factors described in Table 15. If a pavement's design SN (SN_{eff}) does not equal or exceed the SN_{req}, the pavement may not support traffic and may fail or exhibit distress sooner than expected.

Analysis of Existing Recycled Designs

A structural coefficient of 0.39 was used for CIR in when analyzing the designs of the projects in Christiansburg, VA, as this was the value found from GPR and FWD analysis on the recycled sections. It was assumed that the layer beneath the CIR was graded aggregate, 21A/21B, with a structural coefficient of 0.12. The results of the Recycled Design analysis are in Table 16 below. The SN_{eff} is the effective SN of the in-place pavement. The SN_{req} is the required SN based on the subgrade M_R (8,154 psi) and design traffic.

Table 16. Christiansburg Existing Recycled Design Analysis

Street	Layer 1	D_1	a_1	Layer 2	D_2	a_2	SN_{eff}	SN_{req}
South Franklin Street	CIR	5.7	0.39	21A/21B	14	0.12	3.90	2.75
George Edward Via	CIR	4.4	0.39	21A/21B	7.2	0.12	2.58	1.42
Independence Boulevard	CIR	3.6	0.39	21A/21B	6.2	0.12	2.15	2.35
Miller	HMA	2.4	0.44	21A/21B [a]	5.8	0.12	1.75	1.41

[a] Note that the CIR that failed on Miller Street was assumed to be in the condition of 21A/21B Graded Aggregate

Notice that in Table 16 above, the SN_{eff} is less than the SN_{req} for Independence Boulevard. This means that the CIR placed (approximately 3.6") is not enough to support design traffic given the assumed structural coefficient for CIR (0.39) and backcalculated M_R of the subgrade. The other recycled sections have a SN_{eff} greater than the SN_{req} and therefore are more likely to support the future traffic.

The SN_{req} (2.35) for Independence Boulevard was calculated using the traffic count that was taken near the High School (1% buses, 1% trucks, ADT of 4700), which may experience more traffic (especially bus traffic) than the section recycled. Therefore, the existing CIR design may be sufficient for the section recycled, but a traffic count specific to that section would be required to analyze the design adequacy. Therefore, the data is not conclusive that the CIR design on Independence Boulevard is inadequate.

The depth range for CIR is typically 2-4" for an asphalt emulsion or emulsified recycling agent (ARRA, 2001). It is recommended that at least 1-1.5" of asphalt remain below the CIR to avoid getting base materials into the recycled mix—HIR and CIR should occur only within the asphalt layers and not include base material. This asphalt may be referred to as the "paving platform" (Idaho, 2010). The ARRA BARM notes that moisture could get trapped between layers if the HIR layer is a similar depth to the surface lift. Additionally, the BARM cautions against making the CIR treatment depth the same as the total asphalt layer, as there "…is an increased risk that portions of the underlying granular base may be incorporated into the CIR mix" (2001).

If the CIR were to extend past the asphalt, such as what happened on Miller Street, the pavement would not have the predicted SN_{eff} and thus may not perform as expected. Therefore, even if the SN_{eff} is greater than the SN_{req} in the design, the quality of construction can result in premature distress or failure and a shorter design life for the pavement.

A general observation and concern regarding the CIR designed for Christiansburg, VA, is that the CIR depth ranges from 3-4" for the projects, while asphalt depths are as low as 1.5" on George Edward Via. This would mean that the CIR depth may extend beyond the asphalt in some cases, which is not typical of CIR but is seen more in FDR, which extends into the unbound material (Stroup-Gardiner, 2011).

Because of the issues listed above, different recycling methods may be more appropriate for certain sections, such as FDR instead of CIR. The following section provides alternate recycled designs as recommended by Bartku, et. al. (2014).

Alternate Recycled Designs

Selection of In-Situ Recycling Method

According to in-situ recycling selection guidelines, the proper in-situ recycling treatment can be chosen knowing certain characteristics of a road (Bartku et.al, 2014). These guidelines are theoretically applied to Independence Boulevard (Table 17).

Table 17. Information Known for Independence Boulevard

Item	Value(s)	Source	In-Situ Recycling Method(s)
Distress	Fatigue Cracking (potentially indicative of base failure) Pothole Patching (potentially heavy)	Figure 8	Using Table 5: **Fatigue Cracking:** HIR (Remixing and Repaving only), CIR, FDR **Potential Base Failure:** FDR only **Patching:** HIR, CIR, FDR*
Depth of Existing Asphalt	3-6” depending on location	Boring Log, Table 10/Appendix C	Using Table 3: • HIR depth is 0.75-2”; if the distresses extend beyond 2” (which fatigue cracking will most likely do), HIR is not a suitable option. • CIR depth is 2-5”, but if there is base failure, the distress depth would extend deeper and require deeper recycling (therefore, FDR may be more appropriate) • FDR can extend into the base layers, so if asphalt thickness is inconsistent (i.e. 3” in one place, 4” in another), may be more appropriate
Traffic	4700 ADT, 1% bus and 1% truck traffic	Traffic Count from Christiansburg	Using Table 6: For <5,000 ADT, HIR and CIR are rated “Fair” and FDR is rated “Very Good”
Roadway Geometry	Steep hill at beginning of project	Christiansburg Interview	Using Table 7: For steep grades, HIR and CIR are rated “Good” and FDR is rated “Very Good”

[a] if patching is heavy (unknown because only 1 photo available to Independence Boulevard’s prior condition), then FDR is more suitable than HIR and CIR.

From Table 17, it is apparent that CIR is appropriate as well as FDR, but that FDR is the ideal recycling method. By following these guidelines, the Town would know that CIR and FDR are both options for Independence Boulevard depending on the depth of distress and the design of the contractor (if the CIR depth in the pavement design did not extend beyond the distress depth or if CIR went deeper than 3," it would not be the most suitable design and method combination).

Because information was unavailable regarding the sections' conditions prior to recycling, assumptions were made as to the appropriate in-situ recycling method. From the information provided from the Boring Logs (Table 10), it was apparent that 3" of CIR may not have been suitable for some of the sections, such as those with 3" or less of existing asphalt. These alternative recycled designs are provided in Table 18.

The FDR pavement design assumed a FDR structural coefficient of 0.20 (Bemanian, 2012; Diefenderfer and Apeagyei, 2011; Babish, 2012). The Christiansburg CIR structural coefficient determined from GPR and FWD data analysis is likely high due to lack of data; this comparison should be made again after more coring or investigation or a general value for CIR should be assumed as was for the FDR. Therefore an average value for the coefficient of CIR was used: 0.30 (ARRA, 2001; Babish, 2012; Bemanian, 2012).

Table 18. Proposed Recycled Designs

Pavement Layers	South Franklin Street	George Edward Via	Independence Boulevard	Miller Street
CIR Design				
CIR Structural Coefficient (a_1)	0.30	0.30	0.30	0.30
CIR depth, in (D_1)	3.00	3.00	4.50	2.50
Aggregate Structural Coefficient (a_2)	0.12	0.12	0.12	0.12
Aggregate depth, in (D_2)	16.7	8.60	5.30	5.70
SN_{eff}	2.89	1.93	1.98	1.43
SN_{req}	2.75	1.42	2.35	1.41
FDR Design				
FDR Structural Coefficient (a_1)	0.20	0.20	0.20	0.20
FDR depth, in (D)	5.0	4.00	12.00	5.50
Aggregate Structural Coefficient (a_2)	0.12	0.12	0.12	0.12
Aggregate depth, in (D_2)	14.7 [a]	7.60 [a]	0 [a]	2.70 [a]
SN_{eff}	2.75	1.71	2.40	1.42
SN_{req}	2.75	1.42	2.35	1.41

[a] In all cases, the aggregate depth was calculated as the total depth of material minus the depth of CIR.

Assumptions

Some assumptions were made, regarding the layer properties, when creating the recycled pavement design. These assumptions, per section, are listed in Table 19:

Table 19. Recycled Design Assumptions

Street	Assumption	Comments
South Franklin Street	CIR Layer $\leq$ 6.0”	The maximum depth of CIR available was determined from the asphalt depth documented in the boring logs (Table 10). If CIR design depth did not reach the bottom of the asphalt layer, the remaining asphalt was assumed to provide the structure of 21A/21B Graded Aggregate (a = 0.12), as the asphalt most likely degraded with age.
George Edward Via	CIR Layer $\leq$ 3.5”	
Independence Boulevard	CIR Layer $\leq$ 4.5”	
Miller Street	CIR Layer $\leq$ 3.5”	

Also note that the depths of aggregate provided in the designs in Table 18 are calculated by subtracting the FDR or CIR layer depth from the total depth of material for that section. The total depth of material for a section was determined by GPR data and is a sum of the CIR depth and the aggregate depth. For example, South Franklin Street had approximately 5.7” of CIR and 14” of aggregate, totaling 19.7” for the GPR-tested pavement structure. In the alternate CIR design proposed for South Franklin Street, the suggested layer depths were 3.00” CIR and 16.7” aggregate, once again totaling 19.7”.

Assuming that the subgrade (determined from FWD and GPR data on South Franklin Street) is the same strength for all sections, the CIR design for Independence Boulevard will not provide enough strength. Because the average asphalt depth on Independence Boulevard was 4.5”, a maximum of 4.5” of CIR could be designed for the section. As seen in Table 18, 4.5” of CIR does not provide enough structure, resulting in a SN_{eff} of 1.98 when a SN of 2.35 is required. Again, this SN_{req} of 2.35 was calculated using the traffic count that was taken near the High School, which may have more traffic (especially bus traffic) than the section recycled. Therefore, the design may be sufficient for the section recycled, but a traffic count specific to the section would be required to analyze the design adequacy. With the information available and using the traffic count provided, FDR would be recommended over CIR, where 12” of FDR will provide the necessary strength for the pavement structure (Table 18).

Alternative Conventional Designs for South Franklin Street

After alternative designs were created for each section, a conventional design comparable to the construction practices of Christiansburg, VA was created. This conventional design was created to determine the potential cost savings from using CIR on South Franklin Street

A bid item form was used to determine Christiansburg’s potential cost savings from recycling South Franklin Street. Additional savings from reduced material transport (as recycling was in-place), reduced construction time, and reduced work zone operations/user delay, were not considered in this analysis. Therefore, the savings of recycling could actually surpass those calculated in this report if other factors were considered.

The alternative conventional design considered for South Franklin Street aligned with the conventional practices of the Town of Christiansburg, which include an overlay and sometimes mill and overlay.

Wayne Nelson of the Town of Christiansburg noted that the predicted conventional design for South Franklin Street would include milling 5” and overlaying with a 3.5” base course and 1.5” surface course. The typical surface course used by Christiansburg, VA is AC Type SM-9.5A. The 3.5” base course was assumed to be AC Type BM-25.0. The structural coefficients for these two layers were assumed to be 0.44 for the SM-9.5A and 0.40 for the BM-25.0, as provided by VDOT (VDOT, 2003). The results of this design are shown in Table 20.

Table 20. Alternative Conventional Design: South Franklin Street

Layer	Material	Structural Coefficient	Depth
Surface	SM-9.5A	0.44	1.5
Base	BM-25.0	0.40	3.5
Subbase	21A/21B	0.12	15
	SN_{eff}	3.76	

From previous calculations, it was determined that South Franklin Street needed at least a SN of 2.75 to support future predicted traffic (Table 15). As seen in Table 20, the SN is well over 2.75 and therefore an adequate design (2
3.76).

From this conventional design, a cost comparison (solely on material, not including transportation or equipment) per SY can be found below. The cost values were gathered from the Bid Form and Revised Cost sheet from the Bid Documents. The quantities were taken from the Material Use document from the Bid documents provided by Christiansburg, VA.

Table 21. Approximate Recycling Cost: South Franklin Street

Item	Cost	Quantity	Total Item Cost
4” CIR	$8.32/SY	17,695.2 SY	$147,224.06
Foamed AC	$699.00/Ton	82.03 Tons	$57,338.97
Add RAP	$175.00/Ton	20 Tons	$3,500.00
Fog Seal	$6.50/Gallon	950 Gallons	$6,175.00
Modified Cape Seal	$6.01/SY	17,695.20 SY	$106,346.95
TOTAL			**$320,584.98**

Table 22. Approximate Conventional Cost: South Franklin Street

Item	Cost	Quantity	Total Item Cost
Profile Milling 5” [a]	$2.54/SY	17,695.2 SY	$44,945.81
Asphalt SM 9.5	$100.00/Ton	1,458 Tons	$145,800.00
Asphalt BM 25.0 [b]	$83.00/Ton	3,403 Tons	$282,449.00
TOTAL			**$473,194.80**

[a] Assumed that the cost of milling 5” was the same cost as the item, milling 0-2”, found in the bid form.

[b] The cost of BM 25.0 was assumed to be $83.00, as found for the Town of Front Royal in a Memorandum to VDOT dated October 2013 (VDOT, 2013).

The quantities for the conventional design were assumed based on values provided in the recycled design. The lane width was assumed to be 12 ft (so both lanes recycled totaled 24 ft in width) and the distance of recycling was 1.27 miles (6,705 feet).

Using the Vulcan Hot Mix Asphalt Calculator, it was determined that the tonnage for 1.5” of HMA for South Franklin Street would be approximately 1,458 tons and for the 3.5” of HMA base mix, approximately 3,403 tons (Vulcan, 2014).

Comparing the totals from Tables 3.24 and 3.25 ($320,584.98 for the Recycling Total and $473,194.80 for the Conventional Total), using CIR on South Franklin Street alone resulted in a cost savings of $152,609.80. Again, this savings does not include material transportation, unused virgin material, and reduced construction time savings.

RECOMMENDATIONS

Based on the GPR results from this study, it is recommended that a combined detailed project-level structural evaluation be used for the testing to support treatment selection and design (for example, using GPR/FWD in addition to a detailed distress survey). Although locations of pavement discontinuities, such as patches, were recorded during FWD testing, it is difficult to denote such items without a tick-mark system in the GPR file or without pictures of the pavement surface at that specific location.

Additionally, GPR testing is recommended for pre-construction investigation. If the construction history or profile of the pavement is unknown, it is difficult to make a pavement design. Although cores were taken before the projects were recycled, they alone do not provide an overall representation for the pavement structure. GPR data should be used to determine the pavement profile and irregularities. The irregularities found in the GPR data may be cored to determine if a special mix design is required for that area.

Although CIR was an appropriate method for 3 of the 4 sections recycled, FDR should have been selected for at least one section (Miller Street). In a similar situation for another local government, it may not be cost-effective to have both CIR and FDR equipment transported to the locality for recycling. Based on a more detailed analysis, in-situ recycling selection guidelines can be used to determine the proper in-situ recycling treatment (Bartku et.al, 2014).

CONCLUSIONS

Despite the limited timeframe available to spend the funds, and the town’s unfamiliarity with pavement recycling, the first experience with CIR was in general positive. The construction time and work zone traffic control for the sections were significantly less than those typical for conventional repaving methods. Additionally, the CIR process reduced the amount of material needed and cost Christiansburg less than a conventional design. Long term performance follow-up would be necessary to determine the effectiveness over the pavement life-cycle.

Overall, the CIR designs provided by the contractor were adequate in regards to structural capacity, except for Independence Boulevard. Furthermore, a recommendations that there be at least 1-1.5” of asphalt material beneath the depth of recycling for any project using CIR or HIR methods (ARRA, 2001; Idaho, 2010) could have would help avoid the problems encountered in Miller Street, where clay material got into the recycled mix. If the required treatment depth extends beyond the asphalt layers, FDR should be used.

It is recommended that future projects include a detailed subsurface investigation should be performed before selecting the treatment and designing the mix design for the recycling. The selection of the most appropriate in-situ recycling method can be determined using available guidelines (e.g., Bartku et al., 2014). This would provide agencies with background knowledge in in-situ recycling methods and help agencies to identify any conflicts in contractor decisions.

Other agencies considering recycling can learn from the experiences presented in the case study and use that knowledge to their advantage when considering recycling methods and on what pavements to use them.

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CHAPTER 4: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

This thesis prepared in-situ pavement recycling method selection guidelines for local governments and documented a local agency's experience and challenges with in-situ pavement recycling. A literature review was performed to collect information relevant to in-situ pavement recycling methods, which provided the foundation of the selection process. The purpose of the selection guidelines is to help local agencies choose the appropriate in-situ pavement recycling method for a project.

After the in-situ recycling practices were outlined and a process for selection was created, these guidelines were applied in a case study. Although some of the distress information was not available for all of the sections recycled, the guidelines were used to suggest alternate in-situ pavement recycling treatments for the various sections. These alternate treatments were designed construction and after the CIR placed on the four sections was structurally analyzed using the FWD and GPR results. Finally, a conventional design was compared for one of the sections to determine potential cost savings.

FINDINGS

Additional information, not directly related to the objectives of this thesis, was gathered in the process. This information includes:

- Most states have yet to publish standards for in-situ pavement recycling
- When starting to use pavement recycling, localities may have to consider the cost of equipment transportation to the area; typically, recycling sections as short as those recycled in Christiansburg, VA may not be cost-effective. However, agencies could coordinate their in-situ recycling schedule with other local or state agencies so that the cost of transporting the equipment is reasonable.
- The construction process of in-situ pavement recycling can greatly affect its performance but some of the potential problems can be avoided through a detailed pavement and site investigation. For example, inconsistent depth of recycling could incorporate base material into the mix and cause premature failure (such as Miller Street).

CONCLUSIONS

This thesis developed in-situ pavement recycling selection guidelines, which can help local agencies understand which pavement recycling method(s) may be appropriate for a project, and emphasizes all the information needed for selecting and designing the most appropriate treatments. Important factors that should be considered include distress types and its depths, layer composition and thicknesses, traffic, geometry, and climate/weather conditions. Ultimately, if more than one in-situ recycling method is appropriate for a project, contractor experience, equipment availability, and cost may govern the selection.

The case study suggested that local agencies can benefit from adding pavement recycling technologies to their pavement maintenance and rehabilitation portfolio. The first experience in the town investigated was in general positive. The construction time and work zone traffic control for the sections were significantly less than those typical for conventional paving methods. Additionally, the CIR process reduced the amount of material needed and cost Christiansburg less than a conventional design. Long term performance follow-up would be necessary to determine the effectiveness over the pavement life-cycle. The main difficulties encountered were related with the lack of a detailed site evaluation before selecting and designing the pavement recycling project. Other agencies considering recycling can learn from the experiences presented in the case study when considering recycling methods and what on pavements to use them.

SIGNIFICANCE

In-situ pavement recycling is a potentially more sustainable alternative to conventional maintenance or rehabilitation and, when applied to the right pavement, can save natural resources, save money, and reduce construction emissions. However, many agencies are still hesitant to start in-situ recycling. By having an idea as to what recycling methods are appropriate and where they should be applied, localities may feel more confident adopting this technology.

In addition, raising awareness of a town's experience with CIR may encourage other local agencies to try the in-situ recycling. In the least, a locality can learn from the challenges faced by the town and prepare for those challenges or work around them.

RECOMMENDATIONS FOR IMPLEMENTATION

The following recommendations can help implement the findings from the thesis work:

1. The in-situ recycling guidelines provided in this study (Chapter 2) could be distributed local transportation localities to promote awareness of the various recycling alternatives available to replace conventional pavement rehabilitation and reconstruction methods.
2. Localities should conduct a detailed pavement and site investigation (preferably including GPR testing) because this investigation can help select the most appropriate treatment and identify potential problems before construction.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future research could include a direct application of the in-situ pavement recycling selection guidelines, in which the present pavement condition, thicknesses, traffic, roadway geometry, and climate, are considered to select the appropriate treatment. Once the in-situ pavement recycling treatment and depth are selected, further research on appropriate mix designs is recommended. This would include consideration of additives, stabilizers, asphalt performance grades, and gradation of the milled material.

APPENDIX A: RECYCLING CHARACTERISTICS CROSS-COMPARISON

Note: Numbers following table items denote reference for each item. References are listed below the table. The Following Table, (23) is a cross-comparison of FDR information.

Table 23. FDR Cross-Comparison

Typical Milling Depth	Does Not Fix/ Do Not Use When	Distress Type Will Fix	Other Notes
• 2-4”, 4-6”, >6”[1] • Depths >6”[1] • Typically 4-12”[2] • “pulverize entire HMA thickness and portion of base or subgrade to a depth of 6-16”[3]	• Clay-like native soils, unless fly ash is used to stabilize[5] • Drainage problems including ditch and regional flooding problems[5]	• Failure in base section[5] • Edge of road failure[5] • Alligator Cracking[1, 3, 4, 6, 7] • Bleeding, Flushing[1] • Block Cracking[1, 5, 6, 7] • Bumps[1] • Edge Cracking[1, 5, 6] • Friction Improvement[1] • Longitudinal Cracks (non-wheel path and wheel path)[1, 7] • Oxidation[1] • Patches[1] • Polishing[1] • Potholes[1] • Raveling[1, 7] • Rutting[1] • Reflective Cracking[1, 5, 6-8] • Shoving[1] • Slippage[1] • Transverse Cracks[1, 5, 6] • Moisture Damage[1] • Ride Quality (distress related)[1] • Minor Profile Corrections • Thermal Cracking[7] • “roads with high spots (heaves) or depressions due to underlying layers”[7] • “heavy pothole patching”[7] • “severe plastic deformation (rutting, shoving, corrugation) contributed to weak deficient base/subbase”[3] • discontinuity cracking, strength[4] • If SR<2.5, IWD>5.0, and existing HMA > 3.5in[4] • If SR<2.5, IWD>5.0, and existing HMA < 3.5in[4]	• Good for AADT 5,000-30,000 and AADT>30,000[1] • Road Geometry: Very Good for Tight Turns, Steep Grades, Castings, Widening, Minor Profile Corrections, Curbs and Gutters[1] • “…recommended for pavements with deep rutting, load-associated cracks, non-load associated thermal cracks, reflection cracks, and pavements with maintenance patches such as spray, skin, pothole, and deep hot mix. It is particularly recommended for pavements having a base or subgrade problem.”[9] • FDR Applications: SR 40 in Franklin County (4400 AADT, 4% trucks, reclaimed 8-10”), SR 30 in Powhatan (2300 AADT, 5% trucks, reclaimed 8-10”)[2] • SR 6 in Goochland County (3900 AADT, 7% trucks, reclaimed 8-10”)[2] • “May involve removing the entire pavement, including the base and subgrade, then replacing it with a new structure.”[10] • “FDR is better for variable thickness pavements”[4]

The Following Table, (24) is a cross-comparison of CIR information, a type of Cold Recycling. CCPR, a method of Cold Recycling that involves transportation to an asphalt plant (RAP is not heated), is in the following table (Table 25).

Table 24. CIR Cross-Comparison

Typical Milling Depth	Does Not Fix/ Do Not Use When	Distress Type Will Fix	Other Notes
• 3”[11] • 1-2”, 1-3”, 2-4”[1] • 3-6”[2] • “Removes 2-4” of HMA surface”[12] • Typical depth of 3”, range is from 2-4”[8] • “The top 2 inches to 4 inches of pavement are reclaimed”[13] • mill up to 3-4”[3] • milling 2-4”[14] • “Recycle depth: Min = 70% exist AC thickness; Max 4” or 75% exist AC thickness, whichever is less.” • 2-5”[15]	• fatigue cracking[9] • cracks from base failures[9] • subgrade and aggregate base are not “sound”[10] • “inadequate base or subgrade support”[13] • “inadequate drainage”[13] • “paving fabrics or inter-layers”[13] • “CIR is best for pavements at least 5” thick”[4] • “CIR requires base support for the heavy train equipment”[4] • CIR equipment requires HMA thickness of at least 3.5in[4] • Subgrade stiffness must be at least 5000psi to support equipment[4] • Not to be used with Rubberized HMA (RHMA), deep cracking, Geosynthetic Pavement Interlayer (GPI), Moisture-related problems (pumping, poor drainage, saturated subgrade material)[14] • Do not use “with nighttime construction work (asphaltic emulsion “breaking” process)”[14] • Weather: minimum pavement temperature must be 60 deg. F, ambient temperature 50 deg F[14] • Recycling train noise may be a concern for urban areas[14] • Limit to roads with 12,000 ADT and 11% trucks or less”[16] • “Do not use for base failures” or if there is pumping[16]	• Alligator Cracking[1, 4, 6] • Block Cracking[1, 4, 6] • Friction Improvement[1] • Longitudinal Crack (wheel path and non-wheel path)[1, 4, 6] • Oxidation[1] • Patches[1, 14] • Polishing[1] • Potholes[1, 4, 6, 14] • Raveling[1, 12, 14] • Rutting[1, 4, 6, 14] • Reflective Cracking[1, 4, 6, 8] • Shoving[1, 4, 6, 14] • Slippage[1, 4, 6, 14] • Transverse Cracks[1, 4, 6] • Moisture Damage[1] • Surface cracking[12] • Ride Quality[4, 6, 14] • “…restoring or improving the cross section profile, crown, cross slope drainage, as well as removing cracked pavement”[8] • Corrugations[6, 14] • discontinuity cracking[4] • If SR<2.5, IWD>5.0, and existing HMA > 3.5in[4] • Medium and wide transfer cracking[3] • Weathering, bleeding[14] • Cracking[14] • “Extensive (>50%) reflective/thermal cracking or rutting (>1/2”). Will correct roughness (IRI > 170).”[16]	• If ESALS > 300,000 an additional overlay is required[11] • Good for AADT 5,000-30,000 and AADT > 30,000, Fair for AADT <5,000[1] • Road Geometry: Very Good for Castings; Good for Steep Grades, Widening, Minor Profile Corrections, Curbs and Gutters; Fair for Tight Turns[1] • A HMA overlay or surface treatment is usually necessary (prevents moisture damage and traffic wear/”abrasion”)[9] • “HMA overlay of 1.5-2” for state highways”[12] • “The important surface deficiencies that could be restored by cold mix recycling are reflection cracking and ride quality.”[9, 15] • “…high production rate and potential cost savings, minimum traffic disruption, ability to retain original profile…”[9] • “CIR is often used on low traffic volume roads or secondary roads where a central hot mix plant may not be convenient for obtaining new HMA for an overlay”[8] • “It can also be used on high volume roadways as a repair to the existing pavement and a mitigation layer for cracking in conjunction with a HMA overlay”[8] • “...more suitable for low-volume roads tan high-volume roads.”[13] • “The recycled material is applied on top of 1 inch of original hot-mix asphalt.”[13] • Good ‘candidate’: 4” of HMA[4] • Foamed asphalt can be used in place of asphalt emulsion[14] • “Emulsified recycling agent less susceptible to moisture than foam. Emulsion must cure 1-3 weeks (under traffic) before capping with HMA”[16]

Table 25. CCPR Cross-Comparison

Typical Milling Depth	Does Not Fix/ Do Not Use When	Distress Type Will Fix	Other Notes
• Same as CIR	• "Secondary low-volume roads that are located at a considerable distance from a central plant" [9, 15] • "where a central hot mix plant may not be convenient for obtaining new HMA for an overlay" [8] • "weather limitations: air temperature of 50 deg. F is preferred, heavy rain must not be occurring" [15]	• Same as CIR	• Used for CIR projects that "…require high rates of production or close control of the mix design." [9, 15] • "viable alternative when stockpiles of high quality RAP are available or when it is not possible to in-place recycle the pavement" [15]

The Following Table, (26) is a cross-comparison of HIR information.

Table 26. HIR Cross-Comparison

Typical Milling Depth	Does Not Fix/ Do Not Use When	Distress Type Will Fix	Other Notes
• 1”, 1-2”[1] • “heated and scarified to a minimal depth (typically 2 in or less)[3] • 1-2”[10] • Surface recycling: ¾-1”, Surface Repaving: 1-2” recycled, 1-2” overlay (sum up to 3”)[3] • Surface recycling: 1”, 1-2”; Remixing: 1-2”, 1-3”; Repaving: 1-2”, 1-3”[2] • “softening the existing asphalt pavement with heat, milling or scarifying to a maximum depth of 2 inches”[17] • “rehabilitate road surfaces with minor deficiencies in the upper 1-2 inches of existing asphalt pavement”[18] • “Surface recycling is the most basic type of [HIR]…scarifying depths of 0.75 to 1.5 inches, with a depth of one inch being most common”[18] • “Remixing…provides the most options for pavement remediation…cost effective solution to rutting, raveling, oxidation, and other flaws in the upper two inches of the pavement…single stage remixing…treats depths of 1 to 2 inches…with 1.5 inches the most common depth. Multiple stage remixing…a way to achieve greater treatment depths with HIR. This process is used for remixing depths of 1.5 to 3.0 inches, with 2 inches being the most common”[18]	• cracking and raveling go below 1-2” of the HMA surface[12] • “HIR is effective at correcting surface distress that is limited to the top… 1 to 2 inches…but depending on the process and extent of cracking, may extend to 3 inches.”[8] • “HIR should only be used if the underlying pavement layers are structurally sound.”[8] • “HIR should not be used on pavements with: multiple chip seals, rubberized hot mix asphalt (RHMA), Geosynthetic Pavement Interlayer (GPI), Structural Inadequacy, greater than 5% alligator cracking, moderate to excessive filled cracks, base or subgrade moisture related problems (poor drainage, pumping, saturated subgrade material”[17] • “Limit to roads with 4000 ADT and 8% trucks or less”[16]	• Alligator Cracking-*Repaving and Remixing*[1] • Friction Improvement-*Repaving*[1] • Longitudinal Cracks (non-wheel path and wheel path)-*Repaving*[1] • Oxidation-Surface Recycling, Remixing, Repaving[1] • Patches-*Remixing*[1] • Polishing-Remixing, Repaving[1] • Potholes-Remixing, Repaving[1] • Raveling- Surface Recycling, Remixing, Repaving[1, 3, 5, 7] • Rutting-*Remixing*[1] • Reflective Cracking-*Repaving*[1] • Shoving-*Remixing*[1] • Slippage-*Repaving*[1] • Moisture Damage-*Repaving*[1] • Ride Quality (distress related)[5, 6] • Minor Profile Corrections[1] • “…effective for correcting minor surface rutting, corrugations, raveling, flushing, loss of surface friction, minor thermal cracking, and minor load associated cracking”[8] • “Pavements with < 5% digouts or alligator cracking. Shallow rutting (< ½”). Bleeding or raveling surfaces OK.”[16]	• Good for AADT 5,000-30,000 and AADT>30,000, Fair for AADT <5,000[2] • Road Geometry: Good for steep grades, Castings, Minor Profile Corrections, Curbs and Gutters; Fair for Widening, Poor for Tight Turns[2] • Primary purpose is to correct surface distresses that are not a result of “…structural inadequacy, such as raveling, cracks, ruts and holes, and shoves and bumps.”[9] • Needs less traffic control[9] • Also used to “…recoat stripped aggregates, re-establish crown and drainage, modify aggregate gradation and asphalt content, and improve surface frictional resistance.”[9] • 1.5” overlay or “microsurfacing wearing course” on top[12] • “best suited for roadways with light traffic”[17]

Table 26 Notes:

SR = Surface Rating degradation rate

IWD: Individual Weighted Distress

IWD = 5: pavement with medium severity transverse cracks, 25 cracks/500 ft or with high severity cracks, 12 cracks/500 ft

Cost/benefits should also be considered with SR and IWD criteria

Mill & Overlay SR < 2.5, multiple transverse cracking, IWD<5

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APPENDIX B: FWD AND GPR LITERATURE REVIEW FOR CASE STUDY

A Literature Review on Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR) was performed in order to accurately understand the potential of FWD and GPR testing to analyze a road's current condition and characteristics. Understanding includes what information the data may provide as well as how to analyze the data, such as using FWD data to backcalculate layer moduli.

Falling Weight Deflectometer (FWD)

FWD is one of the most common devices used to collect data on pavement surface deflections (Harris, 2004). FWD works by measuring strains as a function of load (Lenngren, 2000). FWD works by applying an impulse load on a pavement surface. The load that is dropped is meant to imitate repeated loading of a truck axle (Lenngren, 2000). The impulse force is created when different weights are dropped; the weights usually are 110 lbs, 220 lbs, 440 lbs, or 660 lbs. The weights are dropped from different heights, ranging from 0.8 in to 15in (Al-Qadi, 2003). This load is transferred to the pavement through a loading plate is measured via a loading cell. Velocity transducers are used to measure the pavement deflections resulting from the dropped load (Al-Qadi, 2003).

Figure 18. FWD Equipment (KUAB Brand)

FWD is capable of: "…[measuring] total pavement thickness, [increasing] the number of sample sites, and being nondestructive" (Harris, 2004).

Disadvantages of FWD include the limitations of the method and assumptions required to estimate the thickness (Harris, 2004). Because of the assumptions required in estimating the thickness of a layer, alternative methods are desired to determine layer thickness. Coring provides thickness data but is a destructive technique. Ground Penetrating Radar (GPR) is a nondestructive method used to determine thickness (Lenngren, 2000). GPR will be discussed in more detail in the following section. FWD measurements require a stop at each location, which requires traffic control (Harris, 2004).

Ground Penetrating Radar (GPR)

GPR is considered by some to be the “most promising NDT method” for determining layer thickness in pavement structures (Lenngren, 2000). GPR works by emitting pulses of electromagnetic waves into a pavement. When the pulses that are reflected back, the antennae of the GPR receive the pulse and the amplitude of the returned wave and its arrival time are recorded (Harris, 2004).

The amplitude of the reflected waves can be used to determine the material properties of the pavement layers; in addition, the GPR map can be used to locate the contact points between pavement layers and help to determine layer thickness (Harris, 2004).

The GPR tests the pavement’s material response to excited electromagnetic fields (dielectric constants play a role in this process) (Leng, 2011). These constants affect the material’s conductivity and ability to transmit electric fields, which is ultimately used to differentiate between layer compositions. The GPR’s antennae send EM pulses through the pavement and the reflected echoes from the pavement are recorded.

GPR data is processed by software, such as RADAN, that identifies the reflections caused by the dielectric and electrical conductivity changes (Halim, 2012). The reflections are converted from analog to digital and the software then processes the digital reflections into the thickness of each layer (Halim, 2012). RADAN software assumes an average value for the dielectric constants if no values are available from materials in the field (Halim, 2012).

GPR is capable of measuring more than characteristic of pavement performance, specifically: thickness, density, and moisture content (Schmitt, 2013). It is almost necessary for GPR to measure moisture content, as materials with high moisture contents can affect the signal penetration of the GPR (Halim, 2012). When GPR measures the time difference between the reflected signals as well as the contrast in dielectric properties, it not only can be used to determine layer thickness, but also may be used to locate subsurface defects (such as moisture) (Al-Qadi, 2003).

GPR allows for high-speed data collection and gives a “continuous profile” of the pavement’s dielectric constants (Leng, 2011). This data is available in real time and thus allows for immediate analysis on-site (Lenngren, 2000). GPR is a nondestructive technique for evaluating layer thickness, unlike coring. Coring, in addition to being a destructive technique, also requires time, labor, and traffic control (Harris, 2004). GPR also provides a continuous record of the pavement thickness, which helps to account for the high variation in pavement thickness (which may not be possible with limited coring) (Lenngren, 2000). Thus, GPR may be used as an input for FWD (Al-Qadi, 2003).

GPR is acceptable for network-level studies and provides an economic estimate of pavement overlay thicknesses. For project-level studies, the estimation of pavement overlay thickness is affected by assumptions required in the backcalculation method (Harris, 2004). Identifying the interface between layers with GPR is a subjective process. Interface between bound and unbound layers is less difficult to detect with GPR because of the difference in the dielectric constants (Lenngren, 2000). To an untrained eye, it would be difficult to interpret the interfaces between the layers in the GPR radargram (Lenngren, 2000).

In addition, the interface identification is dependent on the size and shape of the radar wave that is reflected. In order for the interface to appear, the electromagnetic wave must travel to the layer interface and return, the wave must reflect off the layer with enough energy to be noticed by the equipment and recorded, and the wave velocity must be estimated for each

material (Harris, 2004). Background noise can affect the radar wave if it is not detected and tracked, but the noise must be large enough to be noticed (Harris, 2004).
An accurate thickness reading from GPR strongly depends on the pavement's physical properties, the specific GPR unit used, and the data interpretation and processing (Harris, 2004).

Backcalculation

Background

Specifically for flexible pavement, the subgrade resilient modulus (MR) and the effective structural number (SNeff) can be used to analyze the pavement (Chowdhury, 2011). The stiffness of each pavement layer is represented by the elastic modulus; this value cannot be calculated directly. Backcalculation procedures must be performed in order to determine the moduli.

AASHTO has an overlay design procedure that involves Nondestructive Deflection Testing (AASHTO, 1993, Section III-96). The subgrade resilient modulus (MR) may be determined from the deflection testing since the deflections are due to subgrade deformation; the MR may be calculated regardless of how many layers rest above the subgrade (Lee, 2010). A high MR is desired so that it may resist permanent deformation under traffic loading and provide adequate support for the overlying pavement; a low MR usually correlates to soft or weak subgrade soil (Halim, 2012).

The deflection results, in addition to soil classification of the subgrade, may be used to "…backcalculate and validate the subgrade resilient modulus results" (Al-Qadi, 2003). To calculate the MR, the applied load, in pounds, must be known (P), as well as the deflection (dr) at a distance (r), in inches, from the center of the load P. Temperature corrections are not necessary wen determining the MR, as the deflection measured is due only from the subgrade deformation and not from surface deformation (Lee, 2010). The backcalculation requires an adjustment factor, C, to account for the dynamic property of the backcalculated modulus compared to the static peoperty of the latoratory tested subgrade modulus. The relationship between these parameters is shown below (Lee, 2010):

$$\boldsymbol{Design\ M_R = C\left(\frac{0.24P}{d_r r}\right)} \quad (3)$$

where: Design MR = Design Resilient Modulus
C = correction Factor for backcalculation and testing
P = Load
d_r = Deflection at center of load plate
r = radius of load p late

The value for C is recommended to be less than or equal to 0.33 to adjust between the dynamic modulus (backcalculated) and the static subgrade modulus (tested).
Following AASHTO's Design of Pavement Structures, the resilient modulus (M_R), load (P), and deflection at the center of the load plate (d_0, adjusted to a standard temperature of 68°F) are used in conjunction with AASHTO's Figure 5.5 to determine the total pavement thickness (AASHTO, 1993). Once this is completed, the thickness is used to determine a temperature adjustment factor with AASHTO's Figure 5.6.

In addition to determining the subgrade resilient modulus (M_R), backcalculation is also used to determine the effective pavement modulus (E_P) and the effective structural number (SN_{eff}) (Halim, 2012). Because the strength of flexible pavements are affected by temperature, deflections must be corrected to an equivalent value for a temperature of 68°F (20°C) (Al-Qadi, 2003).

The deflection and load data (FWD), in addition to the pavement structure data (GPR), allows for evaluation of the pavement's structural capacity. This capacity can be expressed as the effective Structural Number (SN_{eff}) (Al-Qadi, 2003). To calculate the SN_{eff} for each location, or a group of homogenous locations, the subgrade resilient modulus is necessary, in addition to the condition and total thickness of the pavement layers overlying the subgrade (Al-Qadi, 2003). Because the MR has a significant effect on the SN determined, AASHTO cautions against using high M_R values, as this could lead to an overlay that is too thin (AASHTO, 1993).

Determining SN_{eff} based on NDT (Non-destructive Testing) requires one to assume that the structural capacity is a function of the pavement's total thickness and overall stiffness (E_P); these equations are displayed below (AASHTO, 1993):

$$\boldsymbol{SN_{eff} = 0.0045D\sqrt[3]{E_p}} \tag{4}$$

where: D = total thickness of all layers above subgrade (in)
E_P = effective modulus of pavement layers above subgrade (psi)

The SN_{eff} can then be used to characterize the pavement's current condition or further used in calculations for maintenance and rehabilitation, such as an overlay (AASHTO, 1993).

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APPENDIX C: PROJECT DATA RECEIVED FROM CHRISTIANSBURG, VA

CHRISTIANSBURG RECYCLED SECTIONS

Figure 19. Franklin Street Recycling Location, Photo by Todd Walters, 2014, Used with Permission

Figure 20. George Edward Via and Independence Boulevard Recycling Locations, Photo by Todd Walters, 2014, Used with Permission

Figure 21. Miller Street Recycling Location, Photo by Todd Walters, 2014, Used with Permission

CHRISTIANSBURG BORING SUMMARY

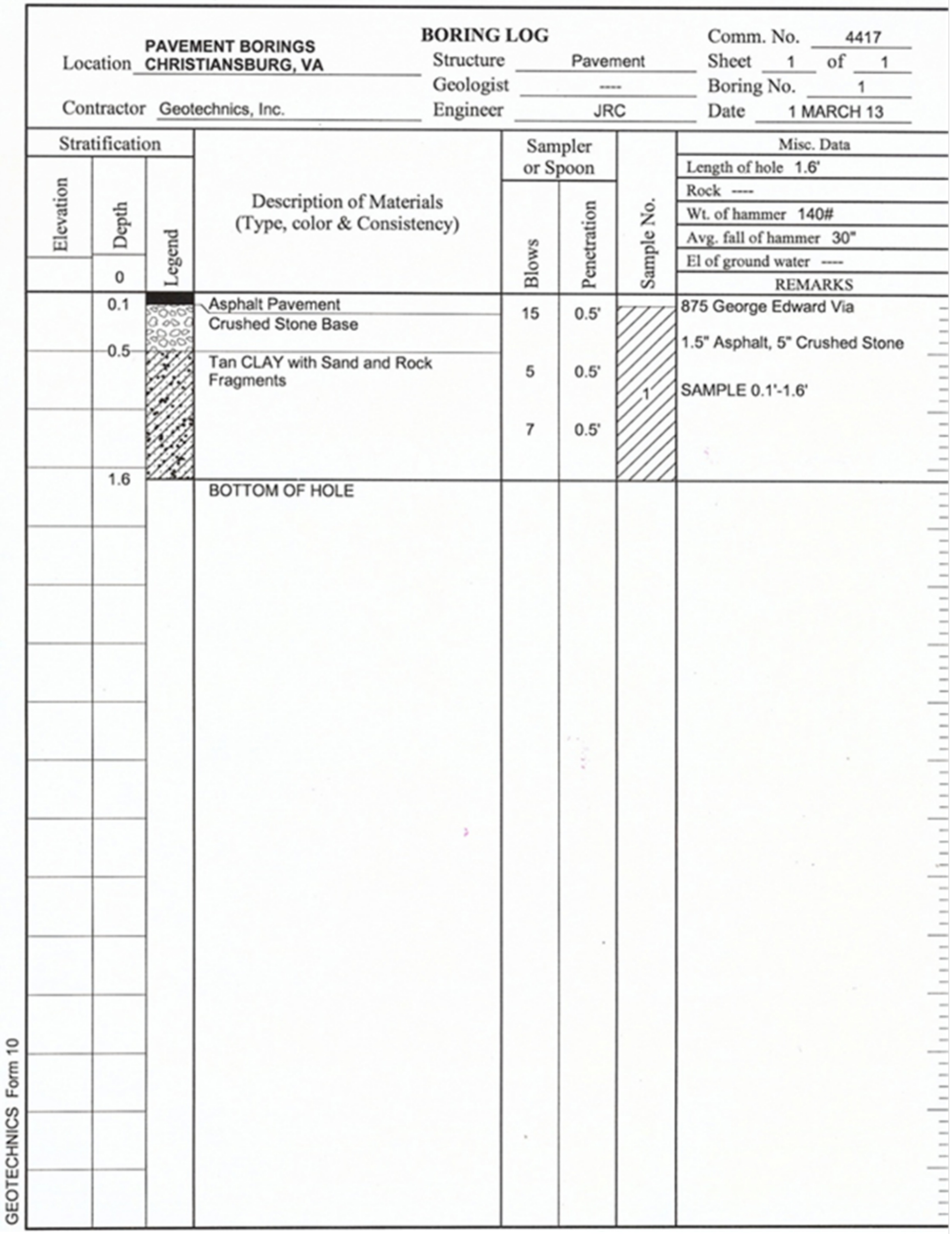
Note: GE, I, M, and SF refer to George Edward Via, Independence Boulevard, Miller Street, and South Franklin Street, respectively.

Table 27. Pavement Maintenance Program Street Investigation, Table by Todd Walters, 2014, Used with Permission

Sample ID	Asphalt Thickness (in)	Stone Thickness (in)	Comments
GE – 1	5	8	Sample taken in front of 1160 George Edward Via
GE – 2	3.5	7	Sample taken in front of 1130 George Edward Via Big Rock found under the stone
GE – 3	1.5	7	Sample taken in front of 1100 George Edward Via Big Rock was found 4.5” from top of asphalt
GE – 4	2	6	Sample taken in front of 1040 George Edward Via Big Rock was found 6” from top of asphalt
GE – 5	4	7	Sample taken in front of 975 George Edward Via
GE – 6	5	6	Sample taken in front of 890 George Edward Via
I -1	6	12	Sample taken near the lower property corner of 355 Independence Blvd
I – 2	5	12	Sample taken in front of 465 Independence Blvd
I – 3	4	3	Sample taken in front of 510 Independence Blvd
I – 4	3	3.5	Sample taken in front of 660 Independence Blvd
M – 1	3	1	Sample taken in front of 311 Miller St
M – 2	4	0	Sample taken in front of 405 Miller St Shell material under the asphalt
M – 3	3.5	0	Sample taken in front of 411 Miller St Shell material under the asphalt
SF – 1	6	5+	Sample taken in front of the north entrance of the power station
SF – 2	6.5	5+	Sample taken in front of 1485 S. Franklin St
SF - 3	6.5	6	Sample taken in front of 1805 S. Franklin St

BORING LOGS

The boring logs provided by the Town of Christiansburg were for George Edward Via only.



BORING LOG

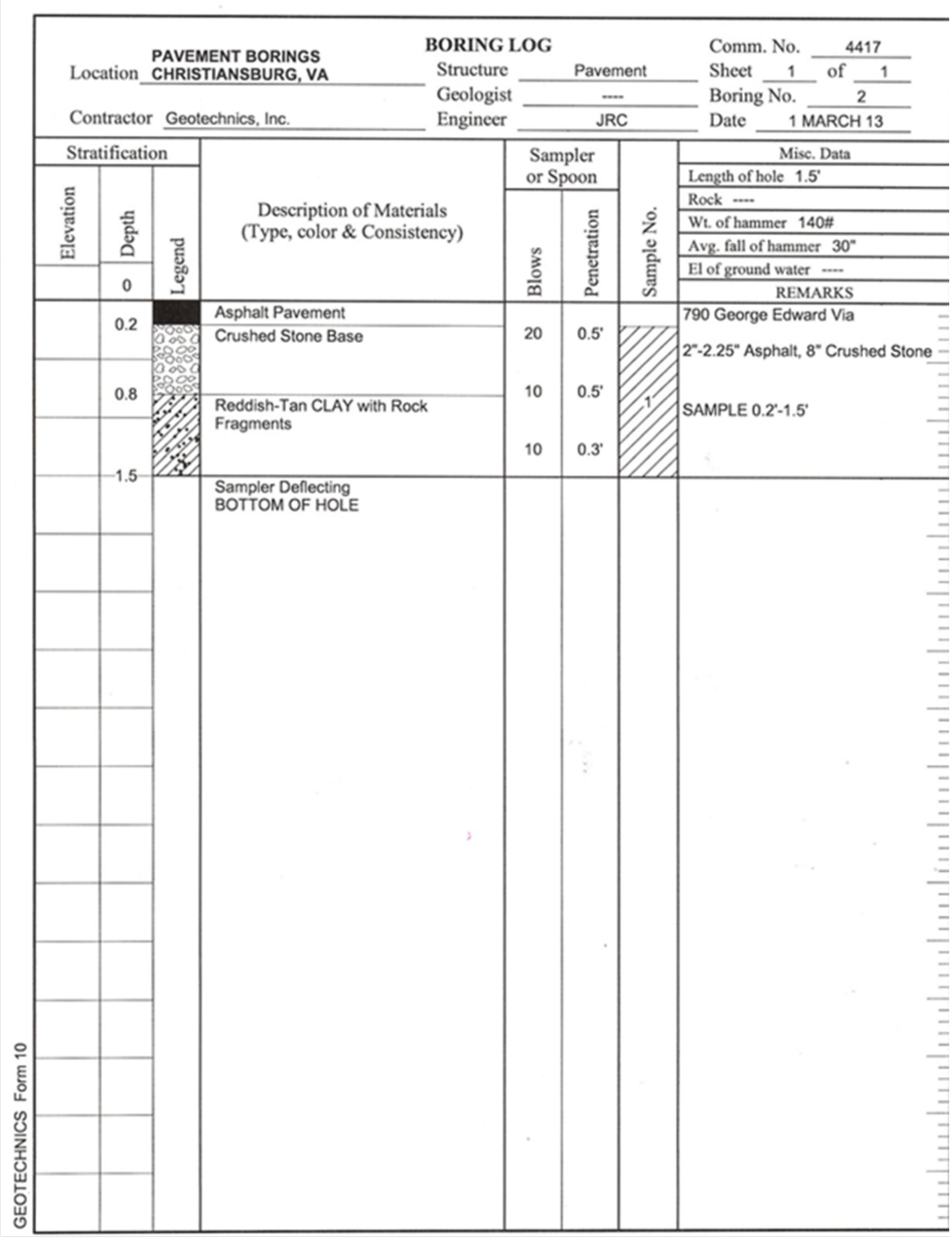
Location PAVEMENT BORINGS CHRISTIANSBURG, VA
Contractor Geotechnics, Inc.
Structure Pavement
Geologist ----
Engineer JRC
Comm. No. 4417
Sheet 1 of 1
Boring No. 1
Date 1 MARCH 13

Misc. Data
Length of hole 1.6'
Rock ----
Wt. of hammer 140#
Avg. fall of hammer 30"
El of ground water ----

Stratification			Description of Materials (Type, color & Consistency)	Sampler or Spoon		Sample No.	REMARKS
Elevation	Depth	Legend		Blows	Penetration		
	0						
	0.1		Asphalt Pavement	15	0.5'	1	875 George Edward Via
			Crushed Stone Base				
	0.5		Tan CLAY with Sand and Rock Fragments	5	0.5'		1.5" Asphalt, 5" Crushed Stone
							SAMPLE 0.1'-1.6'
				7	0.5'		
	1.6		BOTTOM OF HOLE				

GEOTECHNICS Form 10

Figure 22. Boring Log: George Edward Via – 1, Photo from Todd Walters, 2014, Used with Permission



BORING LOG

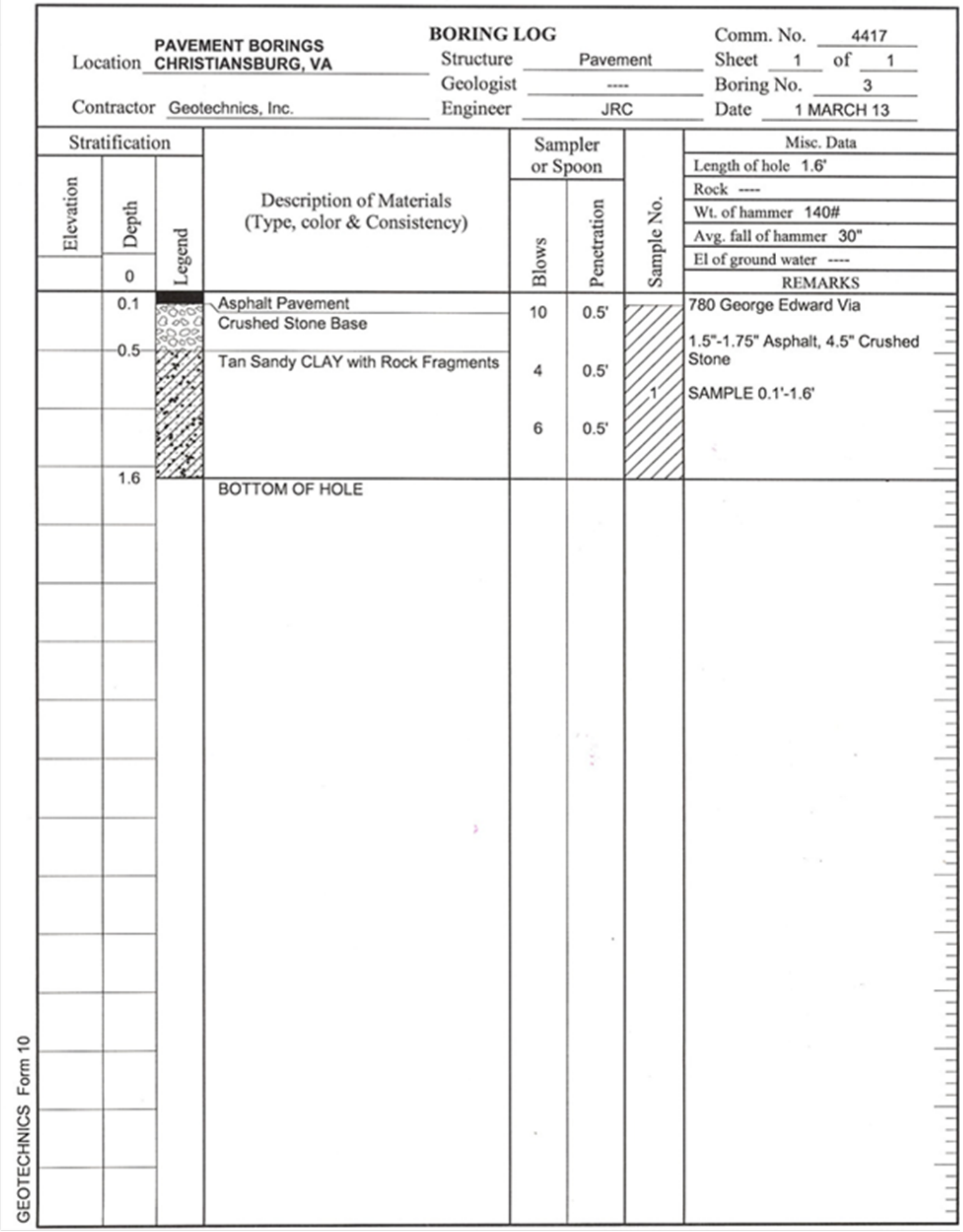
Location PAVEMENT BORINGS CHRISTIANSBURG, VA
Contractor Geotechnics, Inc.
Structure Pavement
Geologist ----
Engineer JRC
Comm. No. 4417
Sheet 1 of 1
Boring No. 2
Date 1 MARCH 13

Misc. Data
Length of hole 1.5'
Rock ----
Wt. of hammer 140#
Avg. fall of hammer 30"
El of ground water ----

Stratification			Description of Materials (Type, color & Consistency)	Sampler or Spoon		Sample No.	REMARKS
Elevation	Depth	Legend		Blows	Penetration		
	0						
	0.2		Asphalt Pavement				790 George Edward Via
			Crushed Stone Base	20	0.5'	1	2"-2.25" Asphalt, 8" Crushed Stone
	0.8		Reddish-Tan CLAY with Rock Fragments	10	0.5'		SAMPLE 0.2'-1.5'
				10	0.3'		
	1.5		Sampler Deflecting BOTTOM OF HOLE				

GEOTECHNICS Form 10

Figure 23. Boring Log: George Edward Via – 2, Photo from Todd Walters, 2014, Used with Permission



BORING LOG

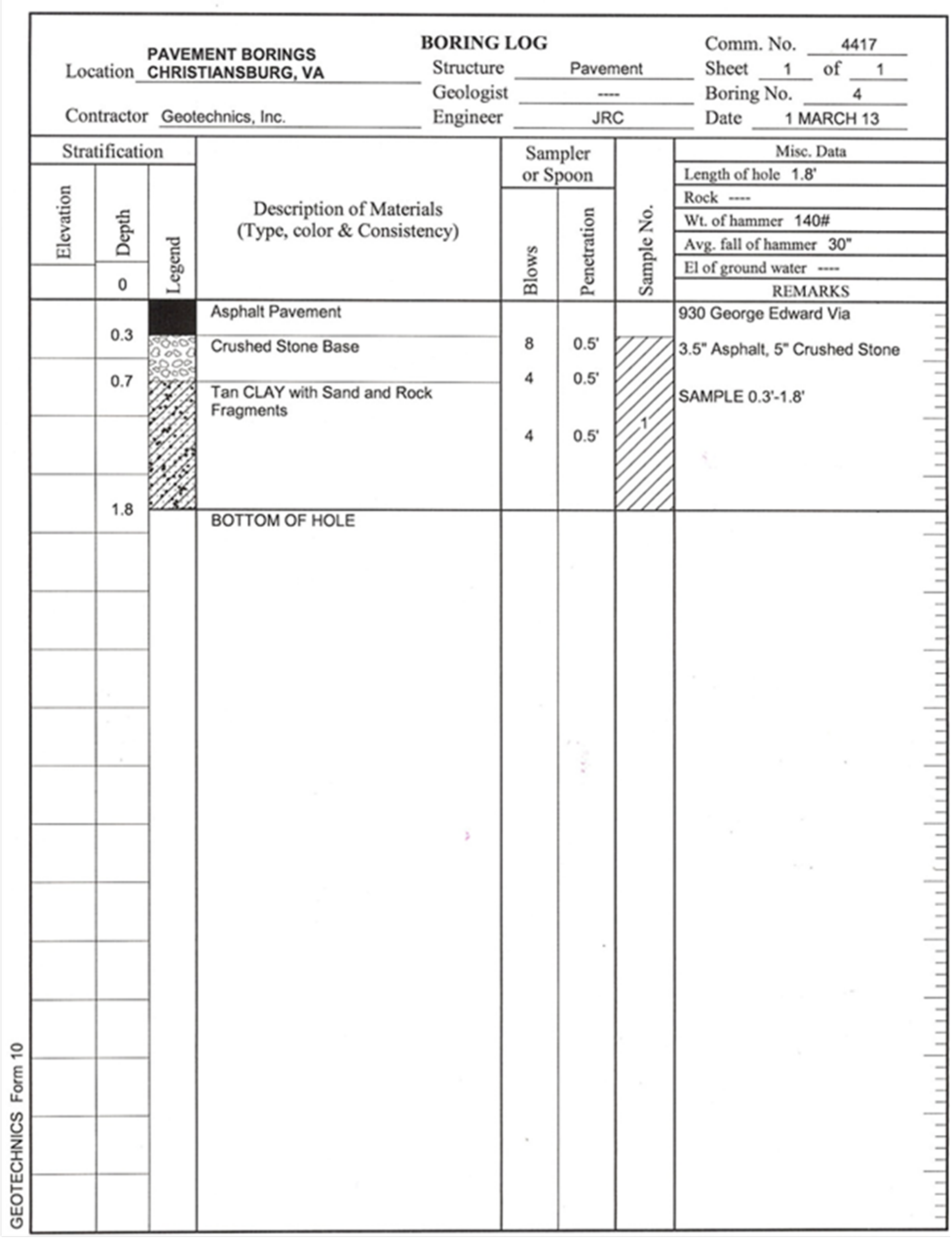
Location PAVEMENT BORINGS CHRISTIANSBURG, VA
Contractor Geotechnics, Inc.
Structure Pavement
Geologist ----
Engineer JRC
Comm. No. 4417
Sheet 1 of 1
Boring No. 3
Date 1 MARCH 13

Misc. Data
Length of hole 1.6'
Rock ----
Wt. of hammer 140#
Avg. fall of hammer 30"
El of ground water ----

Stratification			Description of Materials (Type, color & Consistency)	Sampler or Spoon		Sample No.	REMARKS
Elevation	Depth	Legend		Blows	Penetration		
	0						
	0.1	■	Asphalt Pavement	10	0.5'	1	780 George Edward Via
			Crushed Stone Base				1.5"-1.75" Asphalt, 4.5" Crushed Stone
	0.5		Tan Sandy CLAY with Rock Fragments	4	0.5'		SAMPLE 0.1'-1.6'
				6	0.5'		
	1.6		BOTTOM OF HOLE				

GEOTECHNICS Form 10

Figure 24. Boring Log: George Edward Via – 3, Photo from Todd Walters, 2014, Used with Permission



BORING LOG

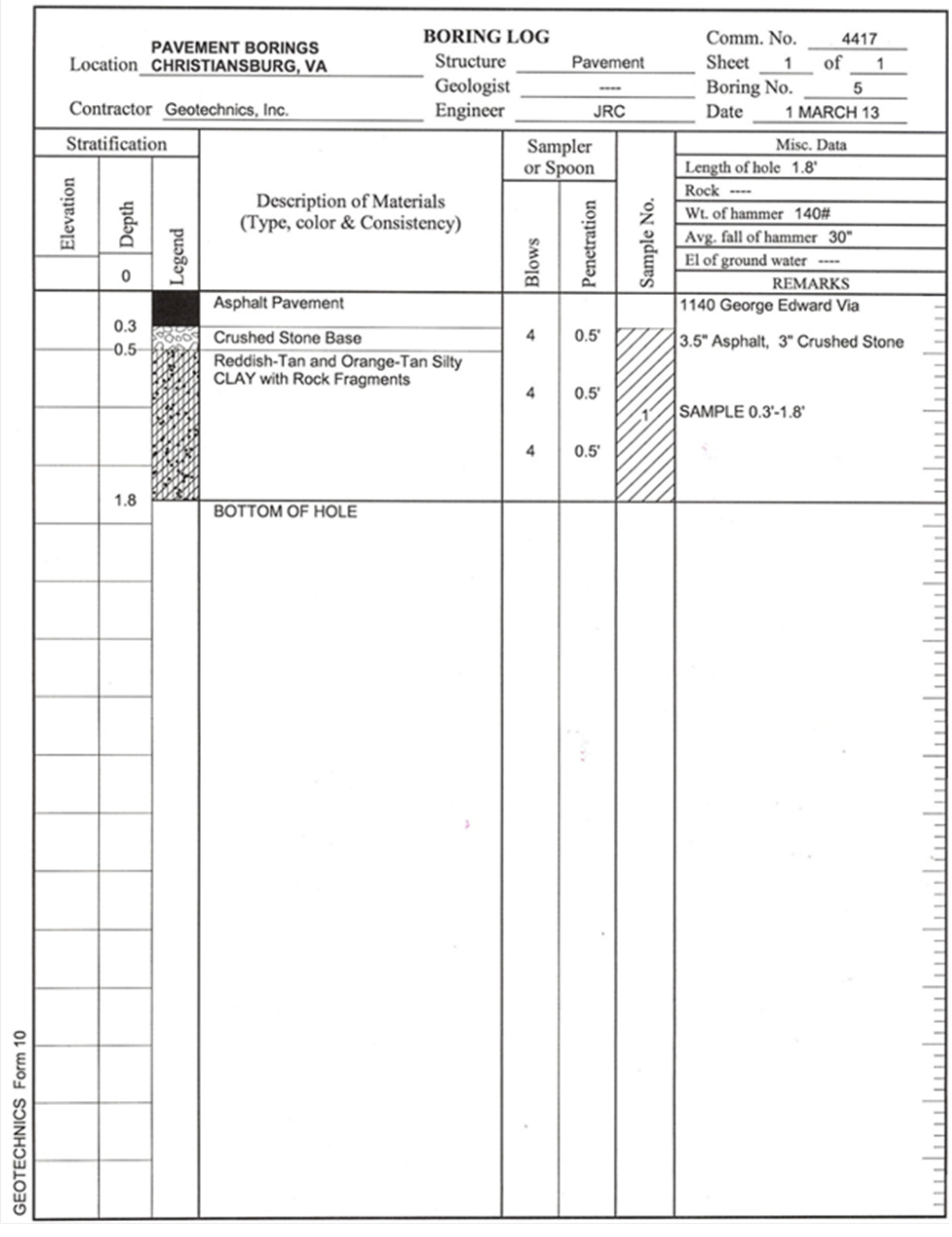
Location PAVEMENT BORINGS CHRISTIANSBURG, VA
Contractor Geotechnics, Inc.
Structure Pavement
Geologist ----
Engineer JRC
Comm. No. 4417
Sheet 1 of 1
Boring No. 4
Date 1 MARCH 13

Misc. Data
Length of hole 1.8'
Rock ----
Wt. of hammer 140#
Avg. fall of hammer 30"
El of ground water ----

Stratification: Elevation	Stratification: Depth	Stratification: Legend	Description of Materials (Type, color & Consistency)	Sampler or Spoon: Blows	Sampler or Spoon: Penetration	Sample No.	REMARKS
	0		Asphalt Pavement				930 George Edward Via
	0.3		Crushed Stone Base	8	0.5'	1	3.5" Asphalt, 5" Crushed Stone
	0.7		Tan CLAY with Sand and Rock Fragments	4 4	0.5' 0.5'		SAMPLE 0.3'-1.8'
	1.8		BOTTOM OF HOLE				

GEOTECHNICS Form 10

Figure 25. Boring Log: George Edward Via – 4, Photo from Todd Walters, 2014, Used with Permission



BORING LOG

Location PAVEMENT BORINGS CHRISTIANSBURG, VA
Contractor Geotechnics, Inc.
Structure Pavement
Geologist ----
Engineer JRC
Comm. No. 4417
Sheet 1 of 1
Boring No. 5
Date 1 MARCH 13

Misc. Data
Length of hole 1.8'
Rock ----
Wt. of hammer 140#
Avg. fall of hammer 30"
El of ground water ----

Stratification			Description of Materials (Type, color & Consistency)	Sampler or Spoon		Sample No.	REMARKS
Elevation	Depth	Legend		Blows	Penetration		
	0						
	0.3	■	Asphalt Pavement				1140 George Edward Via
	0.5		Crushed Stone Base	4	0.5'	1	3.5" Asphalt, 3" Crushed Stone
		▨	Reddish-Tan and Orange-Tan Silty CLAY with Rock Fragments	4	0.5'		SAMPLE 0.3'-1.8'
				4	0.5'		
	1.8		BOTTOM OF HOLE				

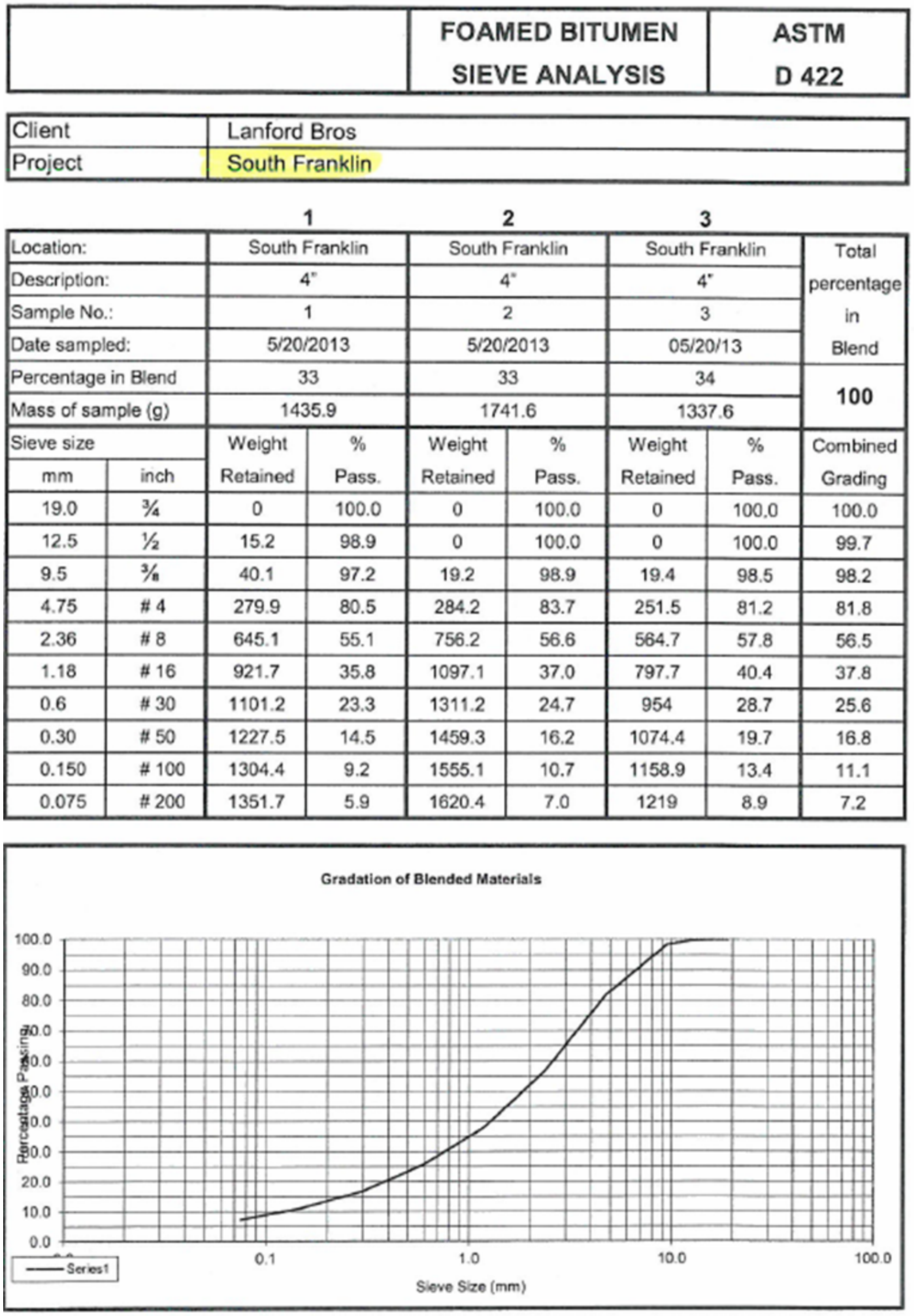
GEOTECHNICS Form 10

Figure 26. Boring Log: George Edward Via – 5, Photo from Todd Walters, 2014, Used with Permission

CHRISTIANSBURG MIX DESIGN

The mix design was available for all recycled sections except for Miller Street.

South Franklin Street

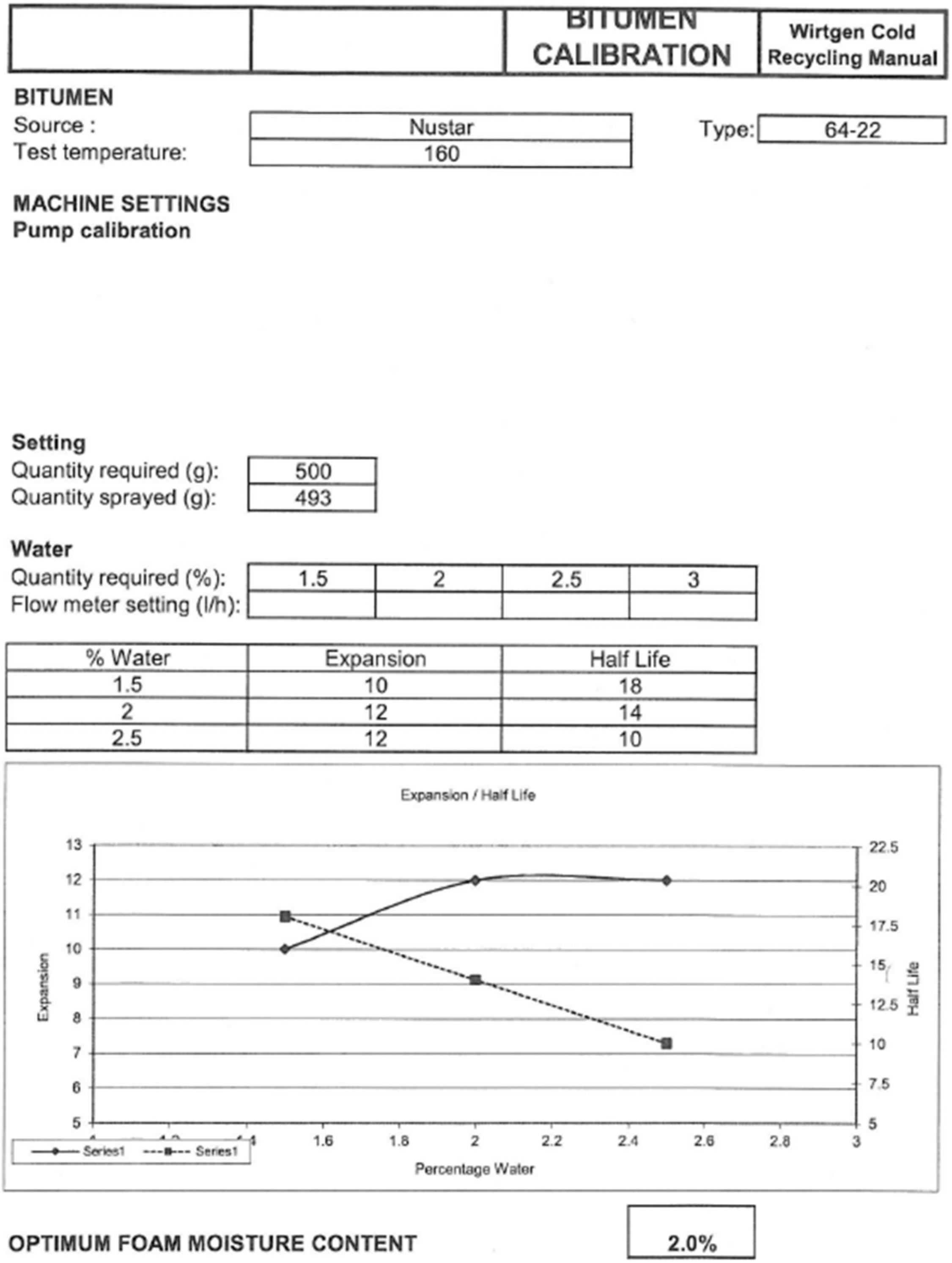


	FOAMED BITUMEN SIEVE ANALYSIS	ASTM D 422

Client	Lanford Bros
Project	South Franklin

		1		2		3		
Location:		South Franklin		South Franklin		South Franklin		Total percentage in Blend
Description:		4"		4"		4"		
Sample No.:		1		2		3		
Date sampled:		5/20/2013		5/20/2013		05/20/13		
Percentage in Blend		33		33		34		100
Mass of sample (g)		1435.9		1741.6		1337.6		
Sieve size		Weight Retained	% Pass.	Weight Retained	% Pass.	Weight Retained	% Pass.	Combined Grading
mm	inch							
19.0	¾	0	100.0	0	100.0	0	100.0	100.0
12.5	½	15.2	98.9	0	100.0	0	100.0	99.7
9.5	⅜	40.1	97.2	19.2	98.9	19.4	98.5	98.2
4.75	# 4	279.9	80.5	284.2	83.7	251.5	81.2	81.8
2.36	# 8	645.1	55.1	756.2	56.6	564.7	57.8	56.5
1.18	# 16	921.7	35.8	1097.1	37.0	797.7	40.4	37.8
0.6	# 30	1101.2	23.3	1311.2	24.7	954	28.7	25.6
0.30	# 50	1227.5	14.5	1459.3	16.2	1074.4	19.7	16.8
0.150	# 100	1304.4	9.2	1555.1	10.7	1158.9	13.4	11.1
0.075	# 200	1351.7	5.9	1620.4	7.0	1219	8.9	7.2

Figure 27. Mix Design: South Franklin Street – 1, Photo from Todd Walters, 2014, Used with Permission



		BITUMEN CALIBRATION	Wirtgen Cold Recycling Manual

BITUMEN

Source :	Nustar	Type:	64-22
Test temperature:	160		

MACHINE SETTINGS
Pump calibration

Setting

Quantity required (g):	500
Quantity sprayed (g):	493

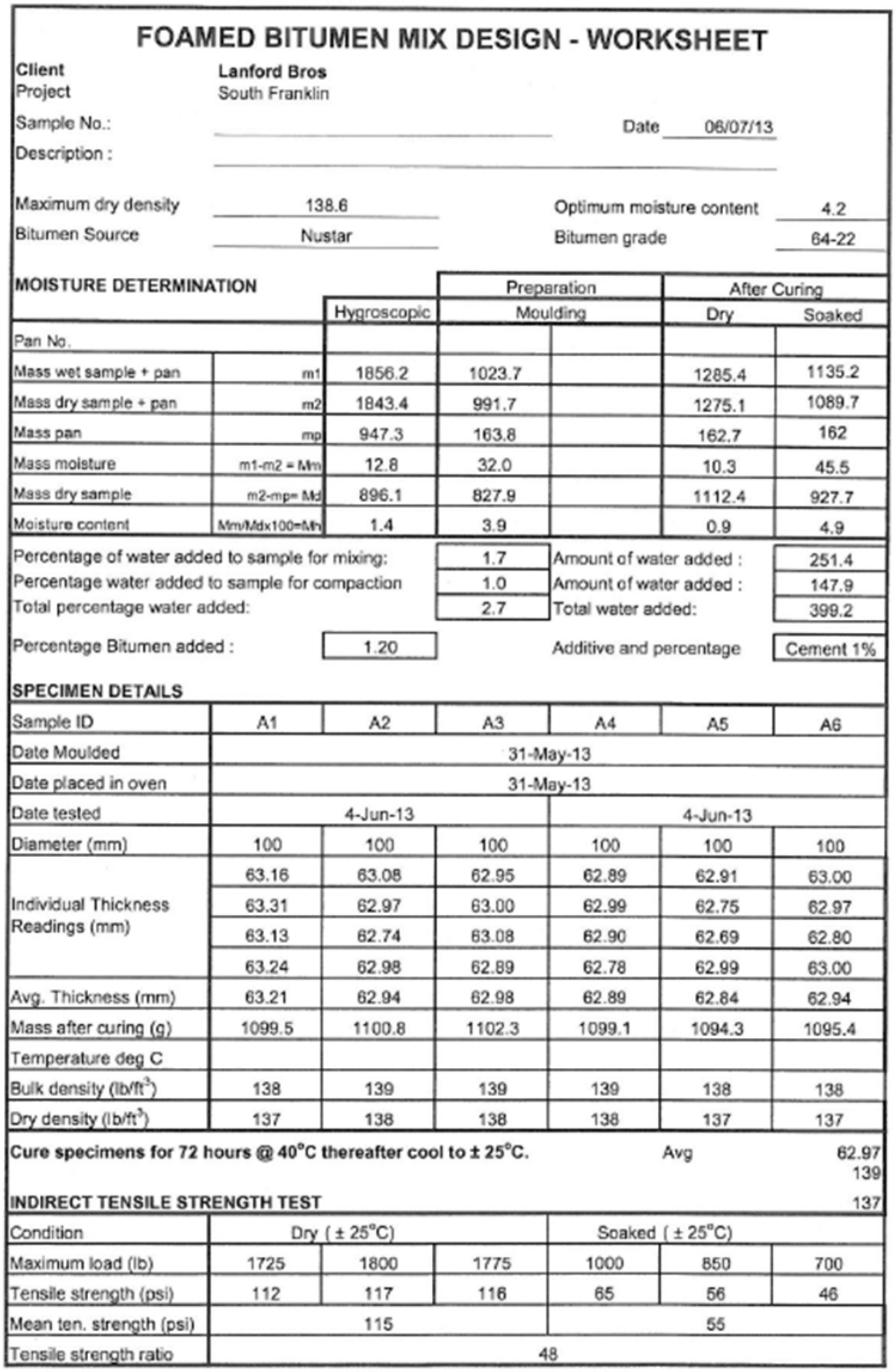
Water

Quantity required (%):	1.5	2	2.5	3
Flow meter setting (l/h):				

% Water	Expansion	Half Life
1.5	10	18
2	12	14
2.5	12	10

OPTIMUM FOAM MOISTURE CONTENT 2.0%

Figure 28. Mix Design: South Franklin Street – 2, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Client **Lanford Bros**
Project South Franklin
Sample No.: ______ Date 06/07/13
Description : ______

Maximum dry density 138.6 Optimum moisture content 4.2
Bitumen Source Nustar Bitumen grade 64-22

MOISTURE DETERMINATION			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	1856.2	1023.7		1285.4	1135.2
Mass dry sample + pan	m2	1843.4	991.7		1275.1	1089.7
Mass pan	mp	947.3	163.8		162.7	162
Mass moisture	m1-m2 = Mm	12.8	32.0		10.3	45.5
Mass dry sample	m2-mp= Md	896.1	827.9		1112.4	927.7
Moisture content	Mm/Mdx100=Mh	1.4	3.9		0.9	4.9

Percentage of water added to sample for mixing:	1.7	Amount of water added :	251.4
Percentage water added to sample for compaction	1.0	Amount of water added :	147.9
Total percentage water added:	2.7	Total water added:	399.2
Percentage Bitumen added :	1.20	Additive and percentage	Cement 1%

SPECIMEN DETAILS

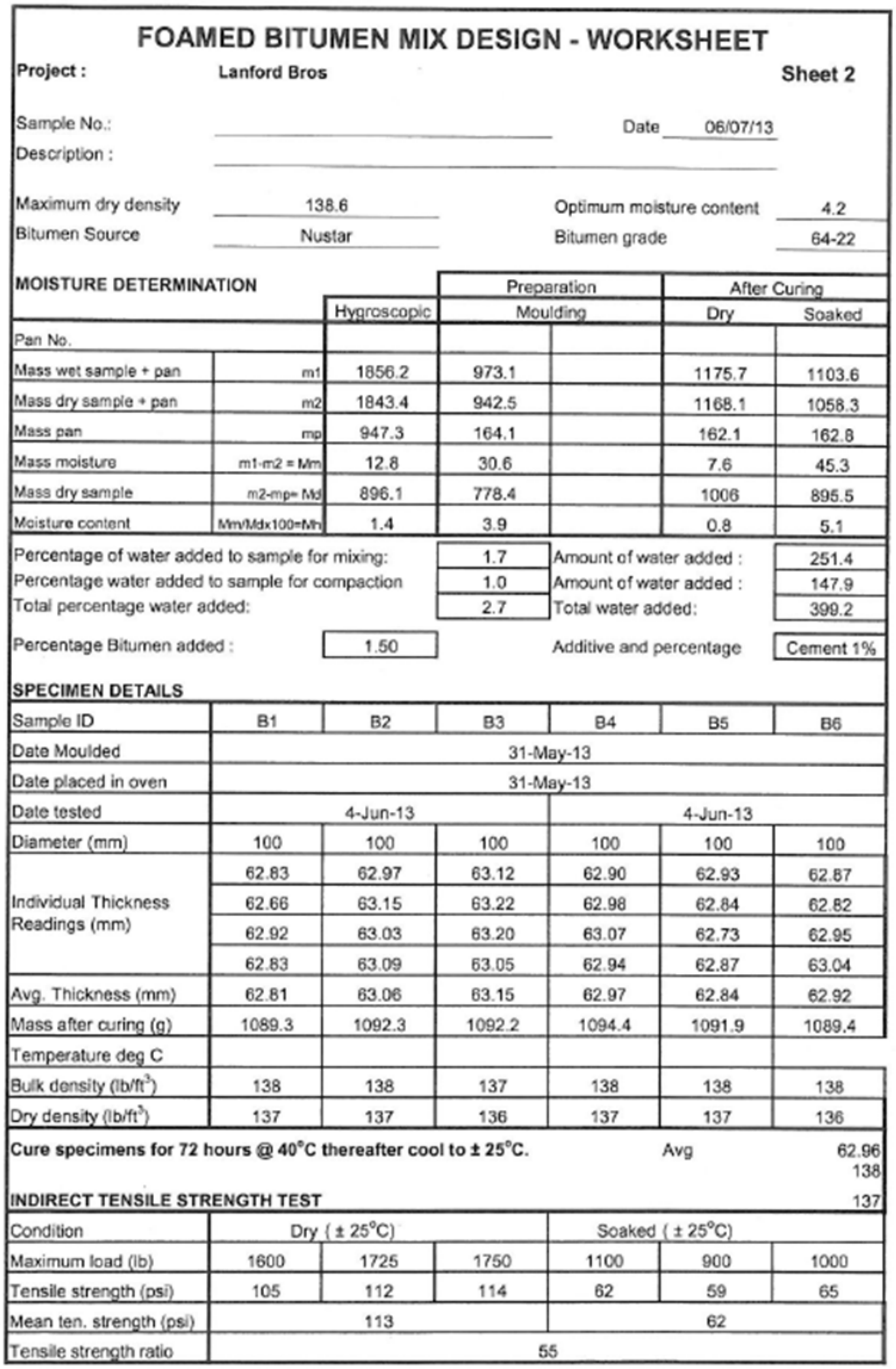
Sample ID	A1	A2	A3	A4	A5	A6
Date Moulded	31-May-13					
Date placed in oven	31-May-13					
Date tested	4-Jun-13			4-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	63.16	63.08	62.95	62.89	62.91	63.00
	63.31	62.97	63.00	62.99	62.75	62.97
	63.13	62.74	63.08	62.90	62.69	62.80
	63.24	62.98	62.89	62.78	62.99	63.00
Avg. Thickness (mm)	63.21	62.94	62.98	62.89	62.84	62.94
Mass after curing (g)	1099.5	1100.8	1102.3	1099.1	1094.3	1095.4
Temperature deg C						
Bulk density (lb/ft^3)	138	139	139	139	138	138
Dry density (lb/ft^3)	137	138	138	138	137	137

Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C. Avg 62.97
139
137

INDIRECT TENSILE STRENGTH TEST

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	1725	1800	1775	1000	850	700
Tensile strength (psi)	112	117	116	65	56	46
Mean ten. strength (psi)	115			55		
Tensile strength ratio	48					

Figure 29. Mix Design: South Franklin Street – 3, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : **Lanford Bros** **Sheet 2**

Sample No.: ______ Date 06/07/13
Description : ______

Maximum dry density 138.6 Optimum moisture content 4.2
Bitumen Source Nustar Bitumen grade 64-22

MOISTURE DETERMINATION			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	1856.2	973.1		1175.7	1103.6
Mass dry sample + pan	m2	1843.4	942.5		1168.1	1058.3
Mass pan	mp	947.3	164.1		162.1	162.8
Mass moisture	m1-m2 = Mm	12.8	30.6		7.6	45.3
Mass dry sample	m2-mp= Md	896.1	778.4		1006	895.5
Moisture content	Mm/Mdx100=Mh	1.4	3.9		0.8	5.1

Percentage of water added to sample for mixing:	1.7	Amount of water added :	251.4
Percentage water added to sample for compaction	1.0	Amount of water added :	147.9
Total percentage water added:	2.7	Total water added:	399.2
Percentage Bitumen added :	1.50	Additive and percentage	Cement 1%

SPECIMEN DETAILS

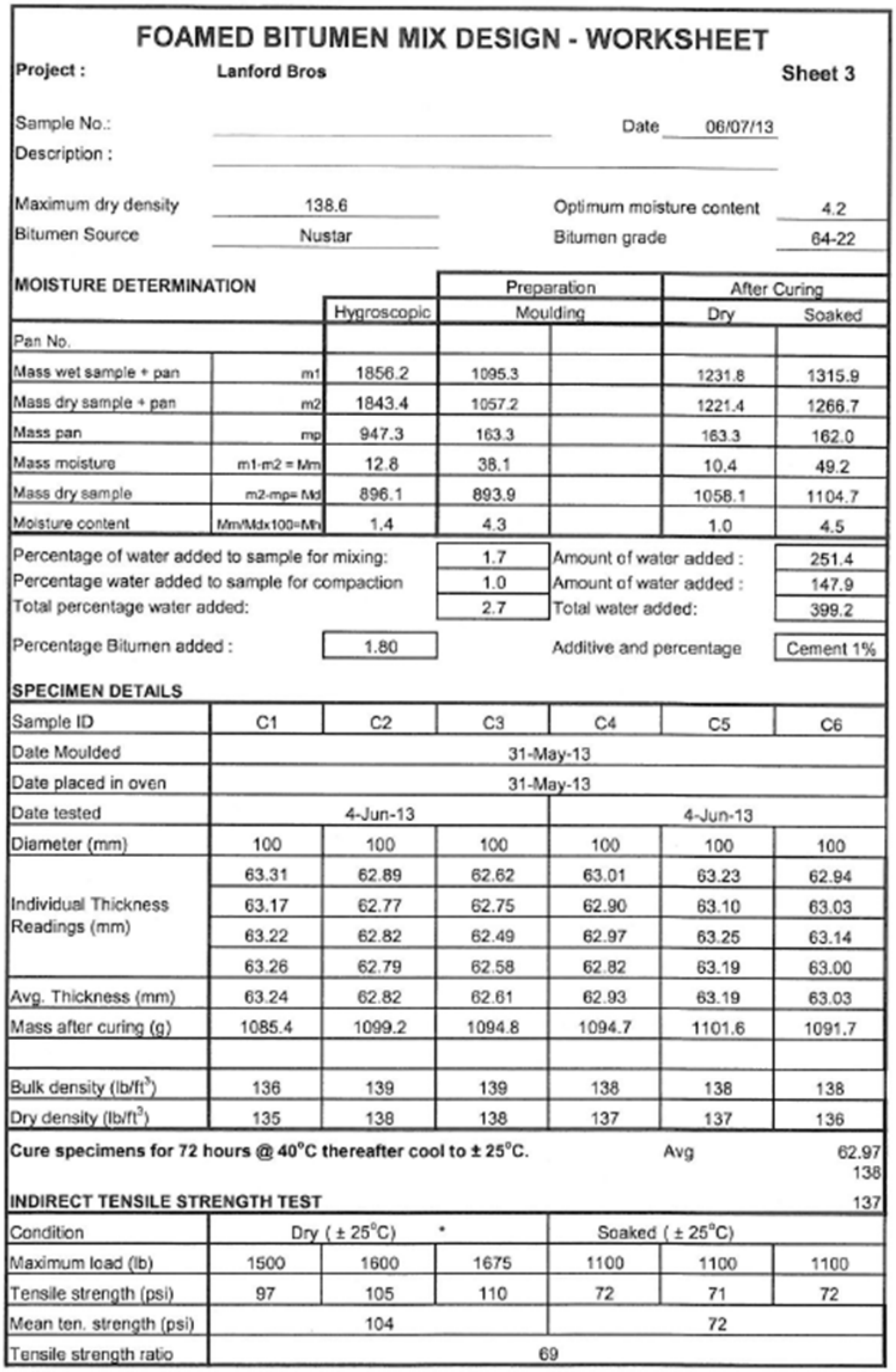
Sample ID	B1	B2	B3	B4	B5	B6
Date Moulded	31-May-13					
Date placed in oven	31-May-13					
Date tested	4-Jun-13			4-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	62.83	62.97	63.12	62.90	62.93	62.87
	62.66	63.15	63.22	62.98	62.84	62.82
	62.92	63.03	63.20	63.07	62.73	62.95
	62.83	63.09	63.05	62.94	62.87	63.04
Avg. Thickness (mm)	62.81	63.06	63.15	62.97	62.84	62.92
Mass after curing (g)	1089.3	1092.3	1092.2	1094.4	1091.9	1089.4
Temperature deg C						
Bulk density (lb/ft^3)	138	138	137	138	138	138
Dry density (lb/ft^3)	137	137	136	137	137	136

Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C. Avg 62.96
138

INDIRECT TENSILE STRENGTH TEST 137

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	1600	1725	1750	1100	900	1000
Tensile strength (psi)	105	112	114	62	59	65
Mean ten. strength (psi)	113			62		
Tensile strength ratio	55					

Figure 30. Mix Design: South Franklin Street – 4, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : **Lanford Bros** **Sheet 3**

Sample No.: ______________ Date 06/07/13
Description : ______________

Maximum dry density 138.6 Optimum moisture content 4.2
Bitumen Source Nustar Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	1856.2	1095.3		1231.8	1315.9
Mass dry sample + pan	m2	1843.4	1057.2		1221.4	1266.7
Mass pan	mp	947.3	163.3		163.3	162.0
Mass moisture	m1-m2 = Mm	12.8	38.1		10.4	49.2
Mass dry sample	m2-mp= Md	896.1	893.9		1058.1	1104.7
Moisture content	Mm/Mdx100=Mh	1.4	4.3		1.0	4.5

Percentage of water added to sample for mixing:	1.7	Amount of water added :	251.4
Percentage water added to sample for compaction	1.0	Amount of water added :	147.9
Total percentage water added:	2.7	Total water added:	399.2
Percentage Bitumen added :	1.80	Additive and percentage	Cement 1%

SPECIMEN DETAILS

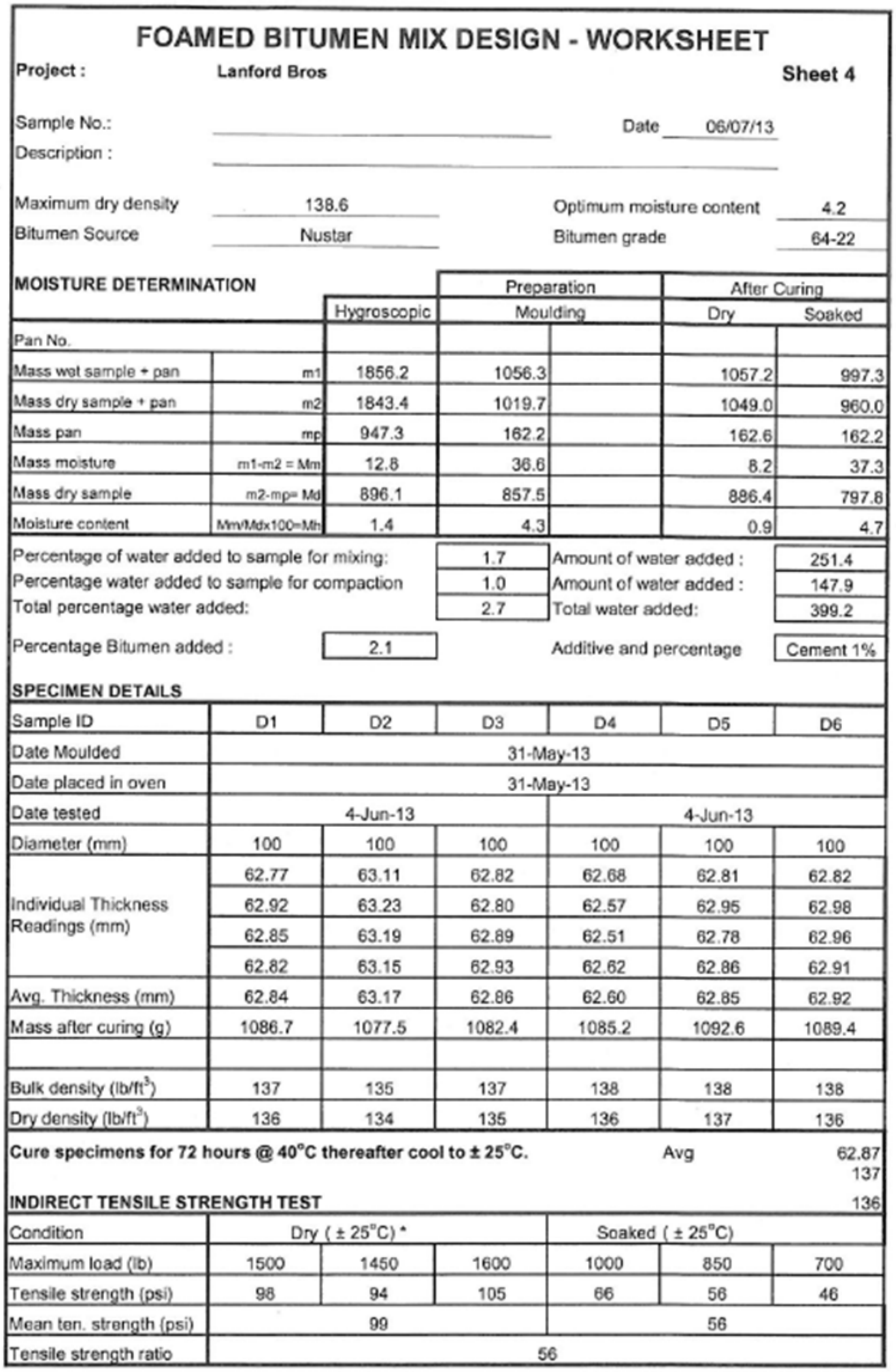
Sample ID	C1	C2	C3	C4	C5	C6
Date Moulded	31-May-13					
Date placed in oven	31-May-13					
Date tested	4-Jun-13			4-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	63.31	62.89	62.62	63.01	63.23	62.94
	63.17	62.77	62.75	62.90	63.10	63.03
	63.22	62.82	62.49	62.97	63.25	63.14
	63.26	62.79	62.58	62.82	63.19	63.00
Avg. Thickness (mm)	63.24	62.82	62.61	62.93	63.19	63.03
Mass after curing (g)	1085.4	1099.2	1094.8	1094.7	1101.6	1091.7
Bulk density (lb/ft^3)	136	139	139	138	138	138
Dry density (lb/ft^3)	135	138	138	137	137	136

Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C. Avg 62.97
138

INDIRECT TENSILE STRENGTH TEST 137

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	1500	1600	1675	1100	1100	1100
Tensile strength (psi)	97	105	110	72	71	72
Mean ten. strength (psi)	104			72		
Tensile strength ratio	69					

Figure 31. Mix Design: South Franklin Street – 5, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : **Lanford Bros** **Sheet 4**

Sample No.: ____________ Date 06/07/13

Description : ____________

Maximum dry density 138.6 Optimum moisture content 4.2

Bitumen Source Nustar Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	1856.2	1056.3		1057.2	997.3
Mass dry sample + pan	m2	1843.4	1019.7		1049.0	960.0
Mass pan	mp	947.3	162.2		162.6	162.2
Mass moisture	m1-m2 = Mm	12.8	36.6		8.2	37.3
Mass dry sample	m2-mp= Md	896.1	857.5		886.4	797.8
Moisture content	Mm/Mdx100=Mh	1.4	4.3		0.9	4.7

Percentage of water added to sample for mixing:	1.7	Amount of water added :	251.4
Percentage water added to sample for compaction	1.0	Amount of water added :	147.9
Total percentage water added:	2.7	Total water added:	399.2
Percentage Bitumen added :	2.1	Additive and percentage	Cement 1%

SPECIMEN DETAILS

Sample ID	D1	D2	D3	D4	D5	D6
Date Moulded	31-May-13					
Date placed in oven	31-May-13					
Date tested	4-Jun-13			4-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	62.77	63.11	62.82	62.68	62.81	62.82
	62.92	63.23	62.80	62.57	62.95	62.98
	62.85	63.19	62.89	62.51	62.78	62.96
	62.82	63.15	62.93	62.62	62.86	62.91
Avg. Thickness (mm)	62.84	63.17	62.86	62.60	62.85	62.92
Mass after curing (g)	1086.7	1077.5	1082.4	1085.2	1092.6	1089.4
Bulk density (lb/ft^3)	137	135	137	138	138	138
Dry density (lb/ft^3)	136	134	135	136	137	136

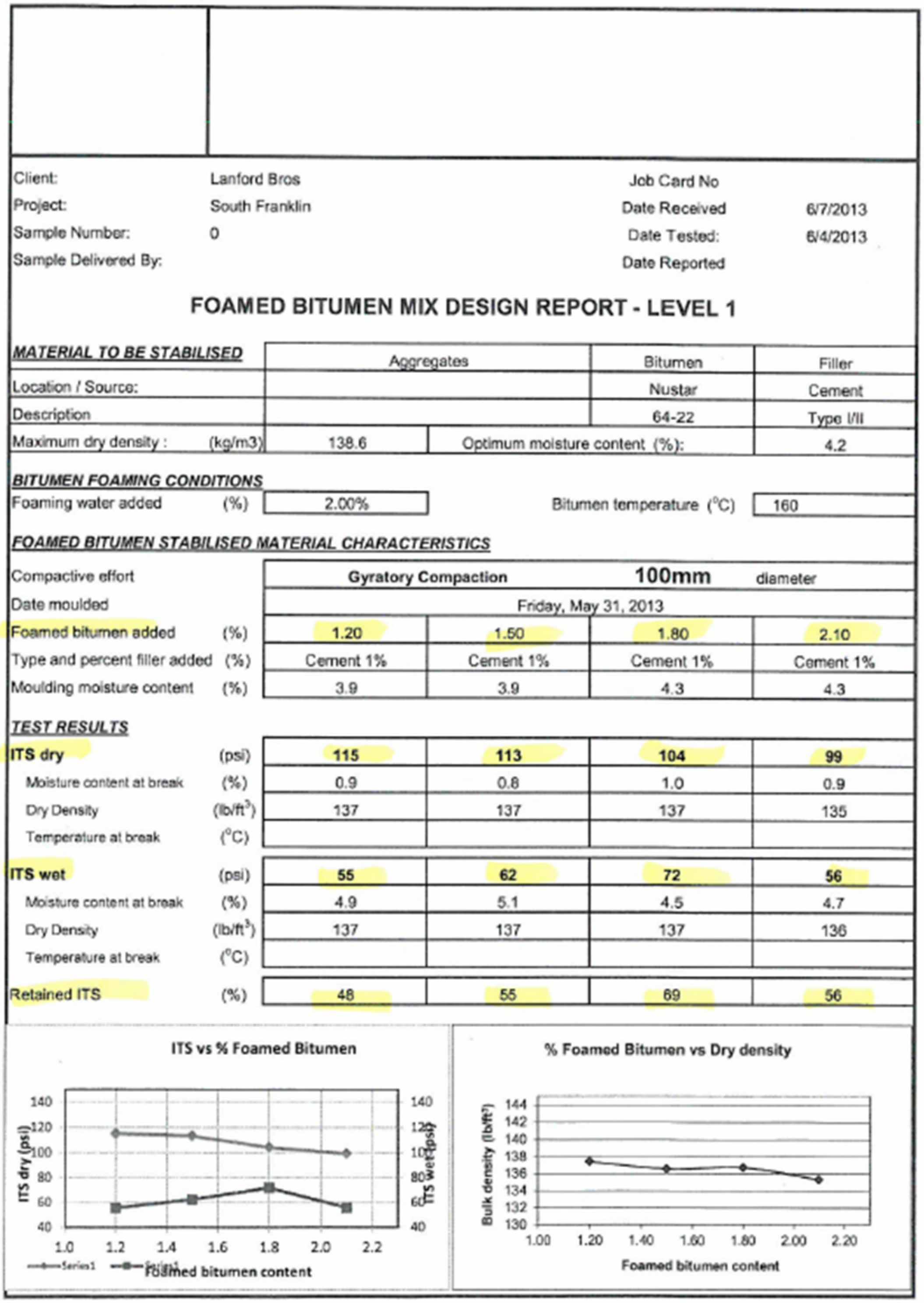
Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C. Avg 62.87

137

INDIRECT TENSILE STRENGTH TEST 136

Condition	Dry (± 25°C) *			Soaked (± 25°C)		
Maximum load (lb)	1500	1450	1600	1000	850	700
Tensile strength (psi)	98	94	105	66	56	46
Mean ten. strength (psi)	99			56		
Tensile strength ratio	56					

Figure 32. Mix Design: South Franklin Street – 6, Photo from Todd Walters, 2014, Used with Permission



Client:	Lanford Bros	Job Card No	
Project:	South Franklin	Date Received	6/7/2013
Sample Number:	0	Date Tested:	6/4/2013
Sample Delivered By:		Date Reported	

FOAMED BITUMEN MIX DESIGN REPORT - LEVEL 1

MATERIAL TO BE STABILISED	Aggregates		Bitumen	Filler
Location / Source:			Nustar	Cement
Description			64-22	Type I/II
Maximum dry density : (kg/m3)	138.6	Optimum moisture content (%):		4.2

BITUMEN FOAMING CONDITIONS

Foaming water added (%)	2.00%	Bitumen temperature (°C)	160

FOAMED BITUMEN STABILISED MATERIAL CHARACTERISTICS

Compactive effort	**Gyratory Compaction**		**100mm**	diameter
Date moulded	Friday, May 31, 2013			
Foamed bitumen added (%)	1.20	1.50	1.80	2.10
Type and percent filler added (%)	Cement 1%	Cement 1%	Cement 1%	Cement 1%
Moulding moisture content (%)	3.9	3.9	4.3	4.3

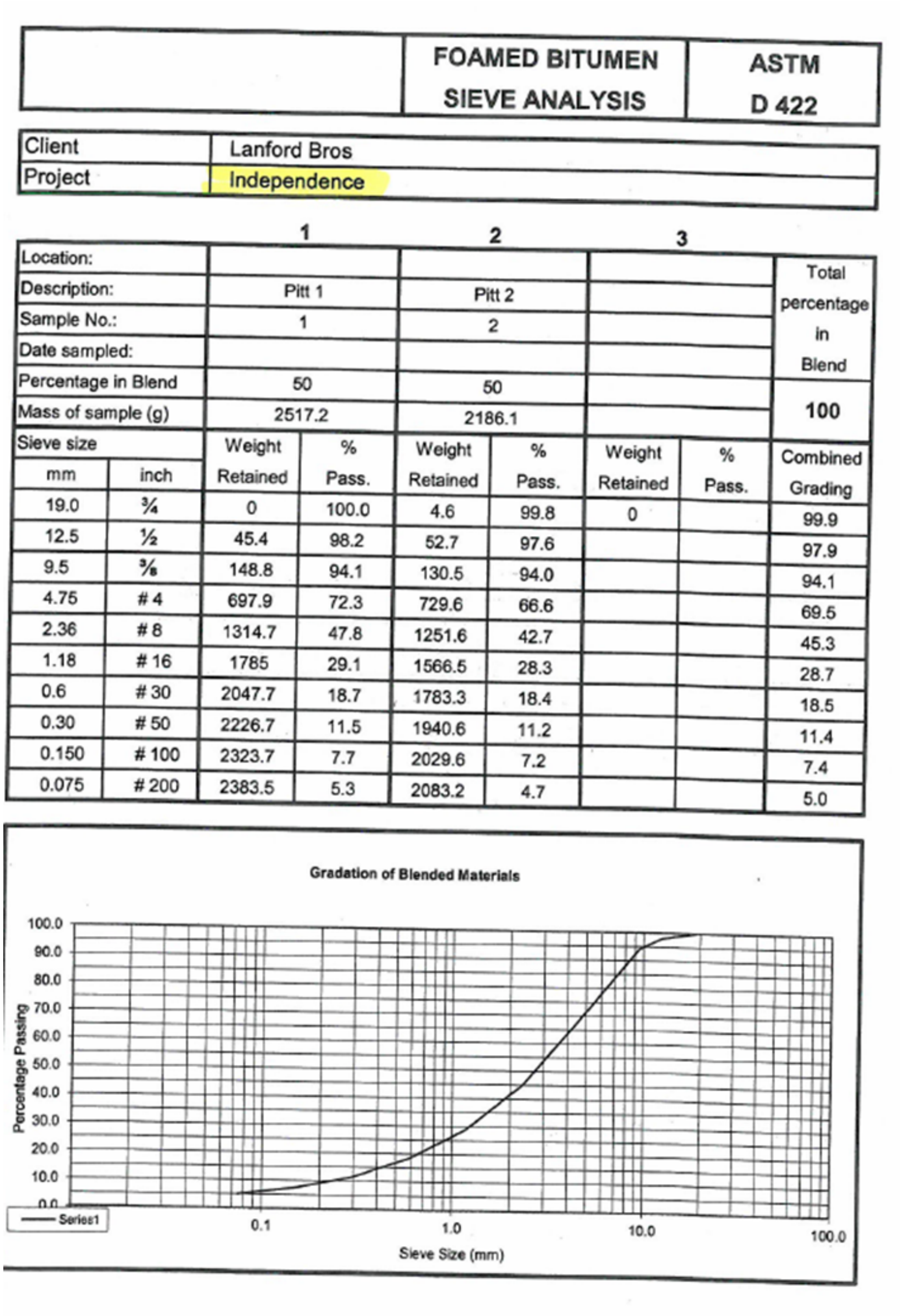
TEST RESULTS

ITS dry (psi)	**115**	**113**	**104**	**99**
Moisture content at break (%)	0.9	0.8	1.0	0.9
Dry Density (lb/ft^3)	137	137	137	135
Temperature at break (°C)				
ITS wet (psi)	**55**	**62**	**72**	**56**
Moisture content at break (%)	4.9	5.1	4.5	4.7
Dry Density (lb/ft^3)	137	137	137	136
Temperature at break (°C)				
Retained ITS (%)	48	55	69	56

Figure 33. Mix Design: South Franklin Street – 7, Photo from Todd Walters, 2014, Used with Permission

Independence Boulevard

Note that Reclamation tested the same material again after the first test did not pass.



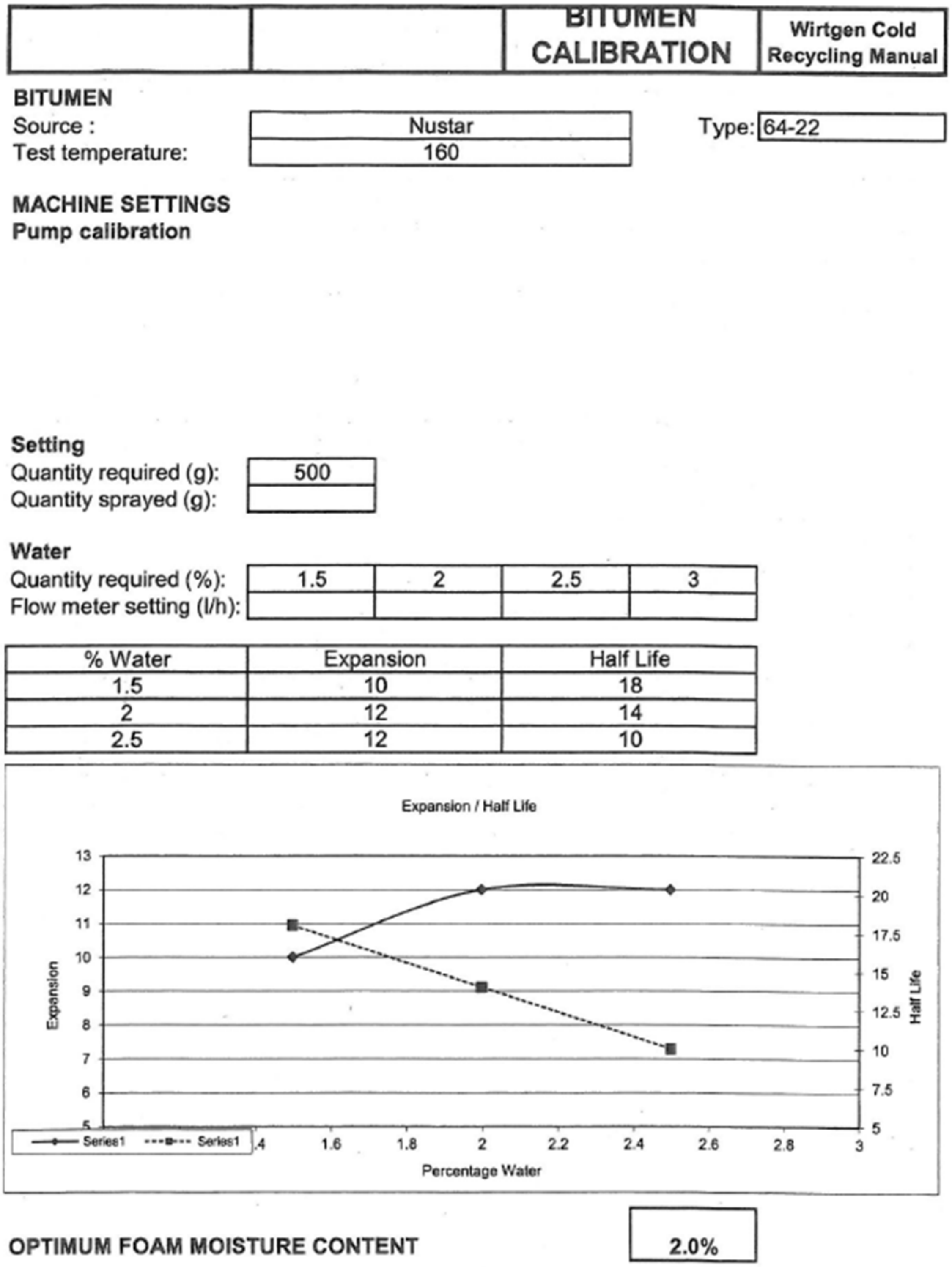
	FOAMED BITUMEN SIEVE ANALYSIS	ASTM D 422

Client	Lanford Bros
Project	Independence

	1	2	3	Total percentage in Blend
Location:				
Description:	Pitt 1	Pitt 2		
Sample No.:	1	2		
Date sampled:				
Percentage in Blend	50	50		
Mass of sample (g)	2517.2	2186.1		100

Sieve size		1		2		3		
mm	inch	Weight Retained	% Pass.	Weight Retained	% Pass.	Weight Retained	% Pass.	Combined Grading
19.0	¾	0	100.0	4.6	99.8	0		99.9
12.5	½	45.4	98.2	52.7	97.6			97.9
9.5	⅜	148.8	94.1	130.5	94.0			94.1
4.75	# 4	697.9	72.3	729.6	66.6			69.5
2.36	# 8	1314.7	47.8	1251.6	42.7			45.3
1.18	# 16	1785	29.1	1566.5	28.3			28.7
0.6	# 30	2047.7	18.7	1783.3	18.4			18.5
0.30	# 50	2226.7	11.5	1940.6	11.2			11.4
0.150	# 100	2323.7	7.7	2029.6	7.2			7.4
0.075	# 200	2383.5	5.3	2083.2	4.7			5.0

Figure 34. Mix Design: Independence Boulevard – 1, Photo from Todd Walters, 2014, Used with Permission



		BITUMEN CALIBRATION	**Wirtgen Cold Recycling Manual**

BITUMEN

Source :	Nustar	Type:	64-22
Test temperature:	160		

MACHINE SETTINGS

Pump calibration

Setting

Quantity required (g):	500
Quantity sprayed (g):	

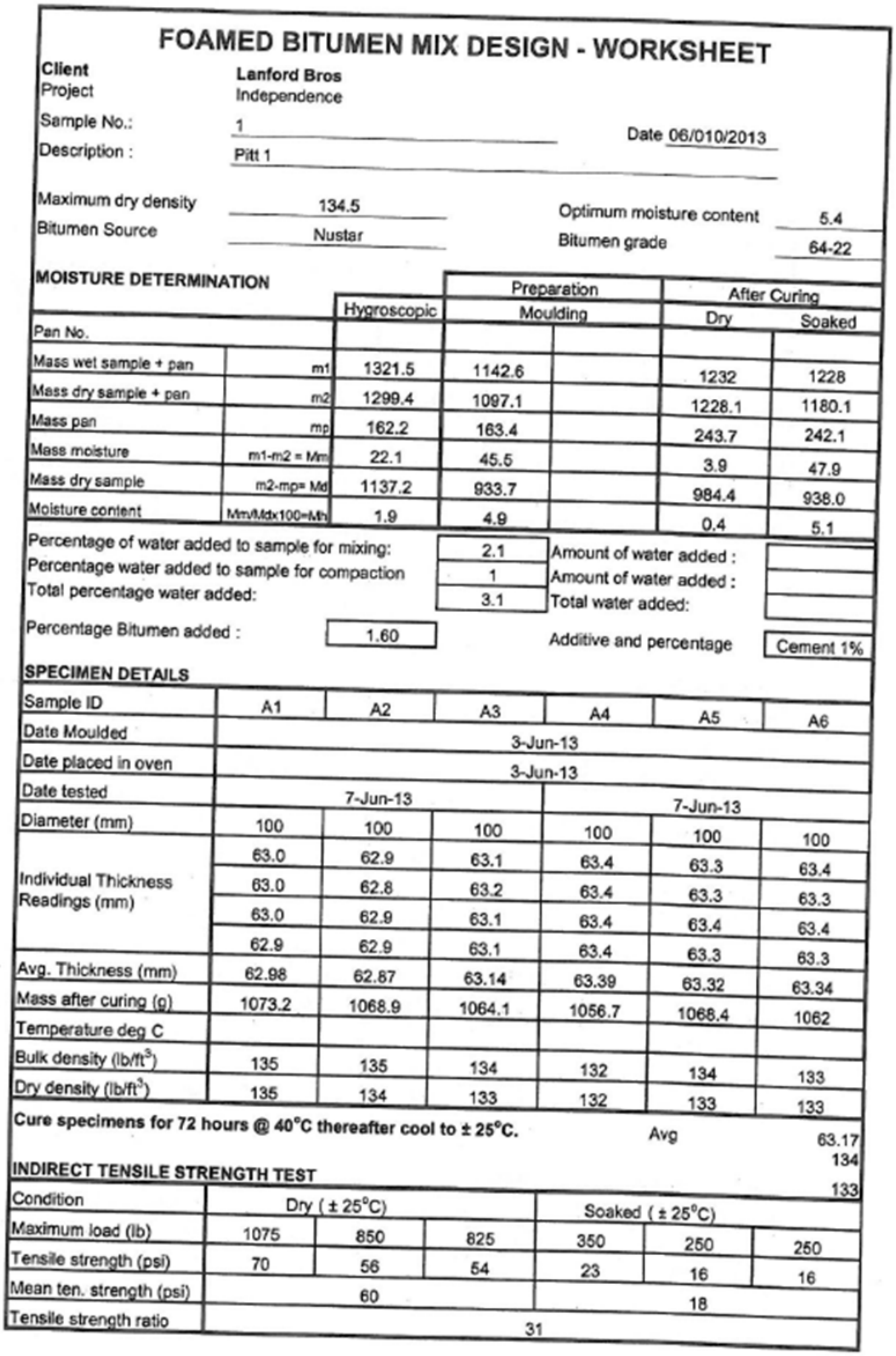
Water

Quantity required (%):	1.5	2	2.5	3
Flow meter setting (l/h):				

% Water	Expansion	Half Life
1.5	10	18
2	12	14
2.5	12	10

OPTIMUM FOAM MOISTURE CONTENT 2.0%

Figure 35. Mix Design: Independence Boulevard – 2, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Client **Lanford Bros**
Project Independence
Sample No.: 1
Date 06/010/2013
Description : Pitt 1

Maximum dry density 134.5
Bitumen Source Nustar
Optimum moisture content 5.4
Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	1321.5	1142.6		1232	1228
Mass dry sample + pan	m2	1299.4	1097.1		1228.1	1180.1
Mass pan	mp	162.2	163.4		243.7	242.1
Mass moisture	m1-m2 = Mm	22.1	45.5		3.9	47.9
Mass dry sample	m2-mp= Md	1137.2	933.7		984.4	938.0
Moisture content	Mm/Mdx100=Mh	1.9	4.9		0.4	5.1

Percentage of water added to sample for mixing:	2.1	Amount of water added :	
Percentage water added to sample for compaction	1	Amount of water added :	
Total percentage water added:	3.1	Total water added:	
Percentage Bitumen added :	1.60	Additive and percentage	Cement 1%

SPECIMEN DETAILS

Sample ID	A1	A2	A3	A4	A5	A6
Date Moulded	3-Jun-13					
Date placed in oven	3-Jun-13					
Date tested	7-Jun-13			7-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	63.0	62.9	63.1	63.4	63.3	63.4
	63.0	62.8	63.2	63.4	63.3	63.3
	63.0	62.9	63.1	63.4	63.4	63.4
	62.9	62.9	63.1	63.4	63.3	63.3
Avg. Thickness (mm)	62.98	62.87	63.14	63.39	63.32	63.34
Mass after curing (g)	1073.2	1068.9	1064.1	1056.7	1068.4	1062
Temperature deg C						
Bulk density (lb/ft^3)	135	135	134	132	134	133
Dry density (lb/ft^3)	135	134	133	132	133	133

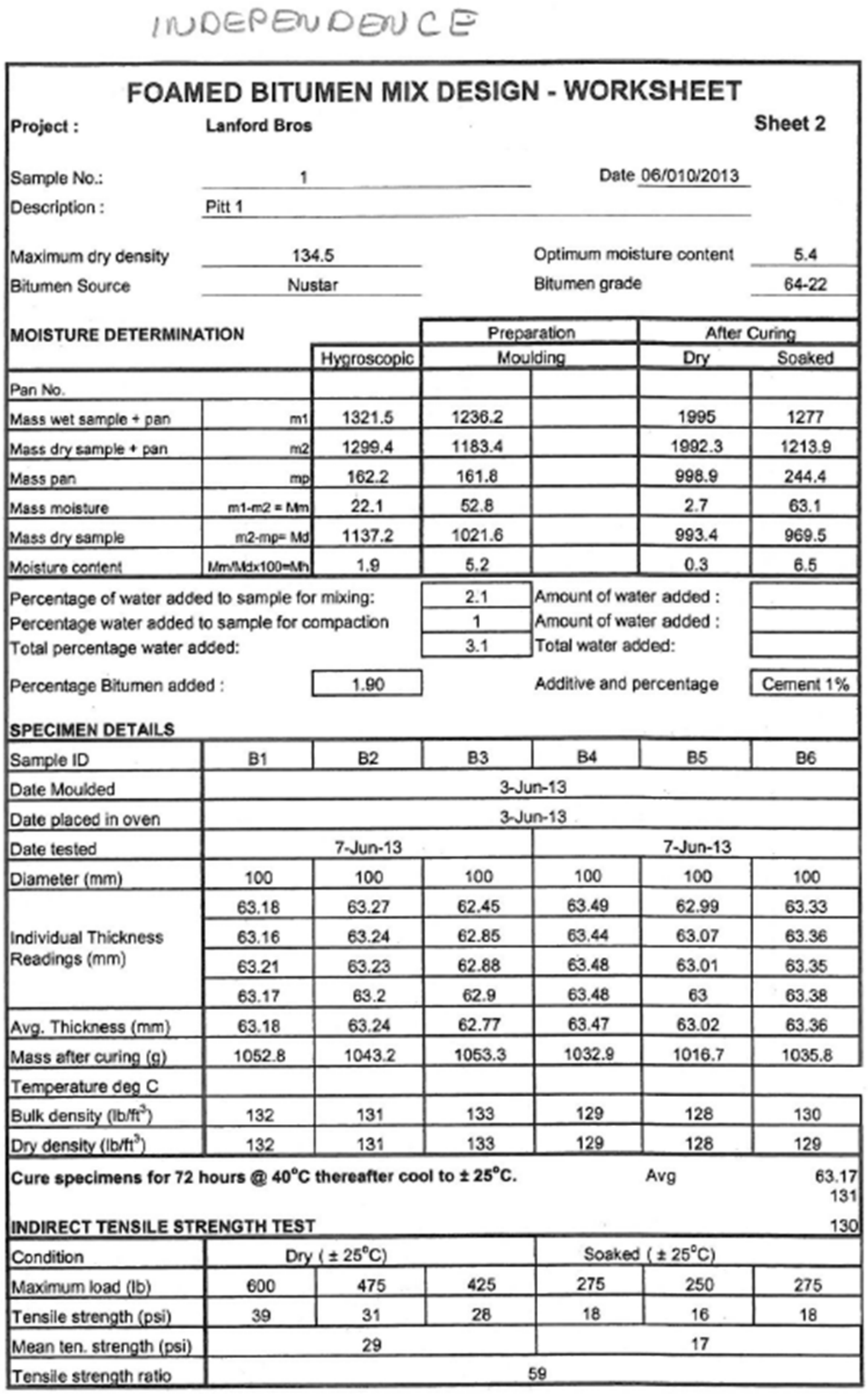
Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C.

Avg 63.17
134
133

INDIRECT TENSILE STRENGTH TEST

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	1075	850	825	350	250	250
Tensile strength (psi)	70	56	54	23	16	16
Mean ten. strength (psi)	60			18		
Tensile strength ratio	31					

Figure 36. Mix Design: Independence Boulevard – 3, Photo from Todd Walters, 2014, Used with Permission



INDEPENDENCE

FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : **Lanford Bros** **Sheet 2**

Sample No.: 1 Date 06/010/2013
Description : Pitt 1

Maximum dry density 134.5 Optimum moisture content 5.4
Bitumen Source Nustar Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	1321.5	1236.2		1995	1277
Mass dry sample + pan	m2	1299.4	1183.4		1992.3	1213.9
Mass pan	mp	162.2	161.8		998.9	244.4
Mass moisture	m1-m2 = Mm	22.1	52.8		2.7	63.1
Mass dry sample	m2-mp= Md	1137.2	1021.6		993.4	969.5
Moisture content	Mm/Mdx100=Mh	1.9	5.2		0.3	6.5

Percentage of water added to sample for mixing:	2.1	Amount of water added :	
Percentage water added to sample for compaction	1	Amount of water added :	
Total percentage water added:	3.1	Total water added:	
Percentage Bitumen added :	1.90	Additive and percentage	Cement 1%

SPECIMEN DETAILS

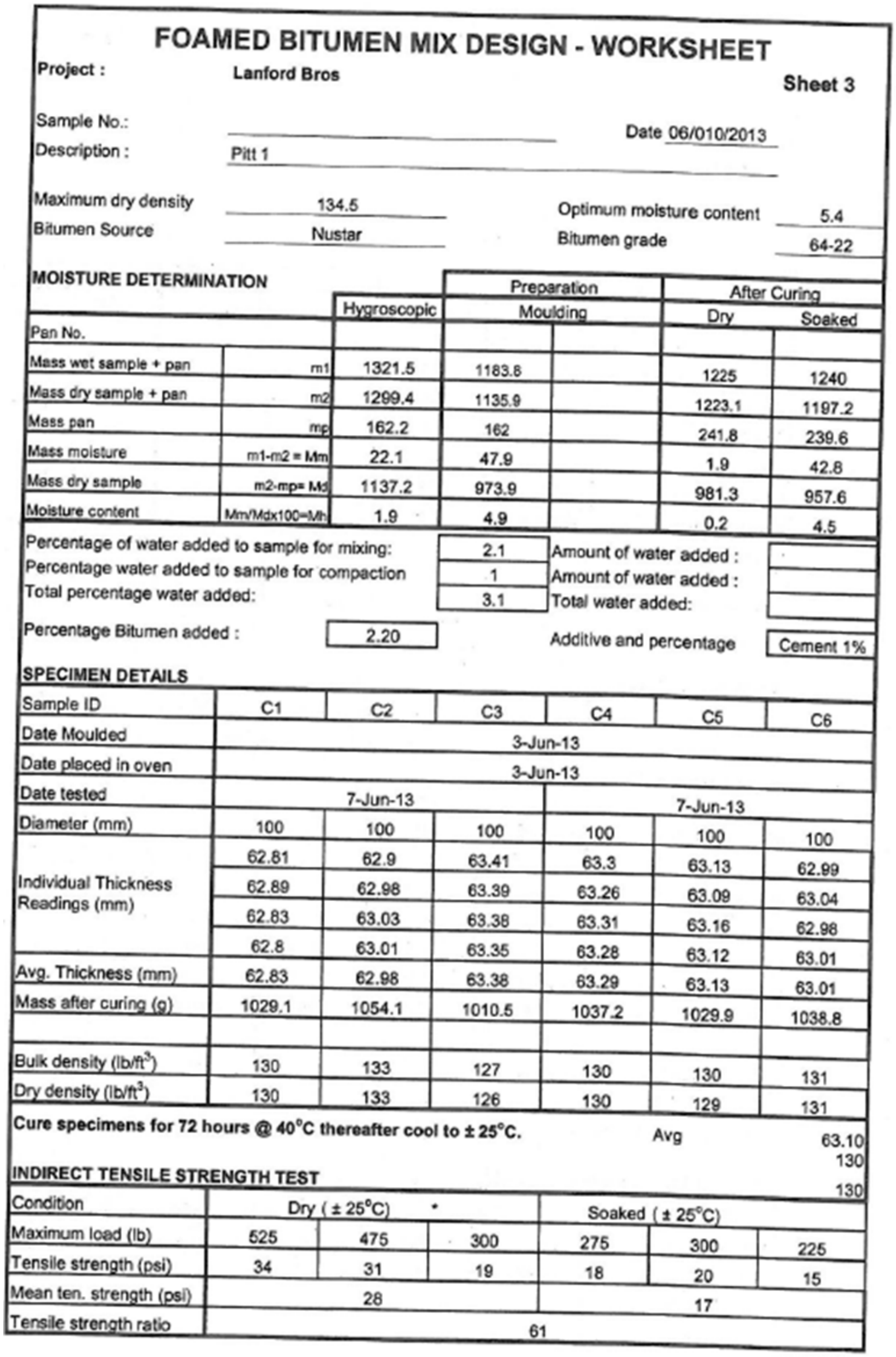
Sample ID	B1	B2	B3	B4	B5	B6
Date Moulded	3-Jun-13					
Date placed in oven	3-Jun-13					
Date tested	7-Jun-13			7-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	63.18	63.27	62.45	63.49	62.99	63.33
	63.16	63.24	62.85	63.44	63.07	63.36
	63.21	63.23	62.88	63.48	63.01	63.35
	63.17	63.2	62.9	63.48	63	63.38
Avg. Thickness (mm)	63.18	63.24	62.77	63.47	63.02	63.36
Mass after curing (g)	1052.8	1043.2	1053.3	1032.9	1016.7	1035.8
Temperature deg C						
Bulk density (lb/ft^3)	132	131	133	129	128	130
Dry density (lb/ft^3)	132	131	133	129	128	129

Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C. Avg 63.17
131

INDIRECT TENSILE STRENGTH TEST 130

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	600	475	425	275	250	275
Tensile strength (psi)	39	31	28	18	16	18
Mean ten. strength (psi)	29			17		
Tensile strength ratio	59					

Figure 37. Mix Design: Independence Boulevard – 4, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : **Lanford Bros** **Sheet 3**

Sample No.:

Date 06/010/2013

Description : Pitt 1

Maximum dry density 134.5

Optimum moisture content 5.4

Bitumen Source Nustar

Bitumen grade 64-22

MOISTURE DETERMINATION

		Hygroscopic	Preparation Moulding		After Curing Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	1321.5	1183.8		1225	1240
Mass dry sample + pan	m2	1299.4	1135.9		1223.1	1197.2
Mass pan	mp	162.2	162		241.8	239.6
Mass moisture	m1-m2 = Mm	22.1	47.9		1.9	42.8
Mass dry sample	m2-mp= Md	1137.2	973.9		981.3	957.6
Moisture content	Mm/Mdx100=Mh	1.9	4.9		0.2	4.5

Percentage of water added to sample for mixing: 2.1

Percentage water added to sample for compaction 1

Total percentage water added: 3.1

Amount of water added :

Amount of water added :

Total water added:

Percentage Bitumen added : 2.20

Additive and percentage Cement 1%

SPECIMEN DETAILS

Sample ID	C1	C2	C3	C4	C5	C6
Date Moulded	3-Jun-13					
Date placed in oven	3-Jun-13					
Date tested	7-Jun-13			7-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	62.81	62.9	63.41	63.3	63.13	62.99
	62.89	62.98	63.39	63.26	63.09	63.04
	62.83	63.03	63.38	63.31	63.16	62.98
	62.8	63.01	63.35	63.28	63.12	63.01
Avg. Thickness (mm)	62.83	62.98	63.38	63.29	63.13	63.01
Mass after curing (g)	1029.1	1054.1	1010.5	1037.2	1029.9	1038.8
Bulk density (lb/ft^3)	130	133	127	130	130	131
Dry density (lb/ft^3)	130	133	126	130	129	131

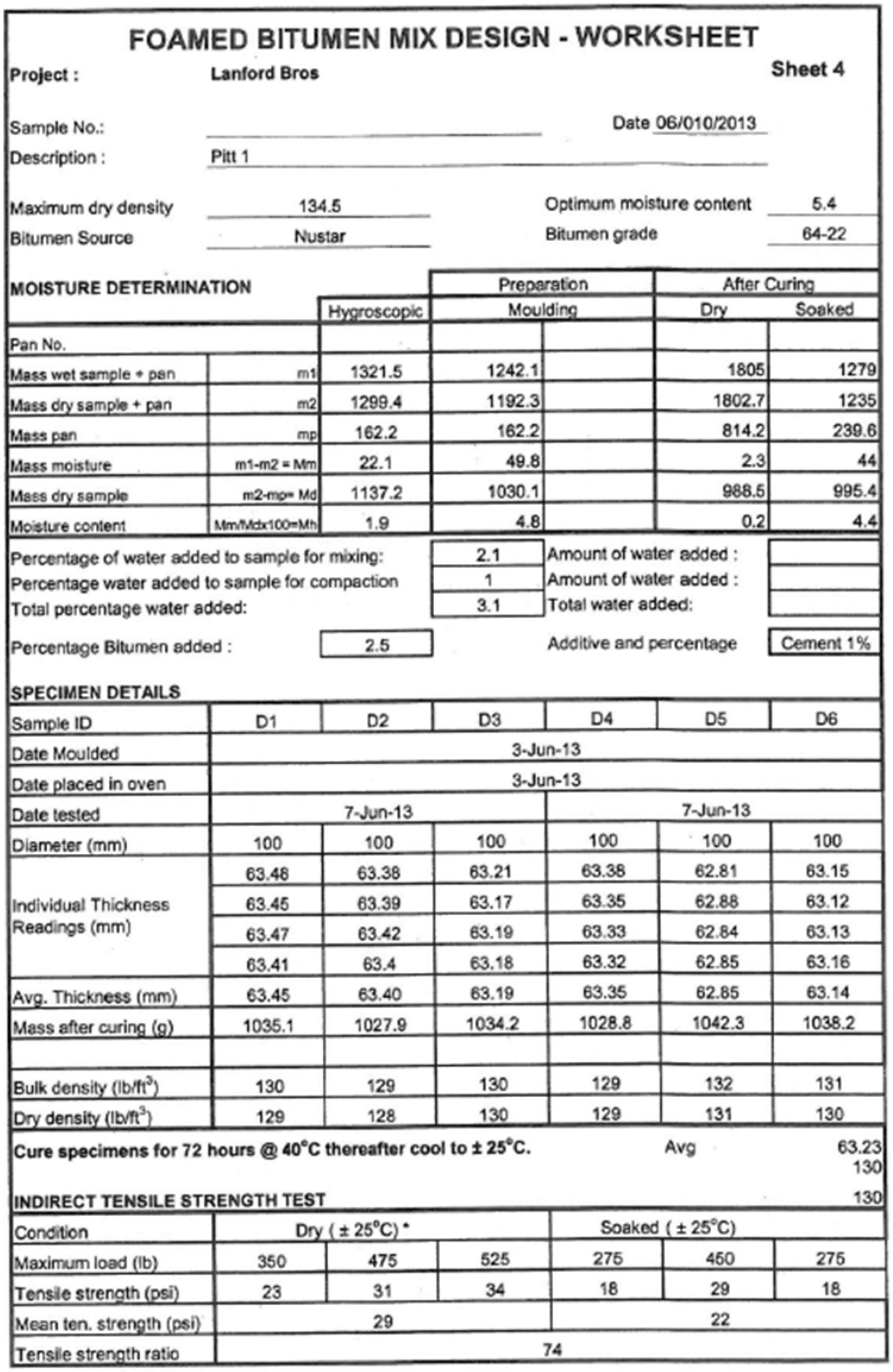
Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C.

Avg 63.10
130
130

INDIRECT TENSILE STRENGTH TEST

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	525	475	300	275	300	225
Tensile strength (psi)	34	31	19	18	20	15
Mean ten. strength (psi)	28			17		
Tensile strength ratio	61					

Figure 38. Mix Design: Independence Boulevard – 5, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : **Lanford Bros** **Sheet 4**

Sample No.: ______ Date 06/010/2013

Description : Pitt 1

Maximum dry density 134.5 Optimum moisture content 5.4

Bitumen Source Nustar Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	1321.5	1242.1		1805	1279
Mass dry sample + pan	m2	1299.4	1192.3		1802.7	1235
Mass pan	mp	162.2	162.2		814.2	239.6
Mass moisture	m1-m2 = Mm	22.1	49.8		2.3	44
Mass dry sample	m2-mp= Md	1137.2	1030.1		988.5	995.4
Moisture content	Mm/Mdx100=Mh	1.9	4.8		0.2	4.4

Percentage of water added to sample for mixing:	2.1	Amount of water added :	
Percentage water added to sample for compaction	1	Amount of water added :	
Total percentage water added:	3.1	Total water added:	
Percentage Bitumen added :	2.5	Additive and percentage	Cement 1%

SPECIMEN DETAILS

Sample ID	D1	D2	D3	D4	D5	D6
Date Moulded	3-Jun-13					
Date placed in oven	3-Jun-13					
Date tested	7-Jun-13			7-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	63.48	63.38	63.21	63.38	62.81	63.15
	63.45	63.39	63.17	63.35	62.88	63.12
	63.47	63.42	63.19	63.33	62.84	63.13
	63.41	63.4	63.18	63.32	62.85	63.16
Avg. Thickness (mm)	63.45	63.40	63.19	63.35	62.85	63.14
Mass after curing (g)	1035.1	1027.9	1034.2	1028.8	1042.3	1038.2
Bulk density (lb/ft^3)	130	129	130	129	132	131
Dry density (lb/ft^3)	129	128	130	129	131	130

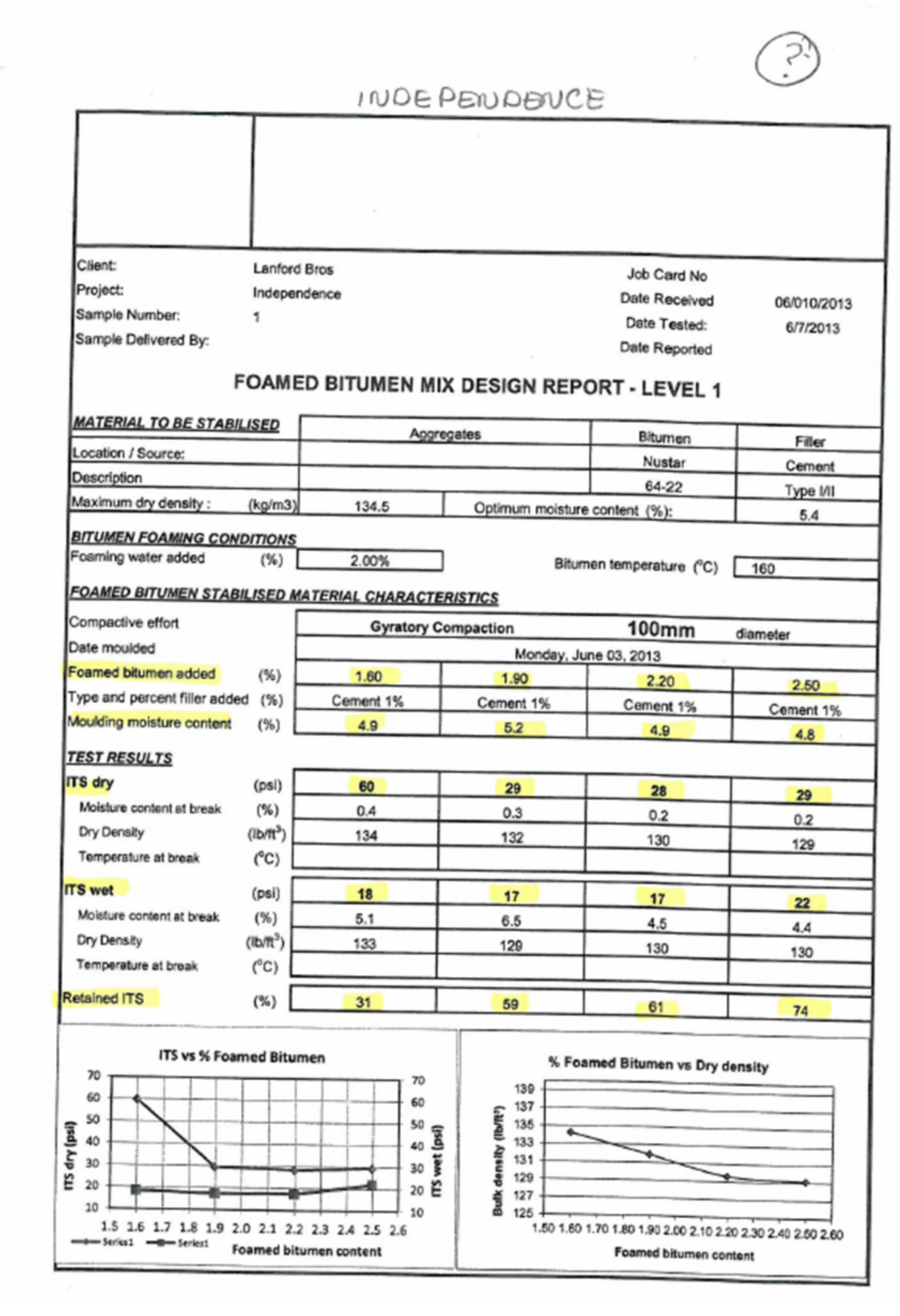
Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C. Avg 63.23

130

INDIRECT TENSILE STRENGTH TEST 130

Condition	Dry (± 25°C) *			Soaked (± 25°C)		
Maximum load (lb)	350	475	525	275	450	275
Tensile strength (psi)	23	31	34	18	29	18
Mean ten. strength (psi)	29			22		
Tensile strength ratio	74					

Figure 39. Mix Design: Independence Boulevard – 6, Photo from Todd Walters, 2014, Used with Permission



?!

INDEPENDENCE

Client:	Lanford Bros	Job Card No	
Project:	Independence	Date Received	06/010/2013
Sample Number:	1	Date Tested:	6/7/2013
Sample Delivered By:		Date Reported	

FOAMED BITUMEN MIX DESIGN REPORT - LEVEL 1

MATERIAL TO BE STABILISED	Aggregates		Bitumen	Filler
Location / Source:			Nustar	Cement
Description			64-22	Type I/II
Maximum dry density : (kg/m3)	134.5	Optimum moisture content (%):		5.4

BITUMEN FOAMING CONDITIONS

Foaming water added (%) 2.00%

Bitumen temperature (°C) 160

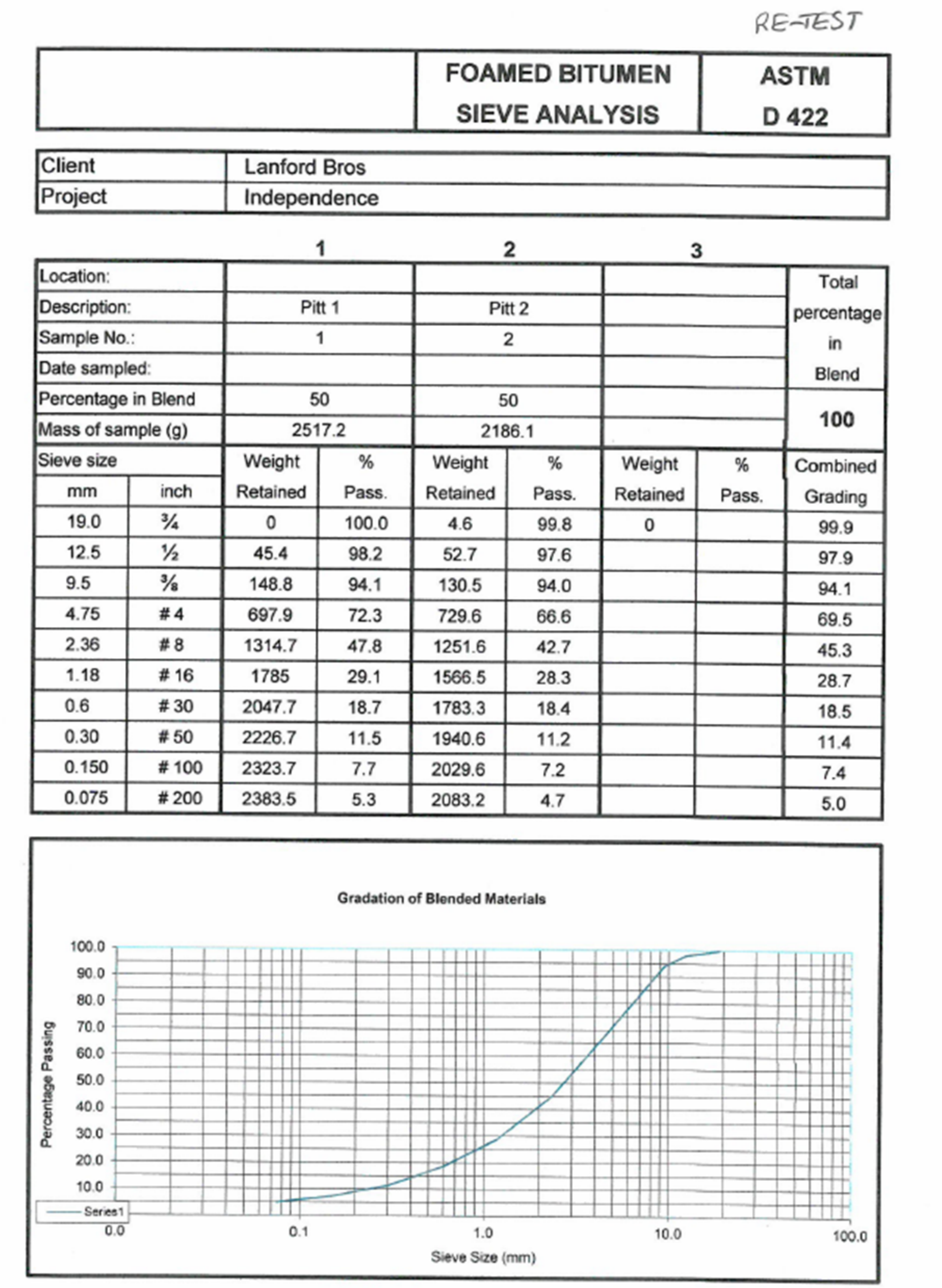
FOAMED BITUMEN STABILISED MATERIAL CHARACTERISTICS

Compactive effort	Gyratory Compaction		100mm	diameter
Date moulded	Monday, June 03, 2013			
Foamed bitumen added (%)	1.60	1.90	2.20	2.50
Type and percent filler added (%)	Cement 1%	Cement 1%	Cement 1%	Cement 1%
Moulding moisture content (%)	4.9	5.2	4.9	4.8

TEST RESULTS

ITS dry (psi)	60	29	28	29
Moisture content at break (%)	0.4	0.3	0.2	0.2
Dry Density (lb/ft³)	134	132	130	129
Temperature at break (°C)				
ITS wet (psi)	18	17	17	22
Moisture content at break (%)	5.1	6.5	4.5	4.4
Dry Density (lb/ft³)	133	129	130	130
Temperature at break (°C)				
Retained ITS (%)	31	59	61	74

Figure 40. Mix Design: Independence Boulevard – 7, Photo from Todd Walters, 2014, Used with Permission



RE-TEST

	FOAMED BITUMEN SIEVE ANALYSIS	**ASTM D 422**

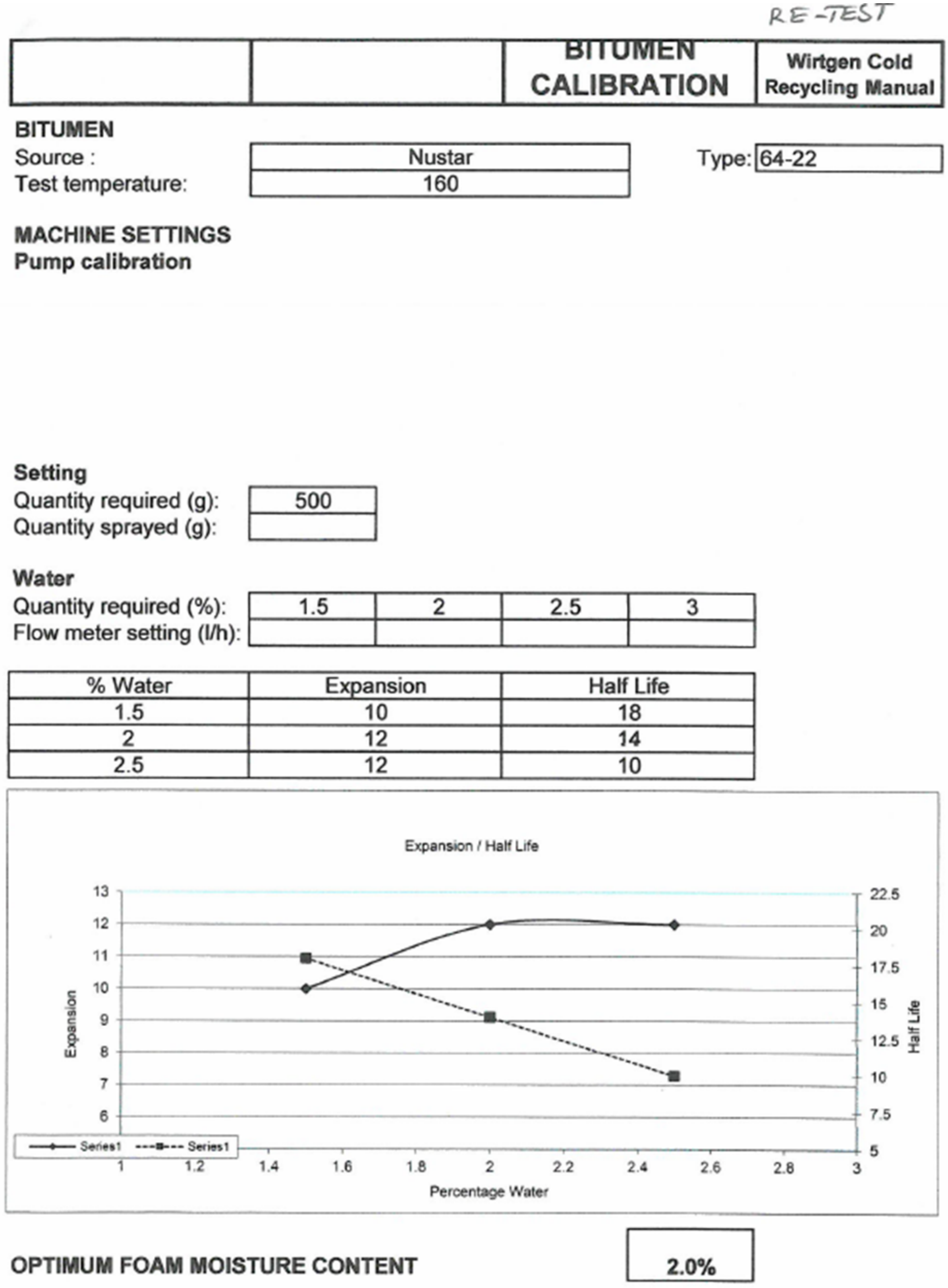
Client	Lanford Bros
Project	Independence

	1	2	3	Total percentage in Blend
Location:				
Description:	Pitt 1	Pitt 2		
Sample No.:	1	2		
Date sampled:				
Percentage in Blend	50	50		100
Mass of sample (g)	2517.2	2186.1		

Sieve size		1		2		3		
mm	inch	Weight Retained	% Pass.	Weight Retained	% Pass.	Weight Retained	% Pass.	Combined Grading
19.0	¾	0	100.0	4.6	99.8	0		99.9
12.5	½	45.4	98.2	52.7	97.6			97.9
9.5	⅜	148.8	94.1	130.5	94.0			94.1
4.75	# 4	697.9	72.3	729.6	66.6			69.5
2.36	# 8	1314.7	47.8	1251.6	42.7			45.3
1.18	# 16	1785	29.1	1566.5	28.3			28.7
0.6	# 30	2047.7	18.7	1783.3	18.4			18.5
0.30	# 50	2226.7	11.5	1940.6	11.2			11.4
0.150	# 100	2323.7	7.7	2029.6	7.2			7.4
0.075	# 200	2383.5	5.3	2083.2	4.7			5.0

Gradation of Blended Materials

Figure 41. Mix Design: Independence Boulevard – 8, Photo from Todd Walters, 2014, Used with Permission



RE-TEST

		BITUMEN CALIBRATION	Wirtgen Cold Recycling Manual

BITUMEN

Source : Nustar   Type: 64-22

Test temperature: 160

MACHINE SETTINGS

Pump calibration

Setting

Quantity required (g):	500
Quantity sprayed (g):	

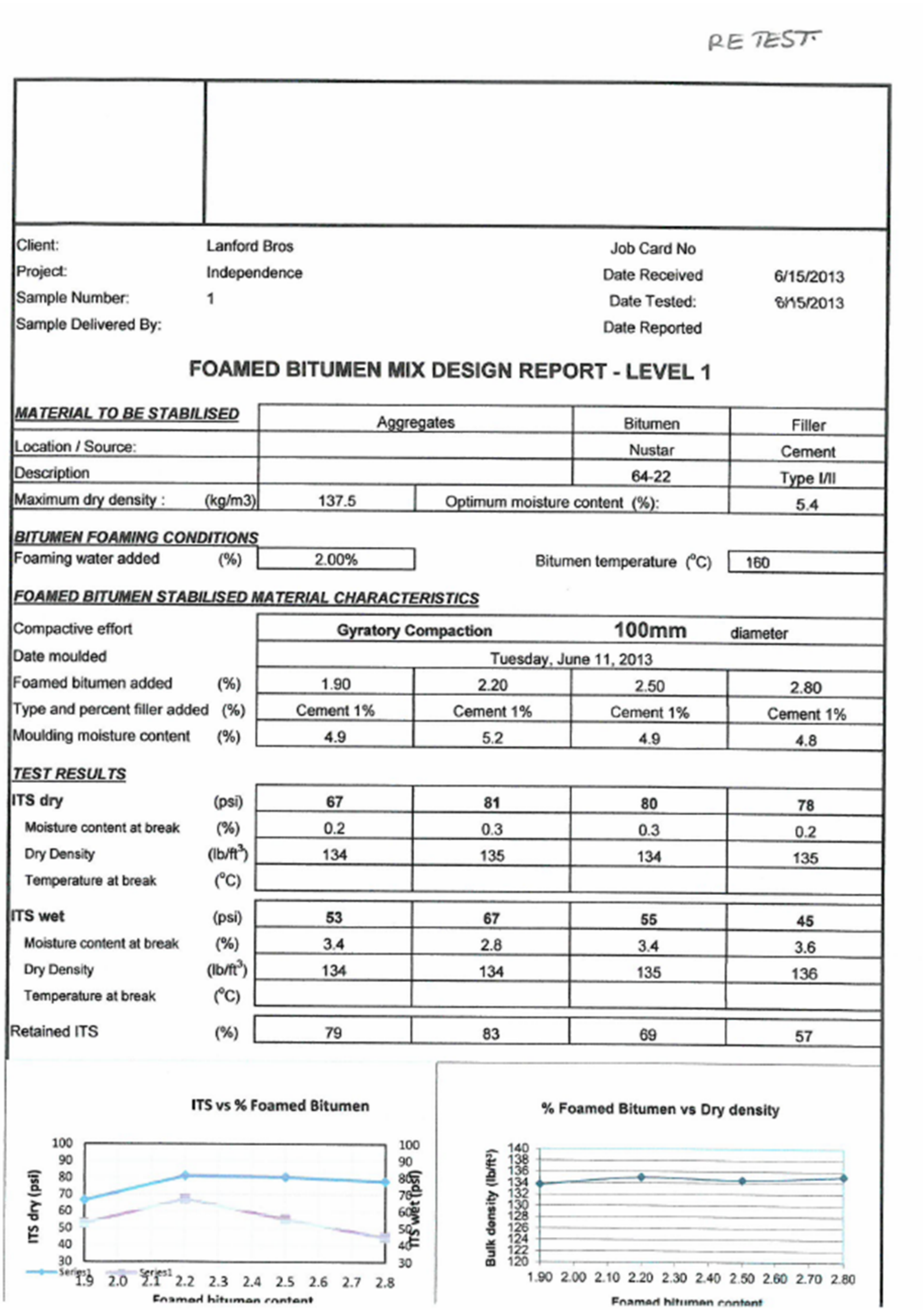
Water

Quantity required (%):	1.5	2	2.5	3
Flow meter setting (l/h):				

% Water	Expansion	Half Life
1.5	10	18
2	12	14
2.5	12	10

OPTIMUM FOAM MOISTURE CONTENT 2.0%

Figure 42. Mix Design: Independence Boulevard – 9, Photo from Todd Walters, 2014, Used with Permission



RE TEST

Client:	Lanford Bros	Job Card No	
Project:	Independence	Date Received	6/15/2013
Sample Number:	1	Date Tested:	6/15/2013
Sample Delivered By:		Date Reported	

FOAMED BITUMEN MIX DESIGN REPORT - LEVEL 1

MATERIAL TO BE STABILISED	Aggregates		Bitumen	Filler
Location / Source:			Nustar	Cement
Description			64-22	Type I/II
Maximum dry density : (kg/m3)	137.5	Optimum moisture content (%):		5.4

BITUMEN FOAMING CONDITIONS

Foaming water added (%)	2.00%	Bitumen temperature (°C)	160

FOAMED BITUMEN STABILISED MATERIAL CHARACTERISTICS

Compactive effort	Gyratory Compaction		100mm	diameter
Date moulded	Tuesday, June 11, 2013			
Foamed bitumen added (%)	1.90	2.20	2.50	2.80
Type and percent filler added (%)	Cement 1%	Cement 1%	Cement 1%	Cement 1%
Moulding moisture content (%)	4.9	5.2	4.9	4.8

TEST RESULTS

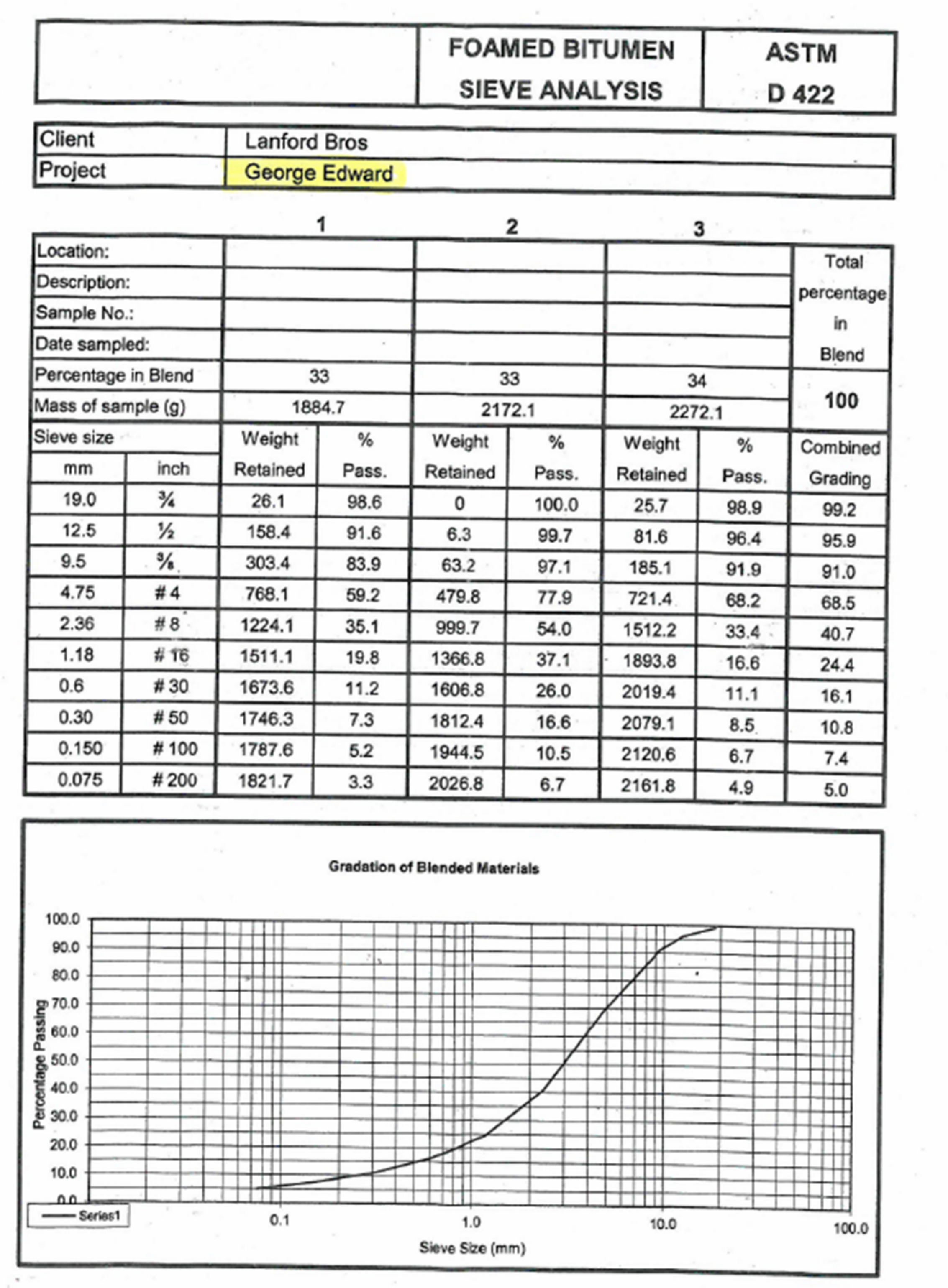
ITS dry (psi)	67	81	80	78
Moisture content at break (%)	0.2	0.3	0.3	0.2
Dry Density (lb/ft³)	134	135	134	135
Temperature at break (°C)				
ITS wet (psi)	53	67	55	45
Moisture content at break (%)	3.4	2.8	3.4	3.6
Dry Density (lb/ft³)	134	134	135	136
Temperature at break (°C)				
Retained ITS (%)	79	83	69	57

ITS vs % Foamed Bitumen

% Foamed Bitumen vs Dry density

Figure 43. Mix Design: Indpendence Boulevard – 10, Photo from Todd Walters, 2014, Used with Permission

George Edward Via

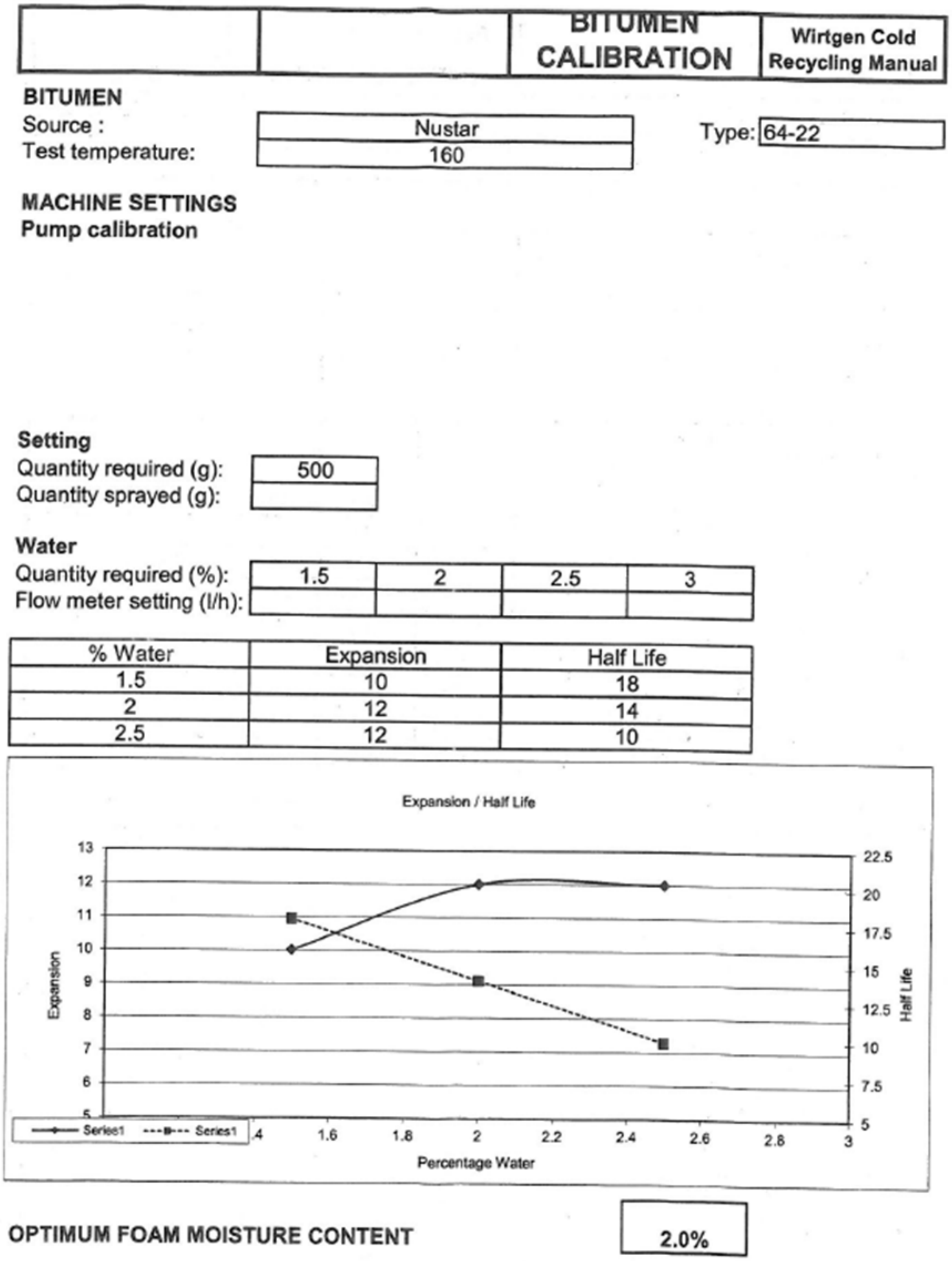


	FOAMED BITUMEN SIEVE ANALYSIS	ASTM D 422

Client	Lanford Bros
Project	George Edward

		1		2		3		
Location:								Total percentage in Blend
Description:								
Sample No.:								
Date sampled:								
Percentage in Blend		33		33		34		100
Mass of sample (g)		1884.7		2172.1		2272.1		
Sieve size		Weight Retained	% Pass.	Weight Retained	% Pass.	Weight Retained	% Pass.	Combined Grading
mm	inch							
19.0	¾	26.1	98.6	0	100.0	25.7	98.9	99.2
12.5	½	158.4	91.6	6.3	99.7	81.6	96.4	95.9
9.5	⅜	303.4	83.9	63.2	97.1	185.1	91.9	91.0
4.75	# 4	768.1	59.2	479.8	77.9	721.4	68.2	68.5
2.36	# 8	1224.1	35.1	999.7	54.0	1512.2	33.4	40.7
1.18	# 16	1511.1	19.8	1366.8	37.1	1893.8	16.6	24.4
0.6	# 30	1673.6	11.2	1606.8	26.0	2019.4	11.1	16.1
0.30	# 50	1746.3	7.3	1812.4	16.6	2079.1	8.5	10.8
0.150	# 100	1787.6	5.2	1944.5	10.5	2120.6	6.7	7.4
0.075	# 200	1821.7	3.3	2026.8	6.7	2161.8	4.9	5.0

Figure 44. Mix Design: George Edward Via – 1, Photo from Todd Walters, 2014, Used with Permission



		BITUMEN CALIBRATION	Wirtgen Cold Recycling Manual

BITUMEN

Source : Nustar

Type: 64-22

Test temperature: 160

MACHINE SETTINGS

Pump calibration

Setting

Quantity required (g): 500

Quantity sprayed (g):

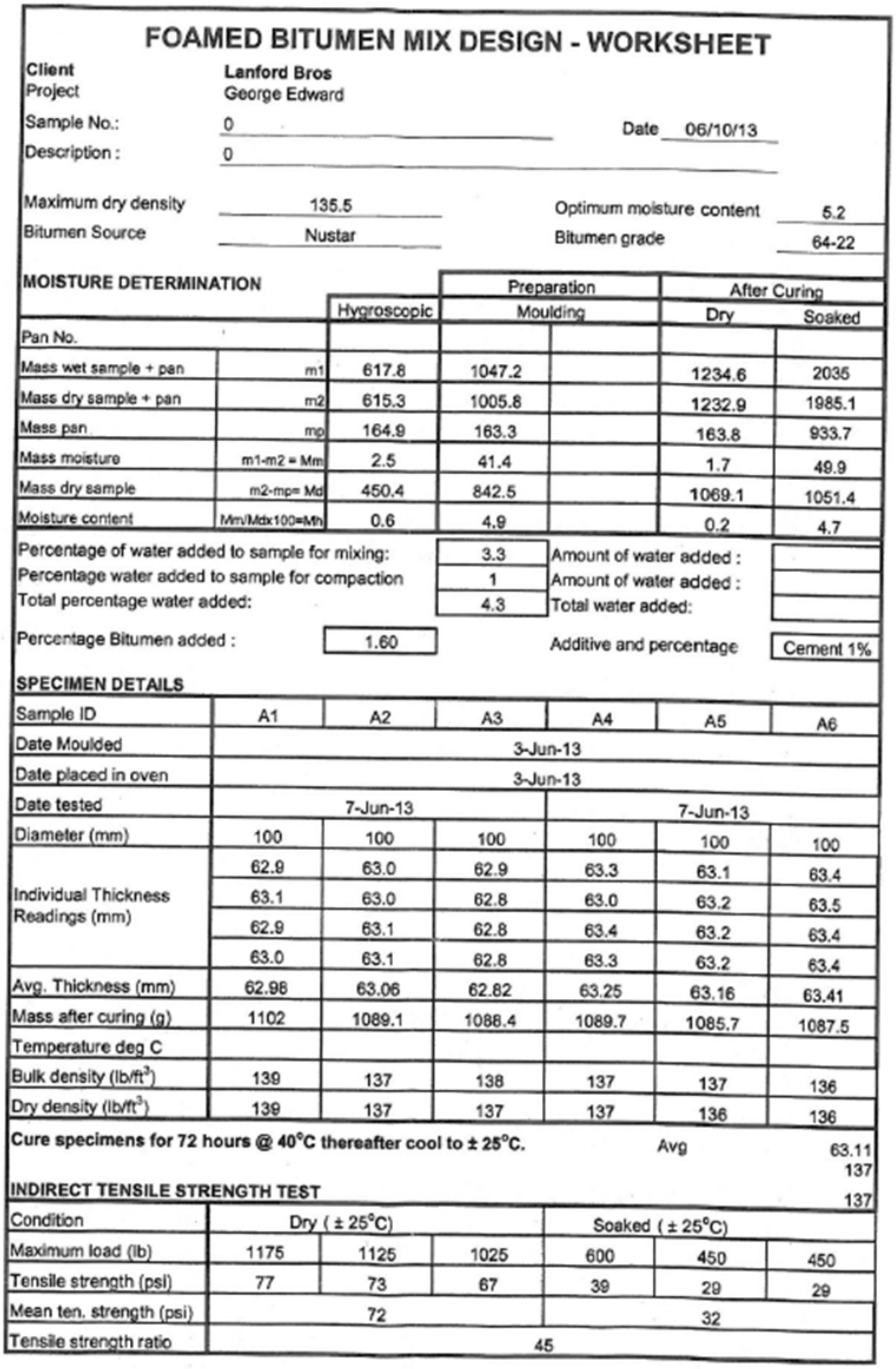
Water

Quantity required (%):	1.5	2	2.5	3
Flow meter setting (l/h):				

% Water	Expansion	Half Life
1.5	10	18
2	12	14
2.5	12	10

OPTIMUM FOAM MOISTURE CONTENT 2.0%

Figure 45. Mix Design: George Edward Via – 2, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Client **Lanford Bros**
Project George Edward
Sample No.: 0 Date 06/10/13
Description : 0

Maximum dry density 135.5
Optimum moisture content 5.2
Bitumen Source Nustar
Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	617.8	1047.2		1234.6	2035
Mass dry sample + pan	m2	615.3	1005.8		1232.9	1985.1
Mass pan	mp	164.9	163.3		163.8	933.7
Mass moisture	m1-m2 = Mm	2.5	41.4		1.7	49.9
Mass dry sample	m2-mp= Md	450.4	842.5		1069.1	1051.4
Moisture content	Mm/Mdx100=Mh	0.6	4.9		0.2	4.7

Percentage of water added to sample for mixing:	3.3	Amount of water added :	
Percentage water added to sample for compaction	1	Amount of water added :	
Total percentage water added:	4.3	Total water added:	
Percentage Bitumen added :	1.60	Additive and percentage	Cement 1%

SPECIMEN DETAILS

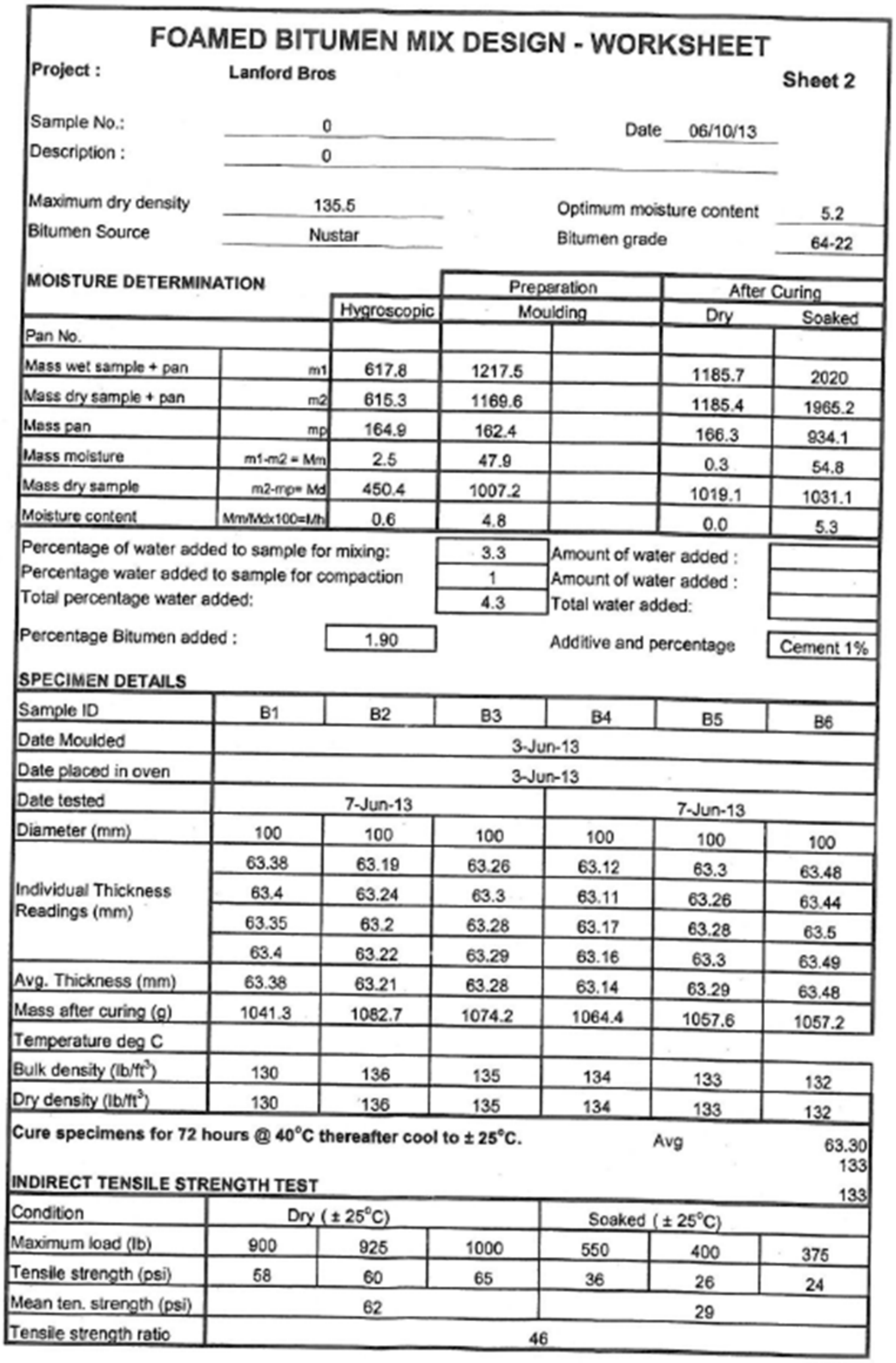
Sample ID	A1	A2	A3	A4	A5	A6
Date Moulded	3-Jun-13					
Date placed in oven	3-Jun-13					
Date tested	7-Jun-13			7-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	62.9	63.0	62.9	63.3	63.1	63.4
	63.1	63.0	62.8	63.0	63.2	63.5
	62.9	63.1	62.8	63.4	63.2	63.4
	63.0	63.1	62.8	63.3	63.2	63.4
Avg. Thickness (mm)	62.98	63.06	62.82	63.25	63.16	63.41
Mass after curing (g)	1102	1089.1	1088.4	1089.7	1085.7	1087.5
Temperature deg C						
Bulk density (lb/ft^3)	139	137	138	137	137	136
Dry density (lb/ft^3)	139	137	137	137	136	136

Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C. Avg 63.11
137
137

INDIRECT TENSILE STRENGTH TEST

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	1175	1125	1025	600	450	450
Tensile strength (psi)	77	73	67	39	29	29
Mean ten. strength (psi)	72			32		
Tensile strength ratio	45					

Figure 46. Mix Design: George Edward Via – 3, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : Lanford Bros

Sheet 2

Sample No.: 0

Date 06/10/13

Description : 0

Maximum dry density 135.5

Optimum moisture content 5.2

Bitumen Source Nustar

Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	617.8	1217.5		1185.7	2020
Mass dry sample + pan	m2	615.3	1169.6		1185.4	1965.2
Mass pan	mp	164.9	162.4		166.3	934.1
Mass moisture	m1-m2 = Mm	2.5	47.9		0.3	54.8
Mass dry sample	m2-mp= Md	450.4	1007.2		1019.1	1031.1
Moisture content	Mm/Mdx100=Mh	0.6	4.8		0.0	5.3

Percentage of water added to sample for mixing:	3.3	Amount of water added :	
Percentage water added to sample for compaction	1	Amount of water added :	
Total percentage water added:	4.3	Total water added:	
Percentage Bitumen added :	1.90	Additive and percentage	Cement 1%

SPECIMEN DETAILS

Sample ID	B1	B2	B3	B4	B5	B6
Date Moulded	3-Jun-13					
Date placed in oven	3-Jun-13					
Date tested	7-Jun-13			7-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	63.38	63.19	63.26	63.12	63.3	63.48
	63.4	63.24	63.3	63.11	63.26	63.44
	63.35	63.2	63.28	63.17	63.28	63.5
	63.4	63.22	63.29	63.16	63.3	63.49
Avg. Thickness (mm)	63.38	63.21	63.28	63.14	63.29	63.48
Mass after curing (g)	1041.3	1082.7	1074.2	1064.4	1057.6	1057.2
Temperature deg C						
Bulk density (lb/ft^3)	130	136	135	134	133	132
Dry density (lb/ft^3)	130	136	135	134	133	132

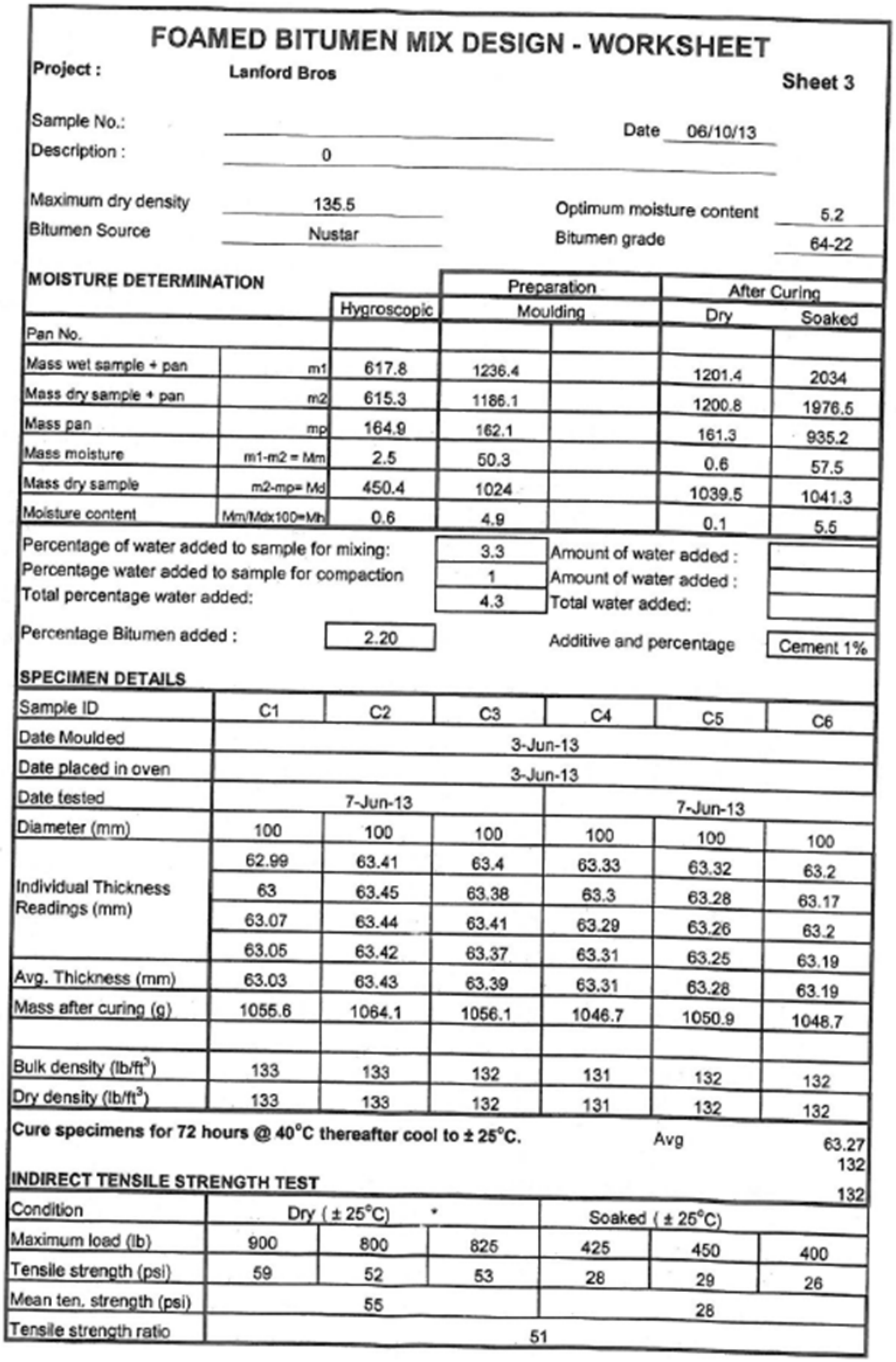
Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C.

Avg 63.30
133
133

INDIRECT TENSILE STRENGTH TEST

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	900	925	1000	550	400	375
Tensile strength (psi)	58	60	65	36	26	24
Mean ten. strength (psi)	62			29		
Tensile strength ratio	46					

Figure 47. Mix Design: George Edward Via – 4, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : Lanford Bros

Sheet 3

Sample No.:

Date 06/10/13

Description : 0

Maximum dry density 135.5

Optimum moisture content 5.2

Bitumen Source Nustar

Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	617.8	1236.4		1201.4	2034
Mass dry sample + pan	m2	615.3	1186.1		1200.8	1976.5
Mass pan	mp	164.9	162.1		161.3	935.2
Mass moisture	m1-m2 = Mm	2.5	50.3		0.6	57.5
Mass dry sample	m2-mp= Md	450.4	1024		1039.5	1041.3
Moisture content	Mm/Mdx100=Mh	0.6	4.9		0.1	5.5

Percentage of water added to sample for mixing: 3.3

Amount of water added :

Percentage water added to sample for compaction 1

Amount of water added :

Total percentage water added: 4.3

Total water added:

Percentage Bitumen added : 2.20

Additive and percentage Cement 1%

SPECIMEN DETAILS

Sample ID	C1	C2	C3	C4	C5	C6
Date Moulded	3-Jun-13					
Date placed in oven	3-Jun-13					
Date tested	7-Jun-13			7-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	62.99	63.41	63.4	63.33	63.32	63.2
	63	63.45	63.38	63.3	63.28	63.17
	63.07	63.44	63.41	63.29	63.26	63.2
	63.05	63.42	63.37	63.31	63.25	63.19
Avg. Thickness (mm)	63.03	63.43	63.39	63.31	63.28	63.19
Mass after curing (g)	1055.6	1064.1	1056.1	1046.7	1050.9	1048.7
Bulk density (lb/ft^3)	133	133	132	131	132	132
Dry density (lb/ft^3)	133	133	132	131	132	132

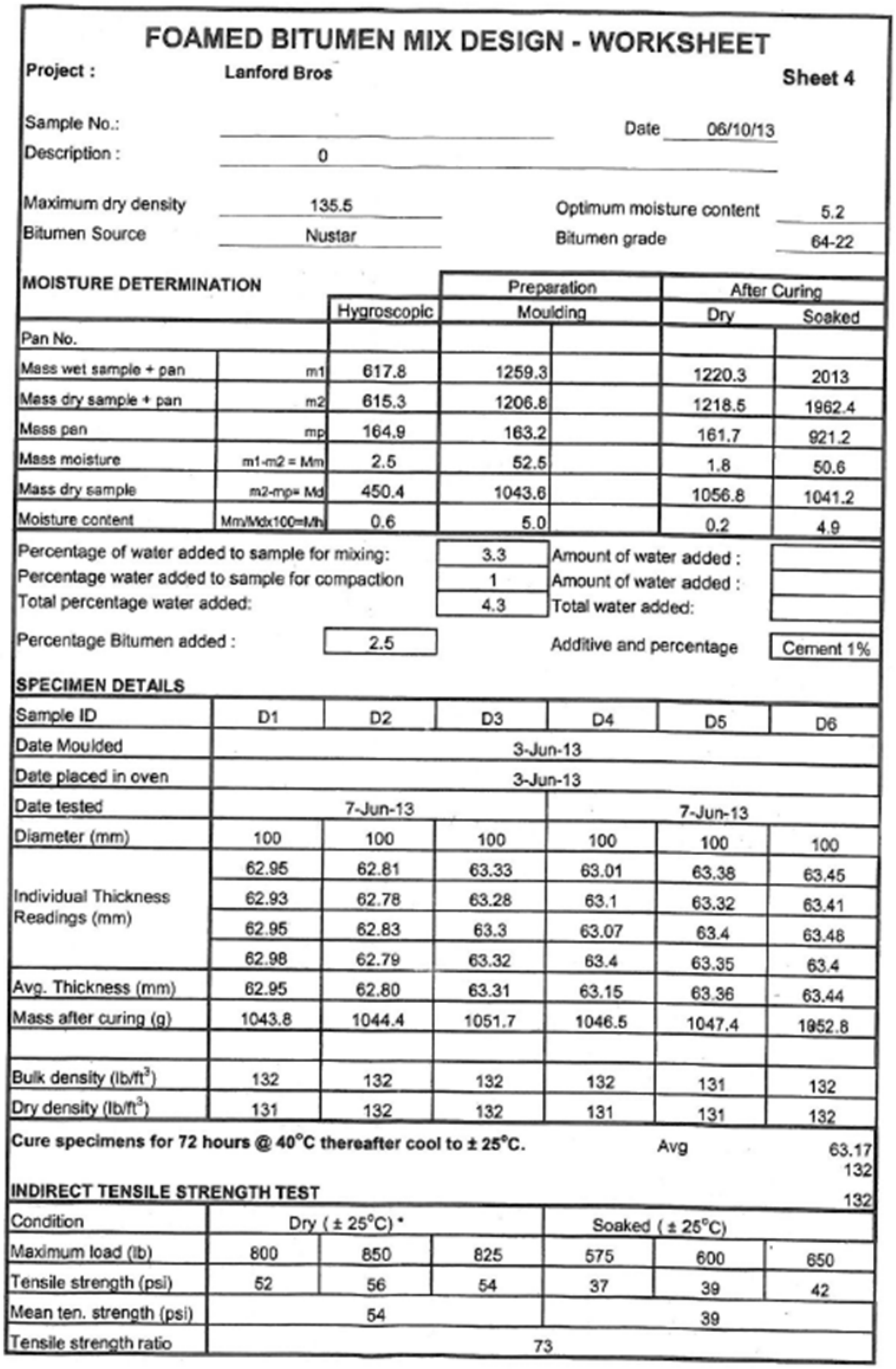
Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C.

Avg 63.27
132
132

INDIRECT TENSILE STRENGTH TEST

Condition	Dry (± 25°C)			Soaked (± 25°C)		
Maximum load (lb)	900	800	825	425	450	400
Tensile strength (psi)	59	52	53	28	29	26
Mean ten. strength (psi)	55			28		
Tensile strength ratio	51					

Figure 48. Mix Design: George Edward Via – 5, Photo from Todd Walters, 2014, Used with Permission



FOAMED BITUMEN MIX DESIGN - WORKSHEET

Project : **Lanford Bros** **Sheet 4**

Sample No.: __________ Date 06/10/13

Description : 0

Maximum dry density 135.5 Optimum moisture content 5.2

Bitumen Source Nustar Bitumen grade 64-22

MOISTURE DETERMINATION

			Preparation		After Curing	
		Hygroscopic	Moulding		Dry	Soaked
Pan No.						
Mass wet sample + pan	m1	617.8	1259.3		1220.3	2013
Mass dry sample + pan	m2	615.3	1206.8		1218.5	1962.4
Mass pan	mp	164.9	163.2		161.7	921.2
Mass moisture	m1-m2 = Mm	2.5	52.5		1.8	50.6
Mass dry sample	m2-mp= Md	450.4	1043.6		1056.8	1041.2
Moisture content	Mm/Mdx100=Mh	0.6	5.0		0.2	4.9

Percentage of water added to sample for mixing:	3.3	Amount of water added :	
Percentage water added to sample for compaction	1	Amount of water added :	
Total percentage water added:	4.3	Total water added:	
Percentage Bitumen added :	2.5	Additive and percentage	Cement 1%

SPECIMEN DETAILS

Sample ID	D1	D2	D3	D4	D5	D6
Date Moulded	3-Jun-13					
Date placed in oven	3-Jun-13					
Date tested	7-Jun-13			7-Jun-13		
Diameter (mm)	100	100	100	100	100	100
Individual Thickness Readings (mm)	62.95	62.81	63.33	63.01	63.38	63.45
	62.93	62.78	63.28	63.1	63.32	63.41
	62.95	62.83	63.3	63.07	63.4	63.48
	62.98	62.79	63.32	63.4	63.35	63.4
Avg. Thickness (mm)	62.95	62.80	63.31	63.15	63.36	63.44
Mass after curing (g)	1043.8	1044.4	1051.7	1046.5	1047.4	1952.8
Bulk density (lb/ft^3)	132	132	132	132	131	132
Dry density (lb/ft^3)	131	132	132	131	131	132

Cure specimens for 72 hours @ 40°C thereafter cool to ± 25°C. Avg 63.17

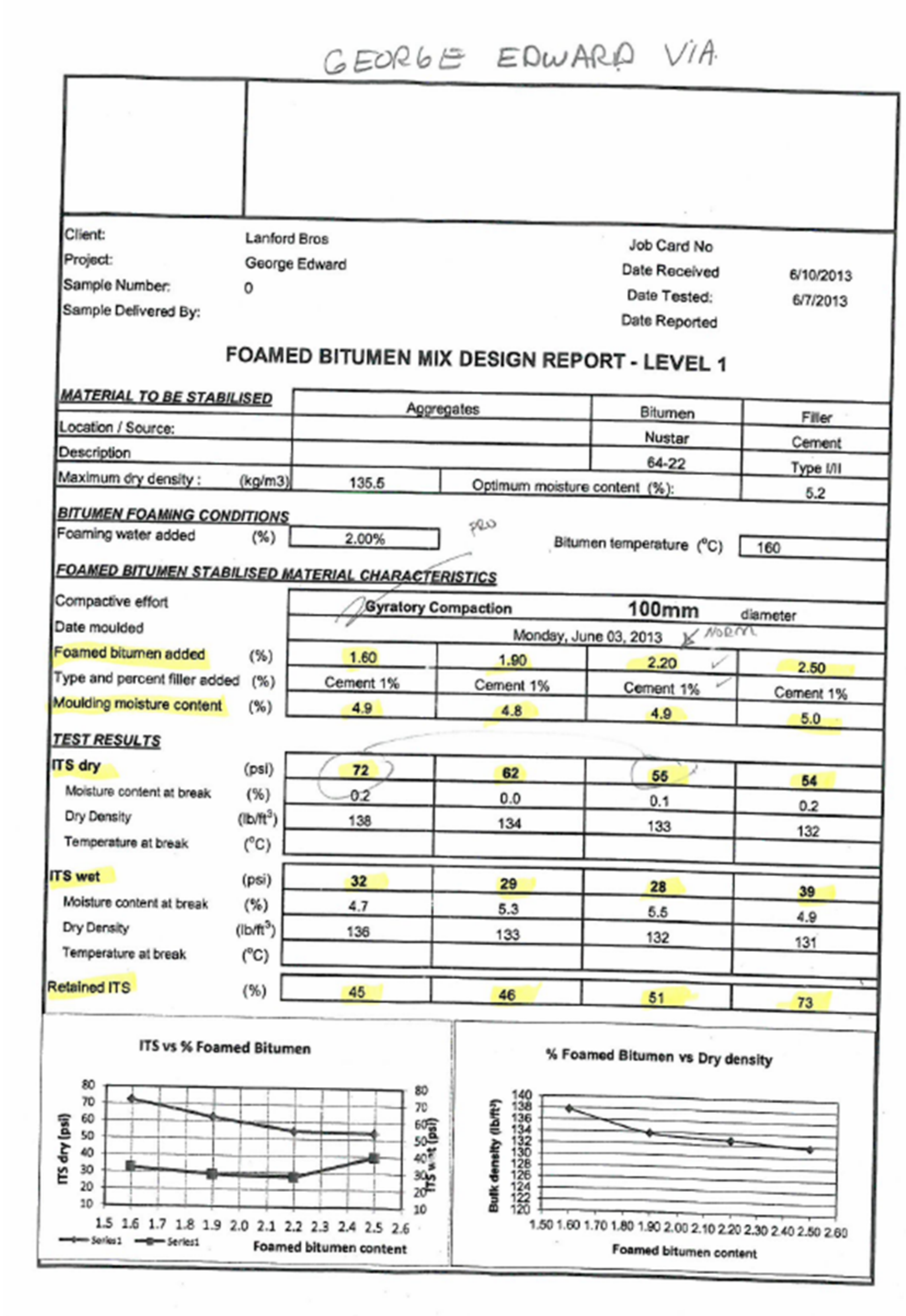
132

132

INDIRECT TENSILE STRENGTH TEST

Condition	Dry (± 25°C) *			Soaked (± 25°C)		
Maximum load (lb)	800	850	825	575	600	650
Tensile strength (psi)	52	56	54	37	39	42
Mean ten. strength (psi)	54			39		
Tensile strength ratio	73					

Figure 49. Mix Design: George Edward Via – 6, Photo from Todd Walters, 2014, Used with Permission



GEORGE EDWARD VIA

Client:	Lanford Bros	Job Card No	
Project:	George Edward	Date Received	6/10/2013
Sample Number:	0	Date Tested:	6/7/2013
Sample Delivered By:		Date Reported	

FOAMED BITUMEN MIX DESIGN REPORT - LEVEL 1

MATERIAL TO BE STABILISED

		Aggregates		Bitumen	Filler
Location / Source:				Nustar	Cement
Description				64-22	Type I/II
Maximum dry density :	(kg/m3)	135.5	Optimum moisture content (%):		5.2

BITUMEN FOAMING CONDITIONS

Foaming water added (%) 2.00% FRO Bitumen temperature (°C) 160

FOAMED BITUMEN STABILISED MATERIAL CHARACTERISTICS

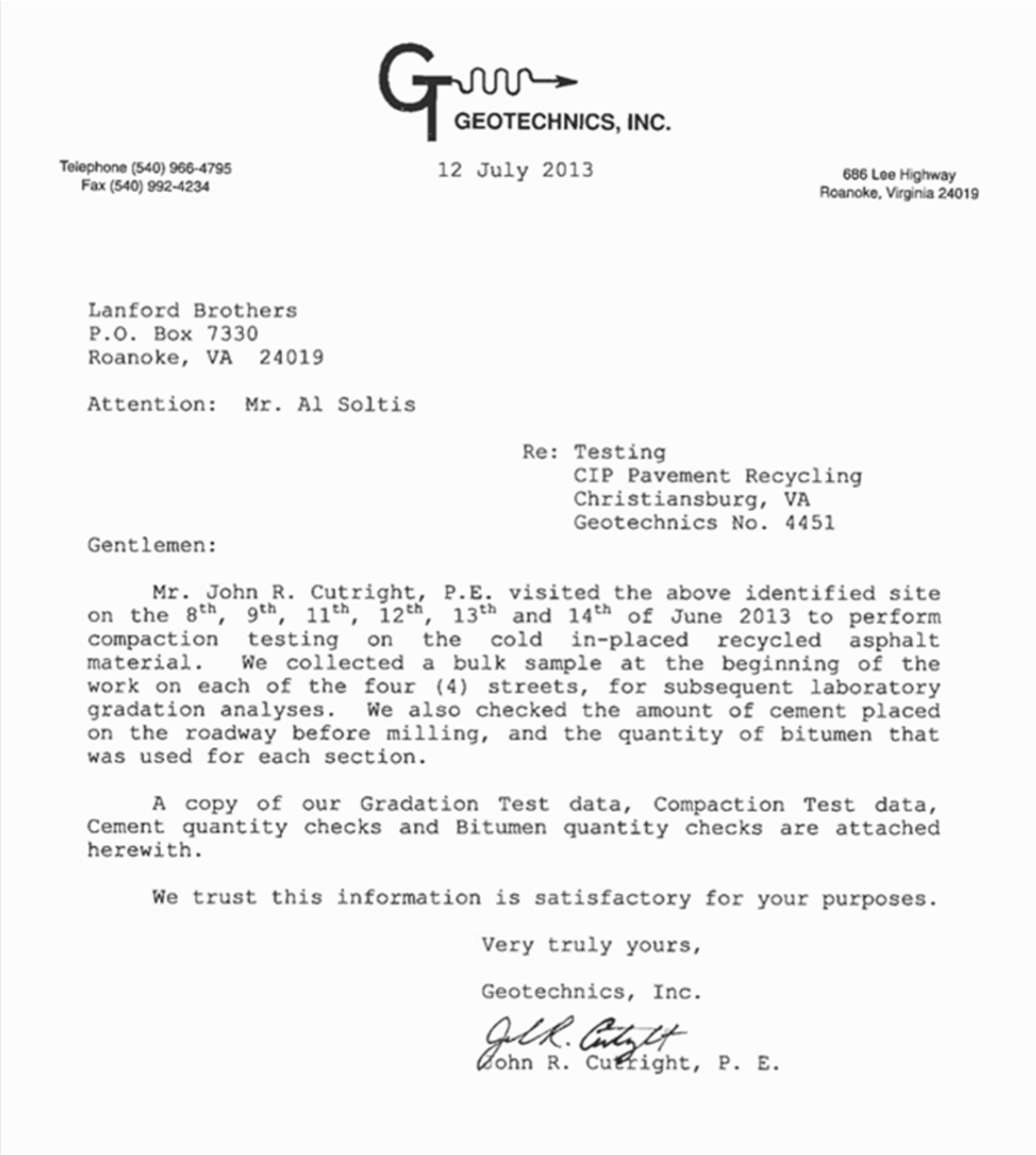
Compactive effort		Gyratory Compaction		100mm	diameter
Date moulded		Monday, June 03, 2013 NORM			
Foamed bitumen added	(%)	1.60	1.90	2.20 ✓	2.50
Type and percent filler added	(%)	Cement 1%	Cement 1%	Cement 1% ✓	Cement 1%
Moulding moisture content	(%)	4.9	4.8	4.9	5.0

TEST RESULTS

ITS dry	(psi)	72	62	55	54
Moisture content at break	(%)	0.2	0.0	0.1	0.2
Dry Density	(lb/ft^3)	138	134	133	132
Temperature at break	(°C)				
ITS wet	(psi)	32	29	28	39
Moisture content at break	(%)	4.7	5.3	5.5	4.9
Dry Density	(lb/ft^3)	136	133	132	131
Temperature at break	(°C)				
Retained ITS	(%)	45	46	51	73

Figure 50. Mix Design: George Edward Via – 7, Photo from Todd Walters, 2014, Used with Permission

RECYCLED MATERIAL: BULK SAMPLE TESTING



GEOTECHNICS, INC.

Telephone (540) 966-4795
Fax (540) 992-4234

686 Lee Highway
Roanoke, Virginia 24019

12 July 2013

Lanford Brothers
P.O. Box 7330
Roanoke, VA 24019

Attention: Mr. Al Soltis

Re: Testing
CIP Pavement Recycling
Christiansburg, VA
Geotechnics No. 4451

Gentlemen:

Mr. John R. Cutright, P.E. visited the above identified site on the 8th, 9th, 11th, 12th, 13th and 14th of June 2013 to perform compaction testing on the cold in-placed recycled asphalt material. We collected a bulk sample at the beginning of the work on each of the four (4) streets, for subsequent laboratory gradation analyses. We also checked the amount of cement placed on the roadway before milling, and the quantity of bitumen that was used for each section.

A copy of our Gradation Test data, Compaction Test data, Cement quantity checks and Bitumen quantity checks are attached herewith.

We trust this information is satisfactory for your purposes.

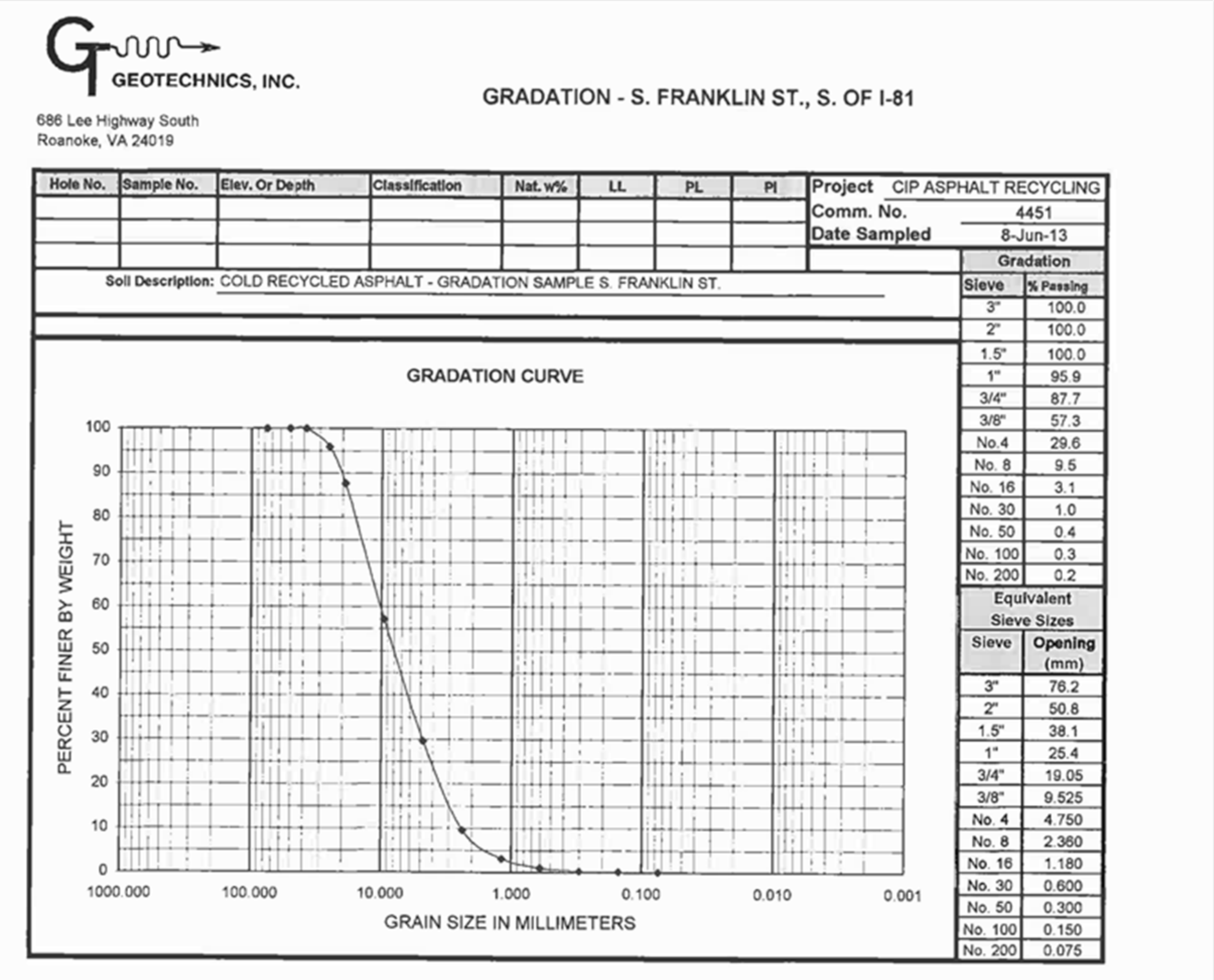
Very truly yours,

Geotechnics, Inc.

John R. Cutright, P. E.

Figure 51. Bulk Sampling, Photo from Todd Walters, 2014, Used with Permission

LABORATORY GRADATION ANALYSIS



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686 Lee Highway South
Roanoke, VA 24019

GRADATION - S. FRANKLIN ST., S. OF I-81

Hole No.	Sample No.	Elev. Or Depth	Classification	Nat. w%	LL	PL	PI

Project CIP ASPHALT RECYCLING
Comm. No. 4451
Date Sampled 8-Jun-13

Soil Description: COLD RECYCLED ASPHALT - GRADATION SAMPLE S. FRANKLIN ST.

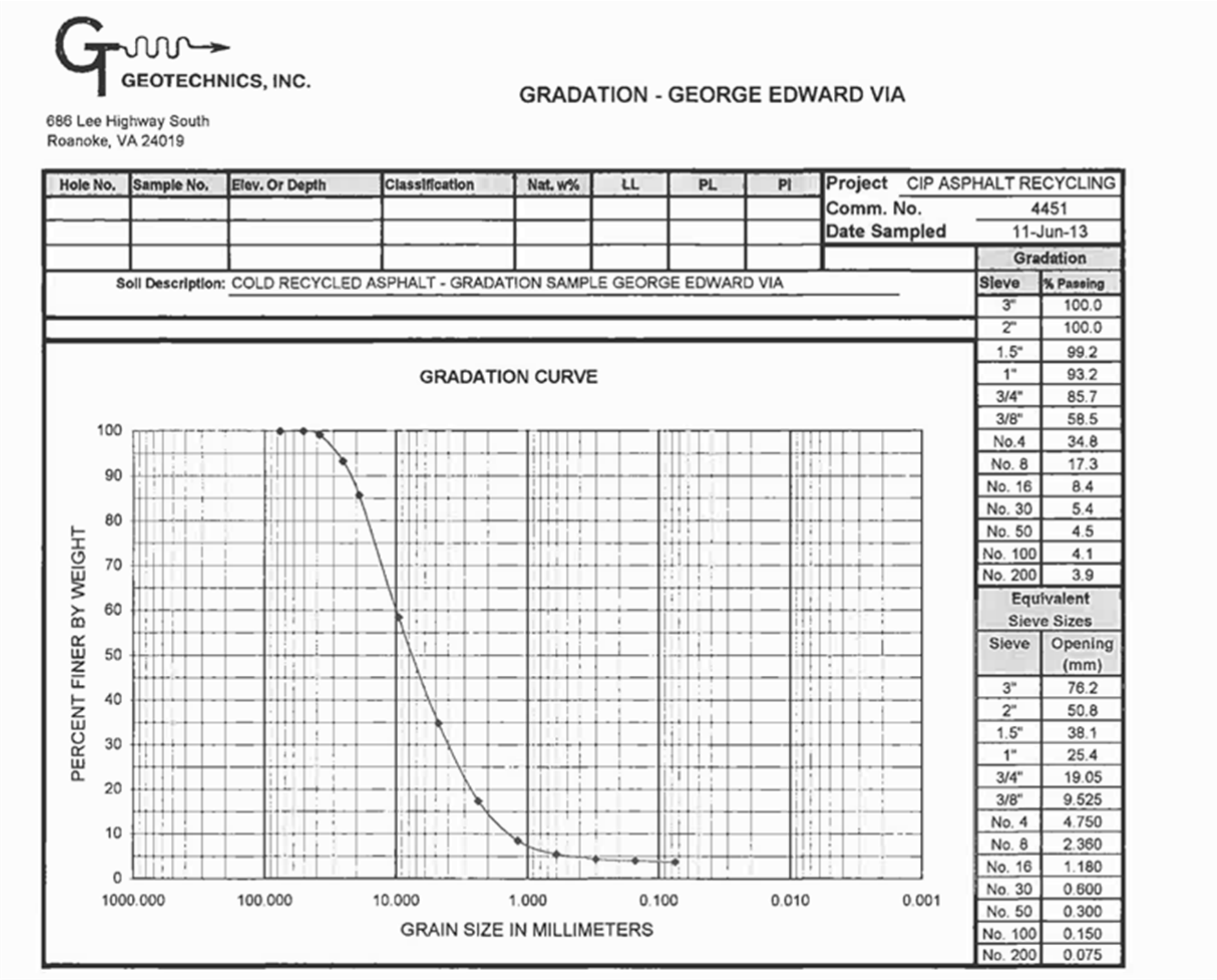
Gradation

Sieve	% Passing
3"	100.0
2"	100.0
1.5"	100.0
1"	95.9
3/4"	87.7
3/8"	57.3
No.4	29.6
No. 8	9.5
No. 16	3.1
No. 30	1.0
No. 50	0.4
No. 100	0.3
No. 200	0.2

Equivalent Sieve Sizes

Sieve	Opening (mm)
3"	76.2
2"	50.8
1.5"	38.1
1"	25.4
3/4"	19.05
3/8"	9.525
No. 4	4.750
No. 8	2.360
No. 16	1.180
No. 30	0.600
No. 50	0.300
No. 100	0.150
No. 200	0.075

Figure 52. Gradation: S. Franklin St., Photo from Todd Walters, 2014, Used with Permission



GEOTECHNICS, INC.

686 Lee Highway South
Roanoke, VA 24019

GRADATION - GEORGE EDWARD VIA

Hole No.	Sample No.	Elev. Or Depth	Classification	Nat. w%	LL	PL	PI

Project CIP ASPHALT RECYCLING
Comm. No. 4451
Date Sampled 11-Jun-13

Soil Description: COLD RECYCLED ASPHALT - GRADATION SAMPLE GEORGE EDWARD VIA

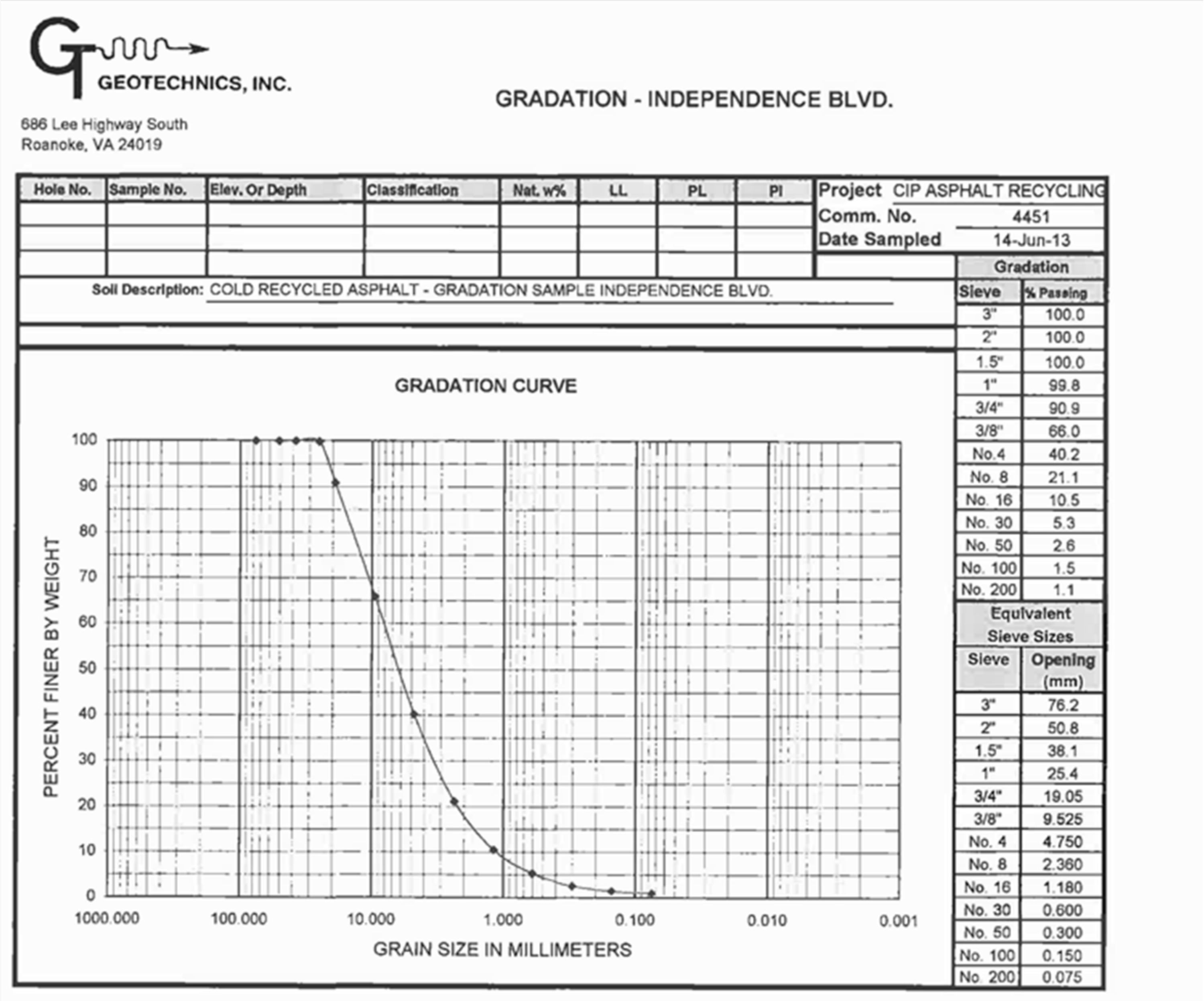
Gradation

Sieve	% Passing
3"	100.0
2"	100.0
1.5"	99.2
1"	93.2
3/4"	85.7
3/8"	58.5
No.4	34.8
No. 8	17.3
No. 16	8.4
No. 30	5.4
No. 50	4.5
No. 100	4.1
No. 200	3.9

Equivalent Sieve Sizes

Sieve	Opening (mm)
3"	76.2
2"	50.8
1.5"	38.1
1"	25.4
3/4"	19.05
3/8"	9.525
No. 4	4.750
No. 8	2.360
No. 16	1.180
No. 30	0.600
No. 50	0.300
No. 100	0.150
No. 200	0.075

Figure 53. Gradation: George Edward Via, Photo from Todd Walters, 2014, Used with Permission



GEOTECHNICS, INC.

686 Lee Highway South
Roanoke, VA 24019

GRADATION - INDEPENDENCE BLVD.

Hole No.	Sample No.	Elev. Or Depth	Classification	Nat. w%	LL	PL	PI

Project CIP ASPHALT RECYCLING
Comm. No. 4451
Date Sampled 14-Jun-13

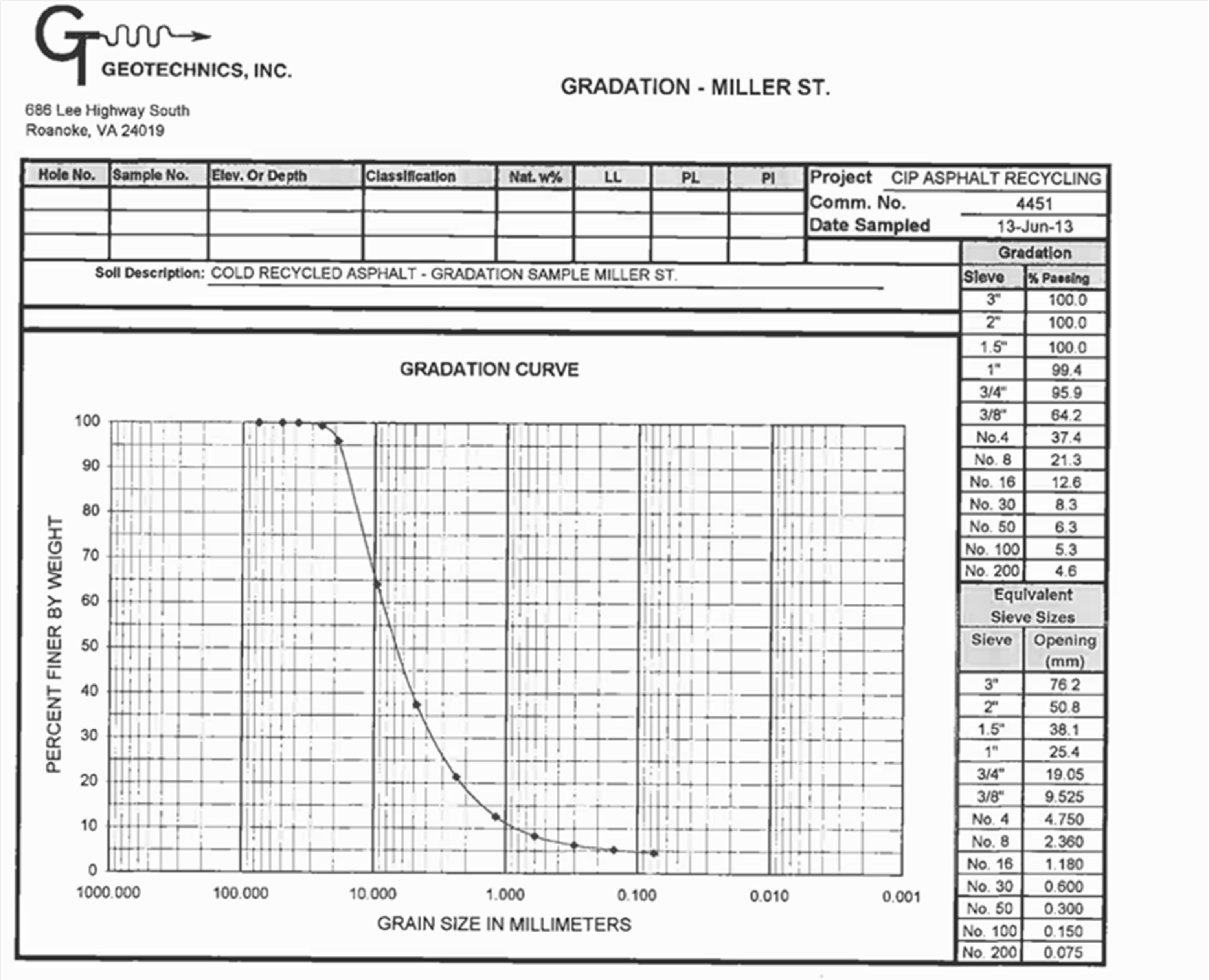
Soil Description: COLD RECYCLED ASPHALT - GRADATION SAMPLE INDEPENDENCE BLVD.

GRADATION CURVE

Gradation	
Sieve	% Passing
3"	100.0
2"	100.0
1.5"	100.0
1"	99.8
3/4"	90.9
3/8"	66.0
No.4	40.2
No. 8	21.1
No. 16	10.5
No. 30	5.3
No. 50	2.6
No. 100	1.5
No. 200	1.1

Equivalent Sieve Sizes	
Sieve	Opening (mm)
3"	76.2
2"	50.8
1.5"	38.1
1"	25.4
3/4"	19.05
3/8"	9.525
No. 4	4.750
No. 8	2.360
No. 16	1.180
No. 30	0.600
No. 50	0.300
No. 100	0.150
No. 200	0.075

Figure 54. Gradation: Independence Boulevard, Photo from Todd Walters, 2014, Used with Permission



GEOTECHNICS, INC.

686 Lee Highway South
Roanoke, VA 24019

GRADATION - MILLER ST.

Hole No.	Sample No.	Elev. Or Depth	Classification	Nat. w%	LL	PL	PI

Project CIP ASPHALT RECYCLING
Comm. No. 4451
Date Sampled 13-Jun-13

Soil Description: COLD RECYCLED ASPHALT - GRADATION SAMPLE MILLER ST.

Gradation

Sieve	% Passing
3"	100.0
2"	100.0
1.5"	100.0
1"	99.4
3/4"	95.9
3/8"	64.2
No.4	37.4
No. 8	21.3
No. 16	12.6
No. 30	8.3
No. 50	6.3
No. 100	5.3
No. 200	4.6

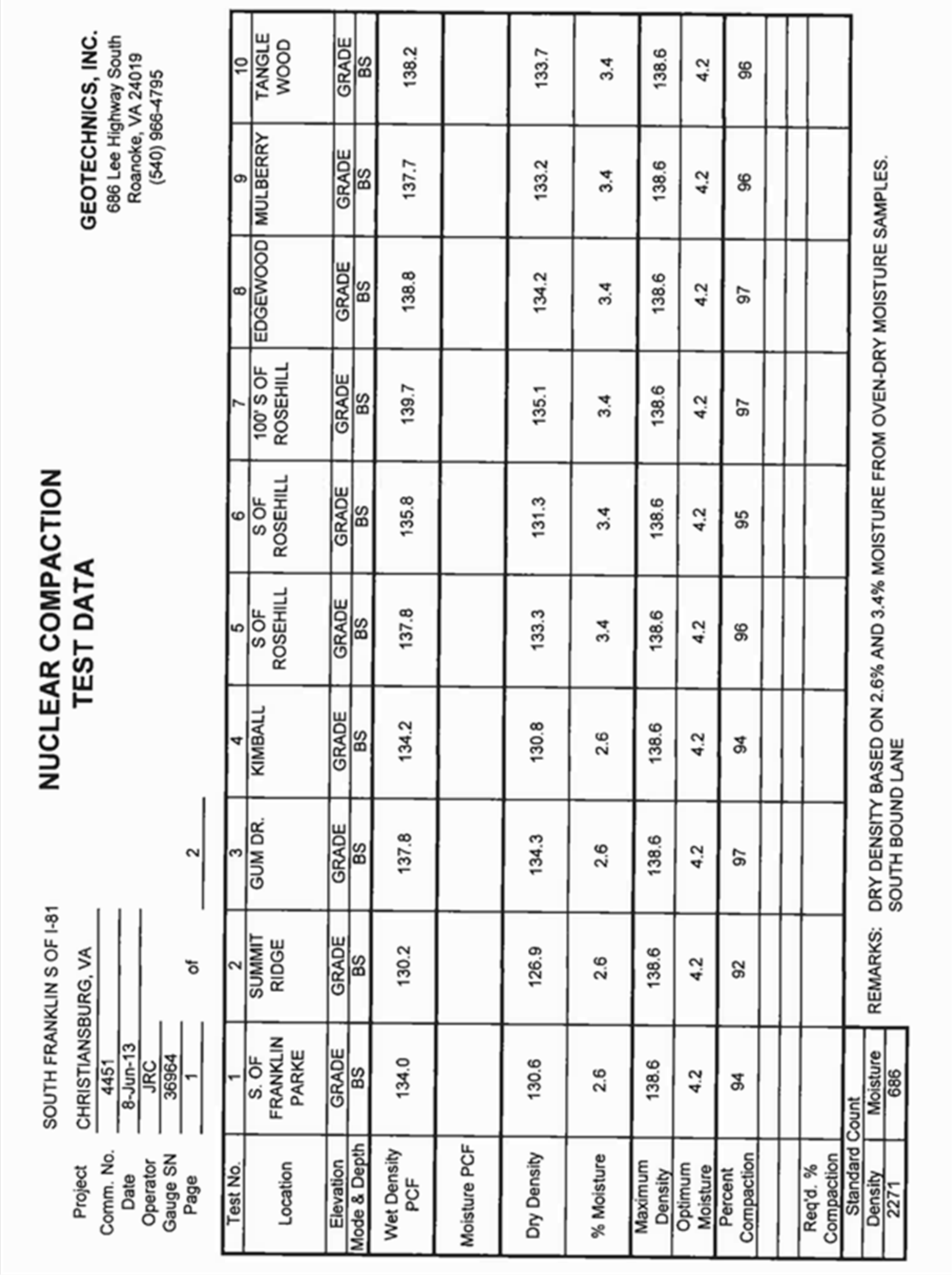
Equivalent Sieve Sizes

Sieve	Opening (mm)
3"	76.2
2"	50.8
1.5"	38.1
1"	25.4
3/4"	19.05
3/8"	9.525
No. 4	4.750
No. 8	2.360
No. 16	1.180
No. 30	0.600
No. 50	0.300
No. 100	0.150
No. 200	0.075

Figure 55. Gradation: Miller Street, Photo from Todd Walters, 2014, Used with Permission

NUCLEAR COMPACTION TEST DATA

South Franklin Street



Project SOUTH FRANKLIN S OF I-81
CHRISTIANSBURG, VA
Comm. No. 4451
Date 8-Jun-13
Operator JRC
Gauge SN 36964
Page 1 of 2

NUCLEAR COMPACTION TEST DATA

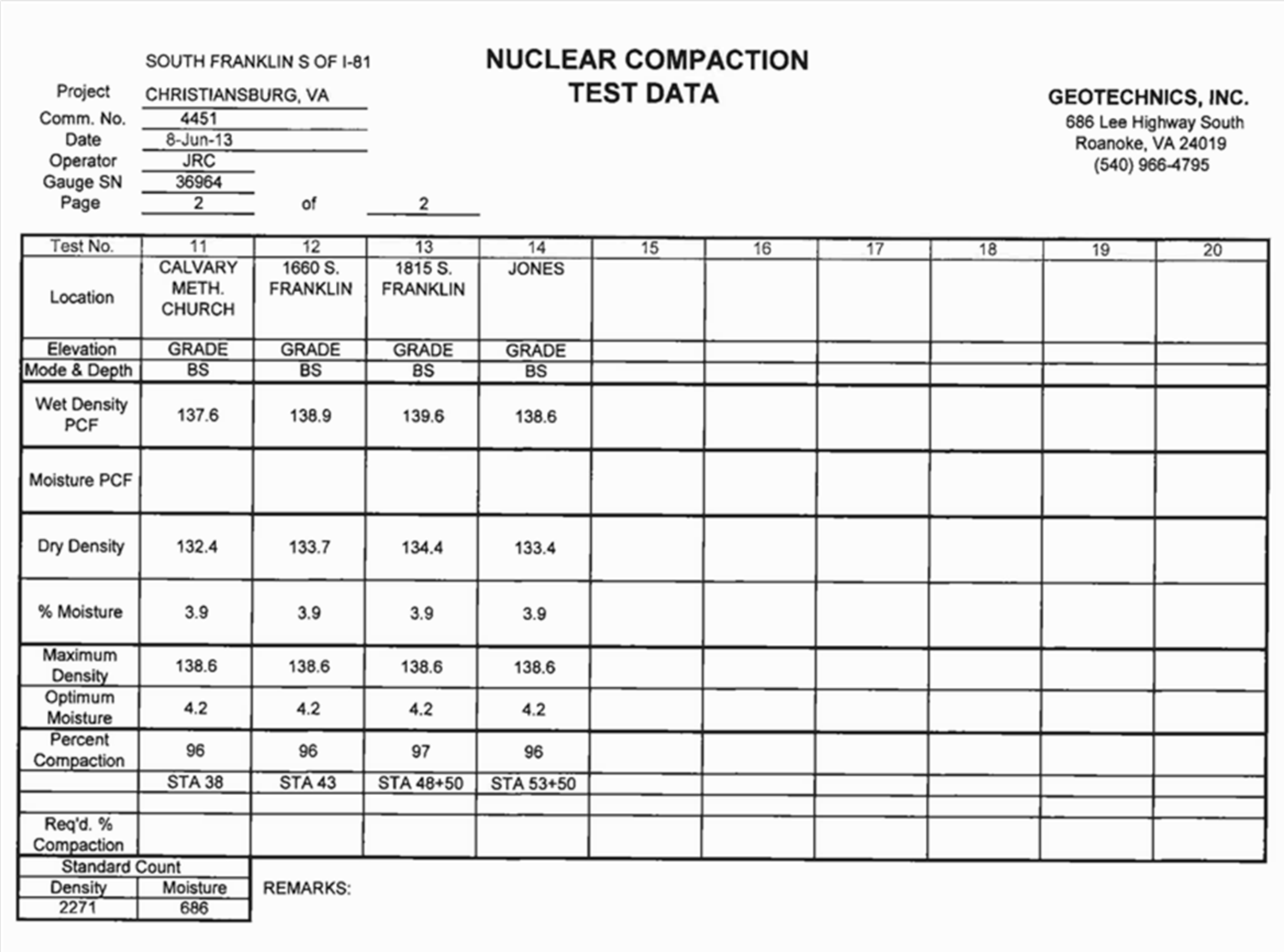
GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Test No.	1	2	3	4	5	6	7	8	9	10
Location	S. OF FRANKLIN PARKE	SUMMIT RIDGE	GUM DR.	KIMBALL	S OF ROSEHILL	S OF ROSEHILL	100' S OF ROSEHILL	EDGEWOOD	MULBERRY	TANGLE WOOD
Elevation	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE
Mode & Depth	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS
Wet Density PCF	134.0	130.2	137.8	134.2	137.8	135.8	139.7	138.8	137.7	138.2
Moisture PCF										
Dry Density	130.6	126.9	134.3	130.8	133.3	131.3	135.1	134.2	133.2	133.7
% Moisture	2.6	2.6	2.6	2.6	3.4	3.4	3.4	3.4	3.4	3.4
Maximum Density	138.6	138.6	138.6	138.6	138.6	138.6	138.6	138.6	138.6	138.6
Optimum Moisture	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Percent Compaction	94	92	97	94	96	95	97	97	96	96
Req'd. % Compaction										

Standard Count	
Density	Moisture
2271	686

REMARKS: DRY DENSITY BASED ON 2.6% AND 3.4% MOISTURE FROM OVEN-DRY MOISTURE SAMPLES.
SOUTH BOUND LANE

Figure 56. Nuclear Compaction Test: South Franklin Street – South of Franklin Parke, Photo from Todd Walters, 2014, Used with Permission



SOUTH FRANKLIN S OF I-81

NUCLEAR COMPACTION TEST DATA

GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Project CHRISTIANSBURG, VA
Comm. No. 4451
Date 8-Jun-13
Operator JRC
Gauge SN 36964
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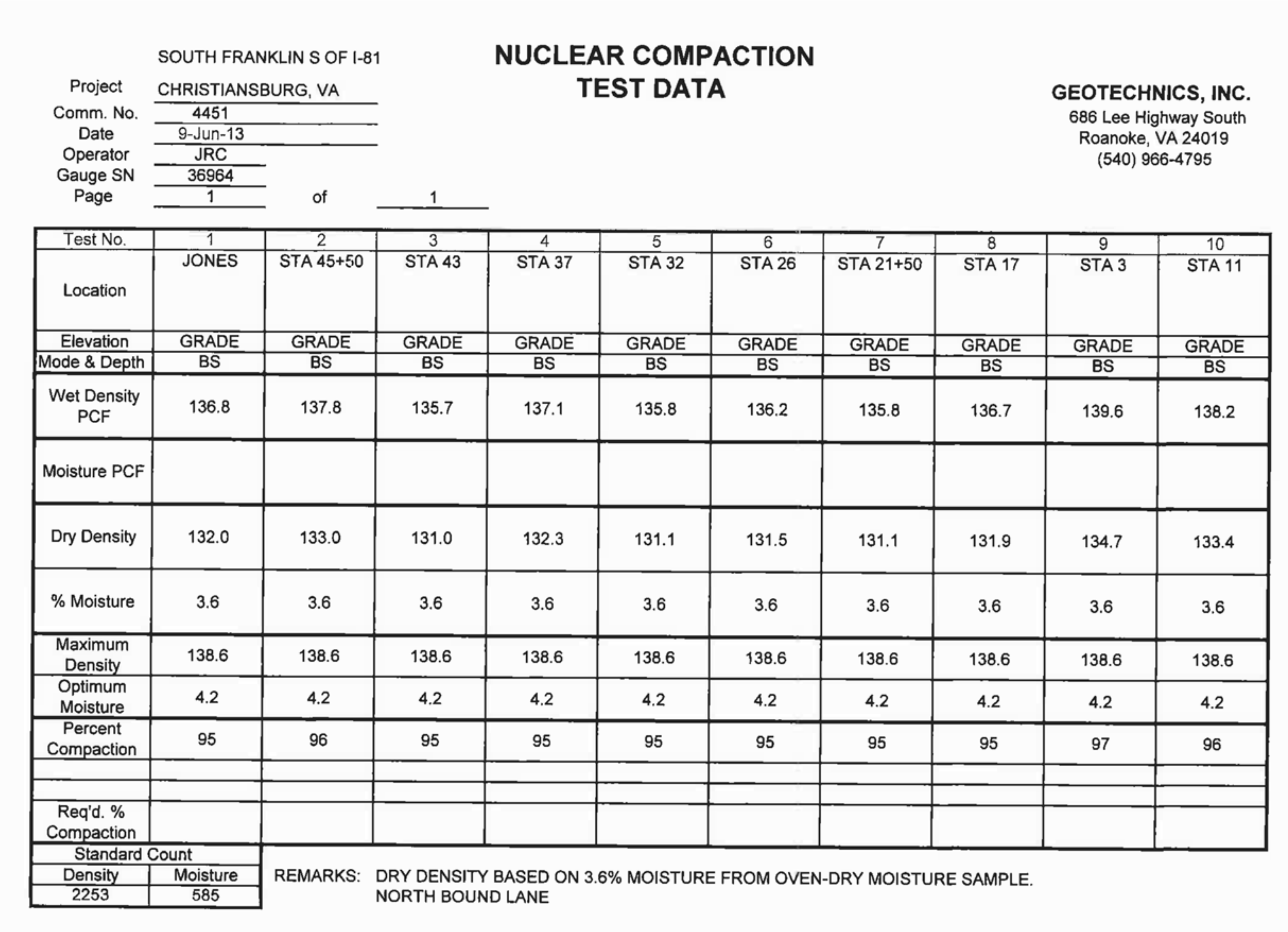
Test No.	11	12	13	14	15	16	17	18	19	20
Location	CALVARY METH. CHURCH	1660 S. FRANKLIN	1815 S. FRANKLIN	JONES						
Elevation	GRADE	GRADE	GRADE	GRADE						
Mode & Depth	BS	BS	BS	BS						
Wet Density PCF	137.6	138.9	139.6	138.6						
Moisture PCF										
Dry Density	132.4	133.7	134.4	133.4						
% Moisture	3.9	3.9	3.9	3.9						
Maximum Density	138.6	138.6	138.6	138.6						
Optimum Moisture	4.2	4.2	4.2	4.2						
Percent Compaction	96	96	97	96						
	STA 38	STA 43	STA 48+50	STA 53+50						
Req'd. % Compaction										

Standard Count	
Density	Moisture
2271	686

REMARKS:

Figure 57. Nuclear Compaction Test: South Franklin Street – at Cavalry Methodist Church, Photo from Todd Walters, 2014, Used with Permission



SOUTH FRANKLIN S OF I-81

NUCLEAR COMPACTION TEST DATA

Project CHRISTIANSBURG, VA
Comm. No. 4451
Date 9-Jun-13
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GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
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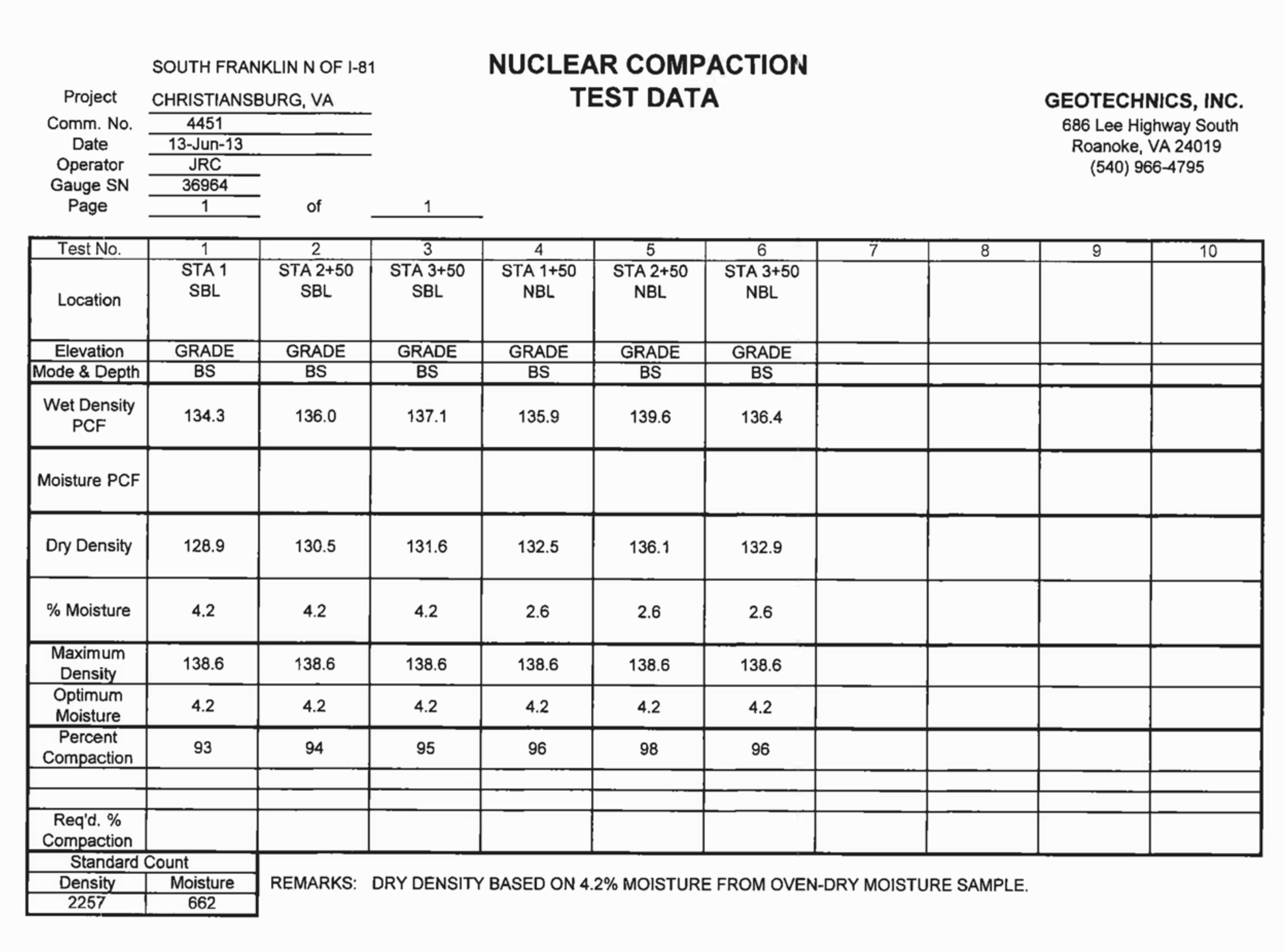
Test No.	1	2	3	4	5	6	7	8	9	10
Location	JONES	STA 45+50	STA 43	STA 37	STA 32	STA 26	STA 21+50	STA 17	STA 3	STA 11
Elevation	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE
Mode & Depth	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS
Wet Density PCF	136.8	137.8	135.7	137.1	135.8	136.2	135.8	136.7	139.6	138.2
Moisture PCF										
Dry Density	132.0	133.0	131.0	132.3	131.1	131.5	131.1	131.9	134.7	133.4
% Moisture	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Maximum Density	138.6	138.6	138.6	138.6	138.6	138.6	138.6	138.6	138.6	138.6
Optimum Moisture	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Percent Compaction	95	96	95	95	95	95	95	95	97	96
Req'd. % Compaction										

Standard Count	
Density	Moisture
2253	585

REMARKS: DRY DENSITY BASED ON 3.6% MOISTURE FROM OVEN-DRY MOISTURE SAMPLE.
NORTH BOUND LANE

Figure 58. Nuclear Compaction Test: South Franklin Street – at Jones St. , Photo from Todd Walters, 2014, Used with Permission



NUCLEAR COMPACTION TEST DATA

GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Project: SOUTH FRANKLIN N OF I-81 CHRISTIANSBURG, VA
Comm. No.: 4451
Date: 13-Jun-13
Operator: JRC
Gauge SN: 36964
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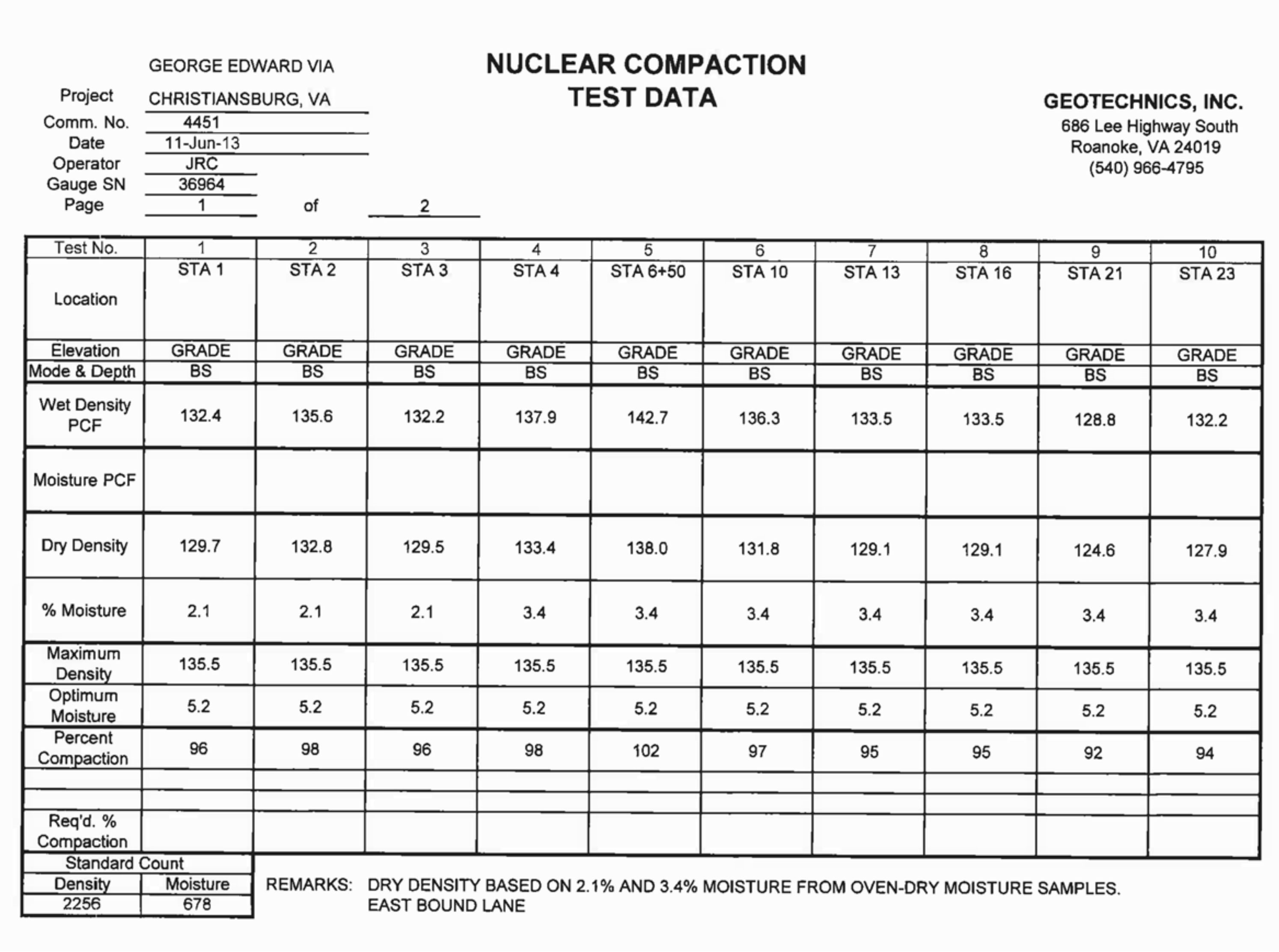
Test No.	1	2	3	4	5	6	7	8	9	10
Location	STA 1 SBL	STA 2+50 SBL	STA 3+50 SBL	STA 1+50 NBL	STA 2+50 NBL	STA 3+50 NBL				
Elevation	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE				
Mode & Depth	BS	BS	BS	BS	BS	BS				
Wet Density PCF	134.3	136.0	137.1	135.9	139.6	136.4				
Moisture PCF										
Dry Density	128.9	130.5	131.6	132.5	136.1	132.9				
% Moisture	4.2	4.2	4.2	2.6	2.6	2.6				
Maximum Density	138.6	138.6	138.6	138.6	138.6	138.6				
Optimum Moisture	4.2	4.2	4.2	4.2	4.2	4.2				
Percent Compaction	93	94	95	96	98	96				
Req'd. % Compaction										

Standard Count	
Density	Moisture
2257	662

REMARKS: DRY DENSITY BASED ON 4.2% MOISTURE FROM OVEN-DRY MOISTURE SAMPLE.

Figure 59. Nuclear Compaction Test: South Franklin Street – North of I-81 Overpass, Photo from Todd Walters, 2014, Used with Permission

George Edward Via



GEORGE EDWARD VIA

NUCLEAR COMPACTION TEST DATA

Project CHRISTIANSBURG, VA
Comm. No. 4451
Date 11-Jun-13
Operator JRC
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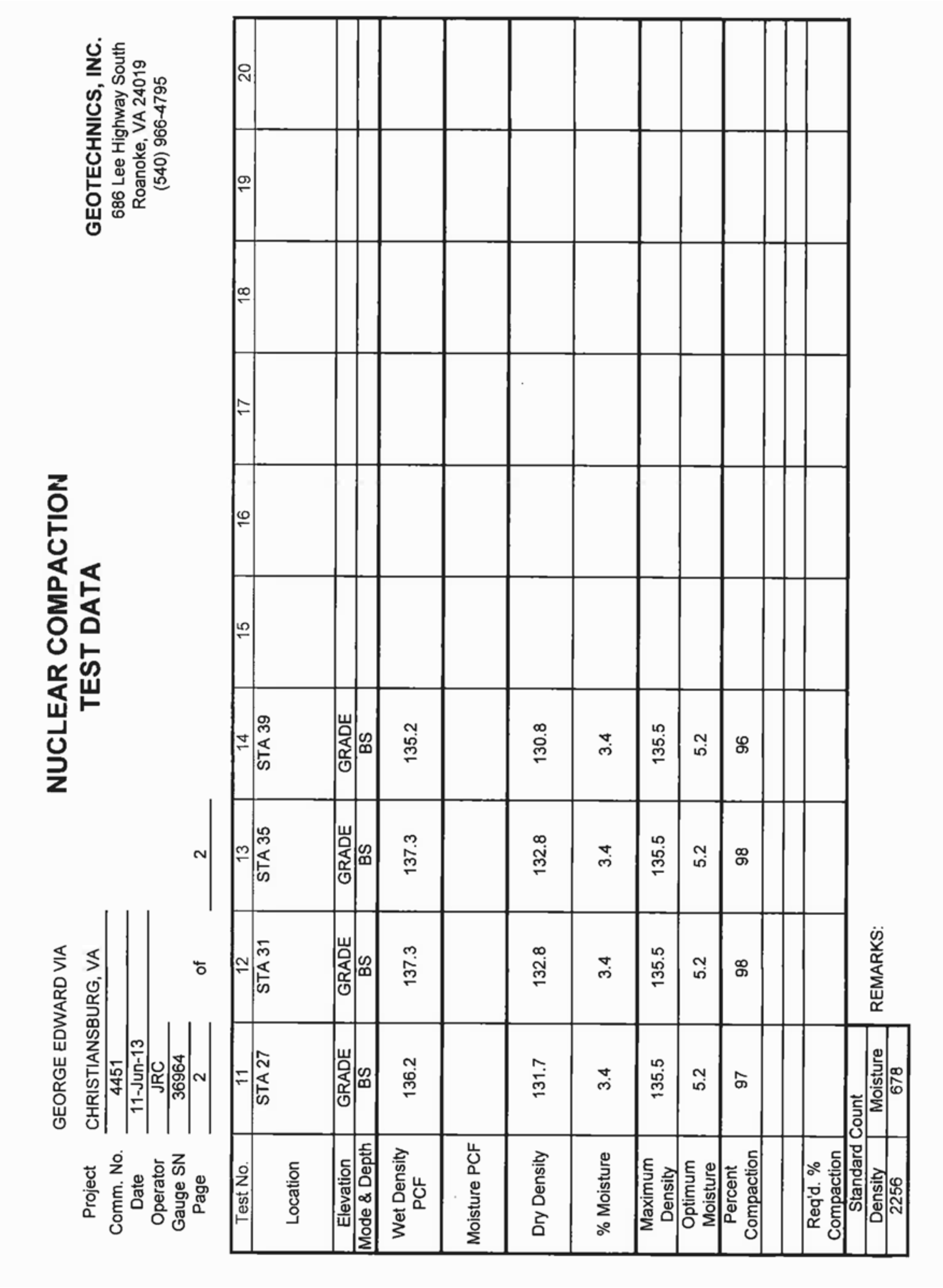
GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Test No.	1	2	3	4	5	6	7	8	9	10
Location	STA 1	STA 2	STA 3	STA 4	STA 6+50	STA 10	STA 13	STA 16	STA 21	STA 23
Elevation	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE
Mode & Depth	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS
Wet Density PCF	132.4	135.6	132.2	137.9	142.7	136.3	133.5	133.5	128.8	132.2
Moisture PCF										
Dry Density	129.7	132.8	129.5	133.4	138.0	131.8	129.1	129.1	124.6	127.9
% Moisture	2.1	2.1	2.1	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Maximum Density	135.5	135.5	135.5	135.5	135.5	135.5	135.5	135.5	135.5	135.5
Optimum Moisture	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Percent Compaction	96	98	96	98	102	97	95	95	92	94
Req'd. % Compaction										

Standard Count	
Density	Moisture
2256	678

REMARKS: DRY DENSITY BASED ON 2.1% AND 3.4% MOISTURE FROM OVEN-DRY MOISTURE SAMPLES.
EAST BOUND LANE

Figure 60. Nuclear Compaction Test: George Edward Via – 1, Photo from Todd Walters, 2014, Used with Permission



GEORGE EDWARD VIA

Project CHRISTIANSBURG, VA

Comm. No. 4451

Date 11-Jun-13

Operator JRC

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NUCLEAR COMPACTION TEST DATA

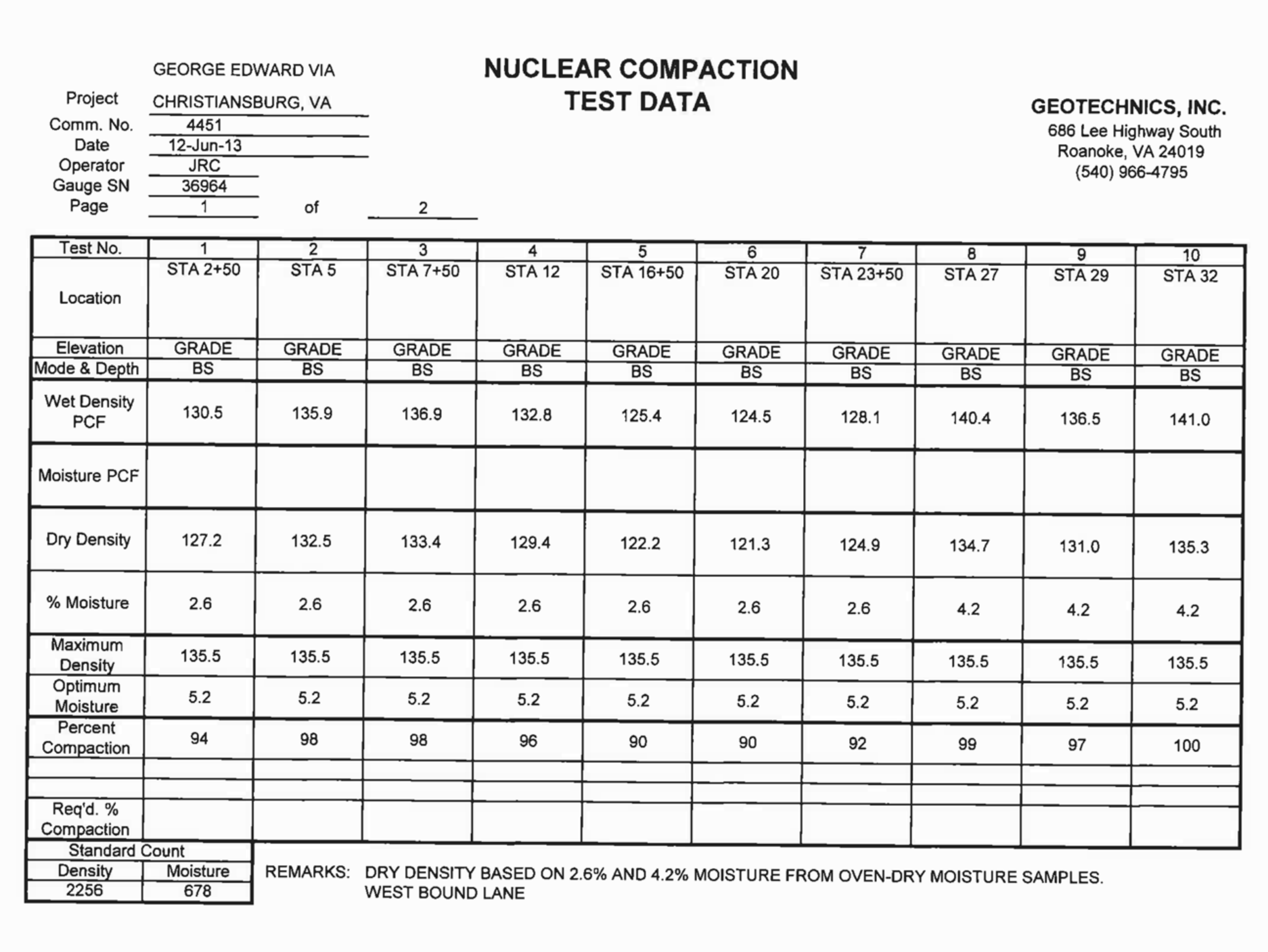
GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Test No.	11	12	13	14	15	16	17	18	19	20
Location	STA 27	STA 31	STA 35	STA 39						
Elevation	GRADE	GRADE	GRADE	GRADE						
Mode & Depth	BS	BS	BS	BS						
Wet Density PCF	136.2	137.3	137.3	135.2						
Moisture PCF										
Dry Density	131.7	132.8	132.8	130.8						
% Moisture	3.4	3.4	3.4	3.4						
Maximum Density	135.5	135.5	135.5	135.5						
Optimum Moisture	5.2	5.2	5.2	5.2						
Percent Compaction	97	98	98	96						
Req'd. % Compaction										

Standard Count	
Density	Moisture
2256	678

REMARKS:

Figure 61. Nuclear Compaction Test: George Edward Via – 2, Photo from Todd Walters, 2014, Used with Permission



NUCLEAR COMPACTION TEST DATA

GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Project: GEORGE EDWARD VIA CHRISTIANSBURG, VA
Comm. No.: 4451
Date: 12-Jun-13
Operator: JRC
Gauge SN: 36964
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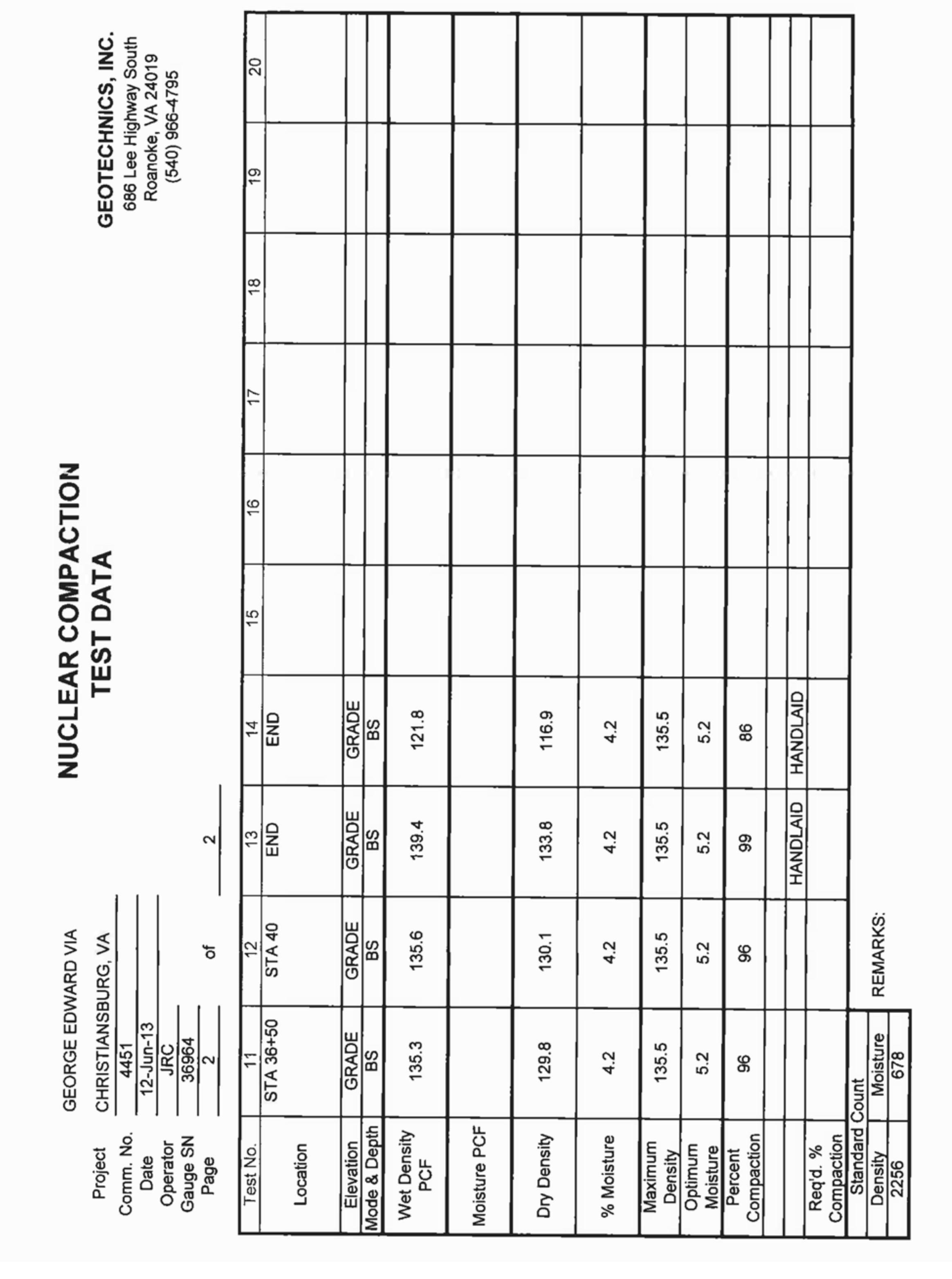
Test No.	1	2	3	4	5	6	7	8	9	10
Location	STA 2+50	STA 5	STA 7+50	STA 12	STA 16+50	STA 20	STA 23+50	STA 27	STA 29	STA 32
Elevation	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE
Mode & Depth	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS
Wet Density PCF	130.5	135.9	136.9	132.8	125.4	124.5	128.1	140.4	136.5	141.0
Moisture PCF										
Dry Density	127.2	132.5	133.4	129.4	122.2	121.3	124.9	134.7	131.0	135.3
% Moisture	2.6	2.6	2.6	2.6	2.6	2.6	2.6	4.2	4.2	4.2
Maximum Density	135.5	135.5	135.5	135.5	135.5	135.5	135.5	135.5	135.5	135.5
Optimum Moisture	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Percent Compaction	94	98	98	96	90	90	92	99	97	100
Req'd. % Compaction										

Standard Count	
Density	Moisture
2256	678

REMARKS: DRY DENSITY BASED ON 2.6% AND 4.2% MOISTURE FROM OVEN-DRY MOISTURE SAMPLES.
WEST BOUND LANE

Figure 62. Nuclear Compaction Test: George Edward Via – 3, Photo from Todd Walters, 2014, Used with Permission



NUCLEAR COMPACTION TEST DATA

GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Project GEORGE EDWARD VIA
CHRISTIANSBURG, VA
Comm. No. 4451
Date 12-Jun-13
Operator JRC
Gauge SN 36964
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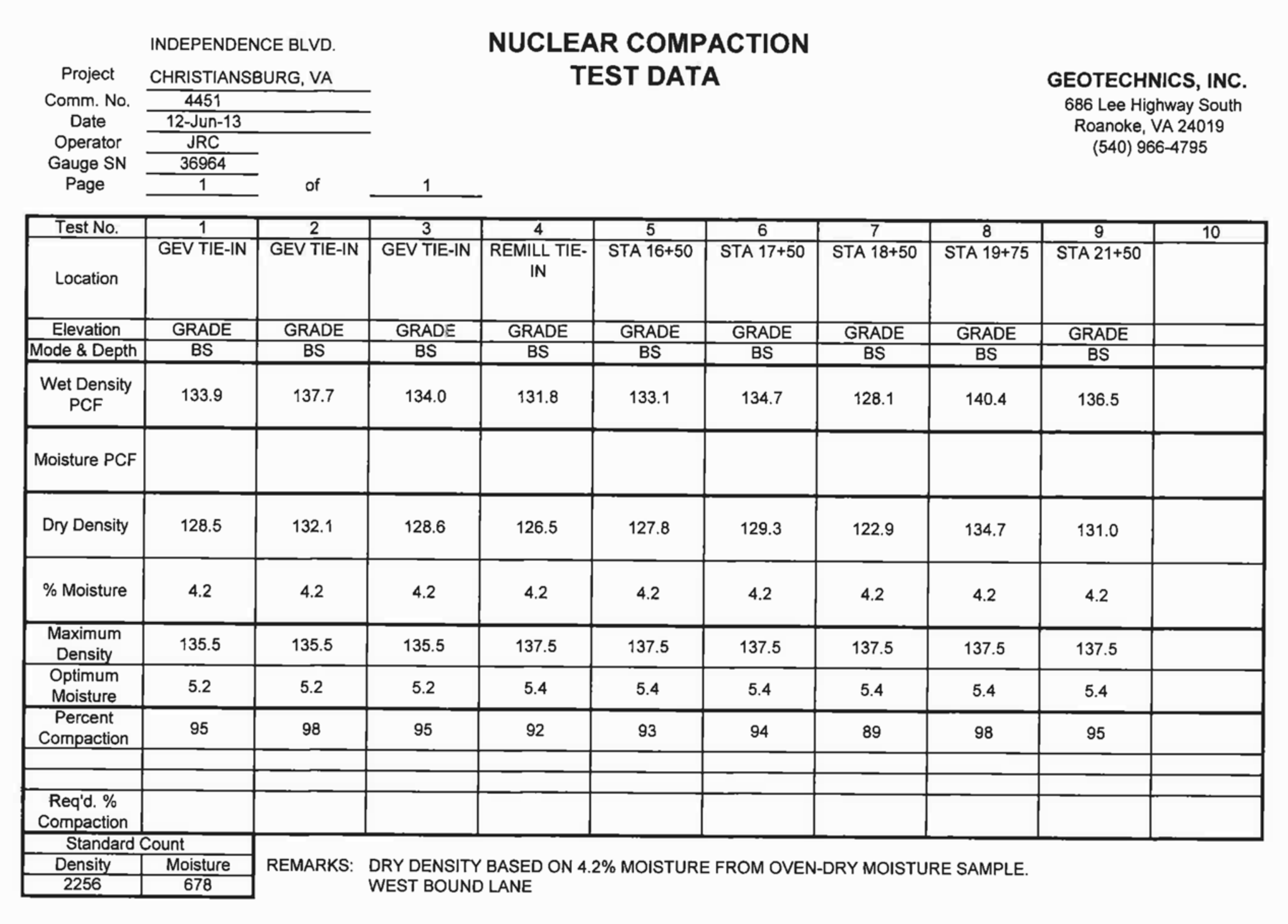
Test No.	11	12	13	14	15	16	17	18	19	20
Location	STA 36+50	STA 40	END	END						
Elevation	GRADE	GRADE	GRADE	GRADE						
Mode & Depth	BS	BS	BS	BS						
Wet Density PCF	135.3	135.6	139.4	121.8						
Moisture PCF										
Dry Density	129.8	130.1	133.8	116.9						
% Moisture	4.2	4.2	4.2	4.2						
Maximum Density	135.5	135.5	135.5	135.5						
Optimum Moisture	5.2	5.2	5.2	5.2						
Percent Compaction	96	96	99	86						
			HANDLAID	HANDLAID						
Req'd. % Compaction										

Standard Count	
Density	Moisture
2256	678

REMARKS:

Figure 63. Nuclear Compaction Test: George Edward Via – 4, Photo from Todd Walters, 2014, Used with Permission

Independence Boulevard



INDEPENDENCE BLVD.
Project CHRISTIANSBURG, VA
Comm. No. 4451
Date 12-Jun-13
Operator JRC
Gauge SN 36964
Page 1 of 1

NUCLEAR COMPACTION TEST DATA

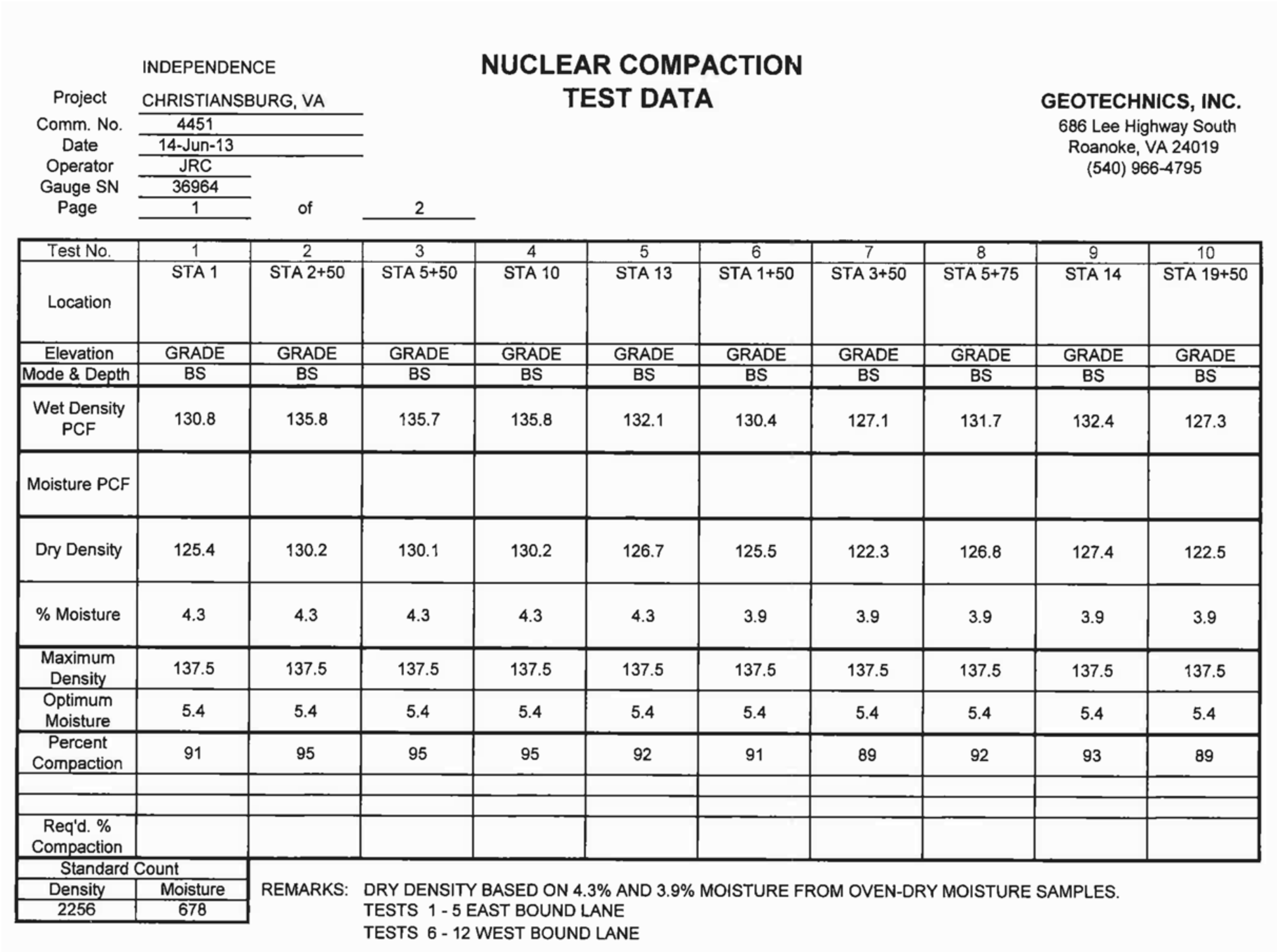
GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Test No.	1	2	3	4	5	6	7	8	9	10
Location	GEV TIE-IN	GEV TIE-IN	GEV TIE-IN	REMILL TIE-IN	STA 16+50	STA 17+50	STA 18+50	STA 19+75	STA 21+50	
Elevation	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	
Mode & Depth	BS	BS	BS	BS	BS	BS	BS	BS	BS	
Wet Density PCF	133.9	137.7	134.0	131.8	133.1	134.7	128.1	140.4	136.5	
Moisture PCF										
Dry Density	128.5	132.1	128.6	126.5	127.8	129.3	122.9	134.7	131.0	
% Moisture	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	
Maximum Density	135.5	135.5	135.5	137.5	137.5	137.5	137.5	137.5	137.5	
Optimum Moisture	5.2	5.2	5.2	5.4	5.4	5.4	5.4	5.4	5.4	
Percent Compaction	95	98	95	92	93	94	89	98	95	
Req'd. % Compaction										

Standard Count	
Density	Moisture
2256	678

REMARKS: DRY DENSITY BASED ON 4.2% MOISTURE FROM OVEN-DRY MOISTURE SAMPLE.
WEST BOUND LANE

Figure 64. Nuclear Compaction Test: Independence Boulevard – 1, Photo from Todd Walters, 2014, Used with Permission



INDEPENDENCE

NUCLEAR COMPACTION TEST DATA

Project CHRISTIANSBURG, VA
Comm. No. 4451
Date 14-Jun-13
Operator JRC
Gauge SN 36964
Page 1 of 2

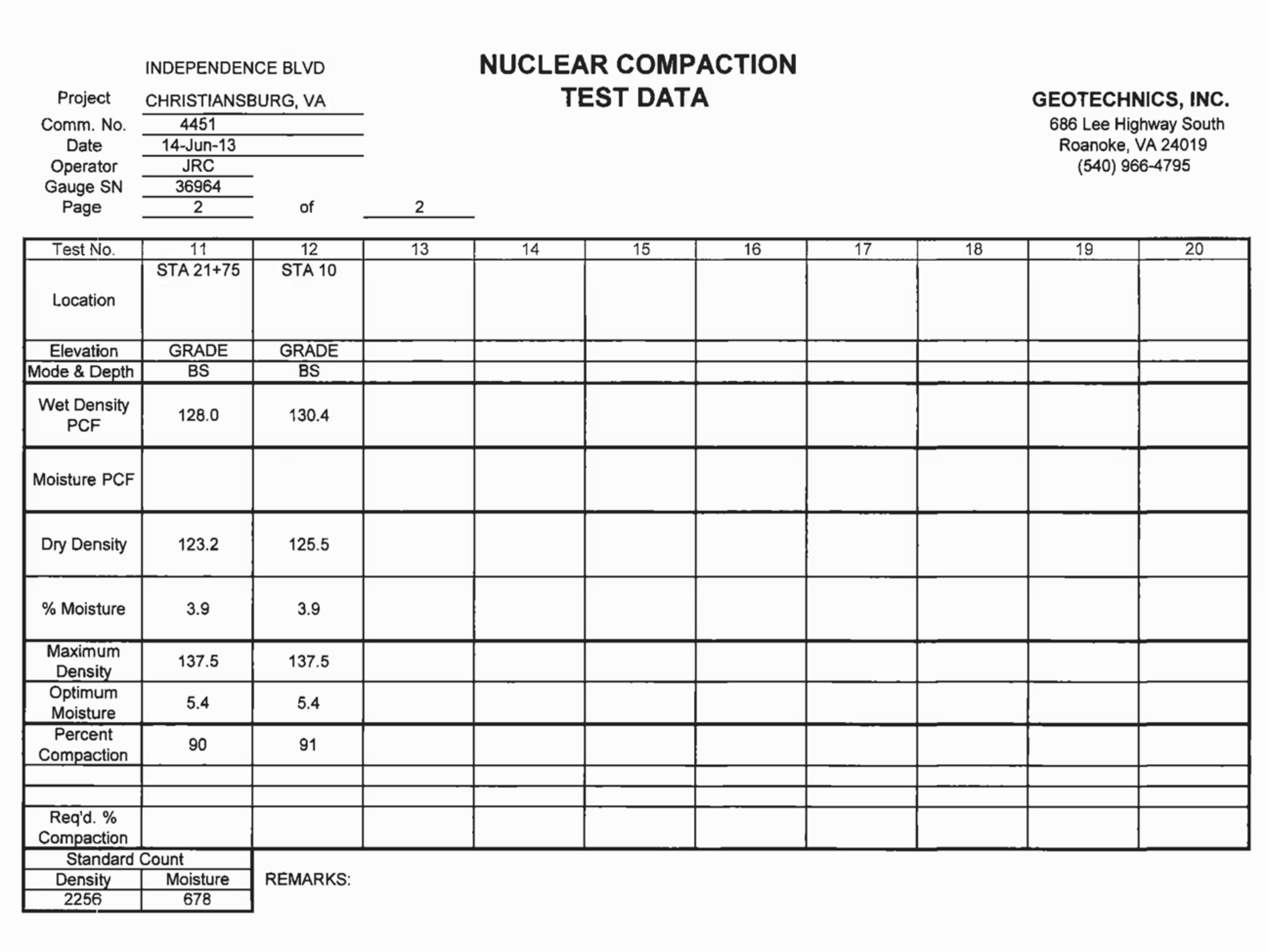
GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Test No.	1	2	3	4	5	6	7	8	9	10
Location	STA 1	STA 2+50	STA 5+50	STA 10	STA 13	STA 1+50	STA 3+50	STA 5+75	STA 14	STA 19+50
Elevation	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE
Mode & Depth	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS
Wet Density PCF	130.8	135.8	135.7	135.8	132.1	130.4	127.1	131.7	132.4	127.3
Moisture PCF										
Dry Density	125.4	130.2	130.1	130.2	126.7	125.5	122.3	126.8	127.4	122.5
% Moisture	4.3	4.3	4.3	4.3	4.3	3.9	3.9	3.9	3.9	3.9
Maximum Density	137.5	137.5	137.5	137.5	137.5	137.5	137.5	137.5	137.5	137.5
Optimum Moisture	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Percent Compaction	91	95	95	95	92	91	89	92	93	89
Req'd. % Compaction										

Standard Count	
Density	Moisture
2256	678

REMARKS: DRY DENSITY BASED ON 4.3% AND 3.9% MOISTURE FROM OVEN-DRY MOISTURE SAMPLES.
TESTS 1 - 5 EAST BOUND LANE
TESTS 6 - 12 WEST BOUND LANE

Figure 65. Nuclear Compaction Test: Independence Boulevard – 2, Photo from Todd Walters, 2014, Used with Permission



INDEPENDENCE BLVD

NUCLEAR COMPACTION
TEST DATA

Project CHRISTIANSBURG, VA
Comm. No. 4451
Date 14-Jun-13
Operator JRC
Gauge SN 36964
Page 2 of 2

GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

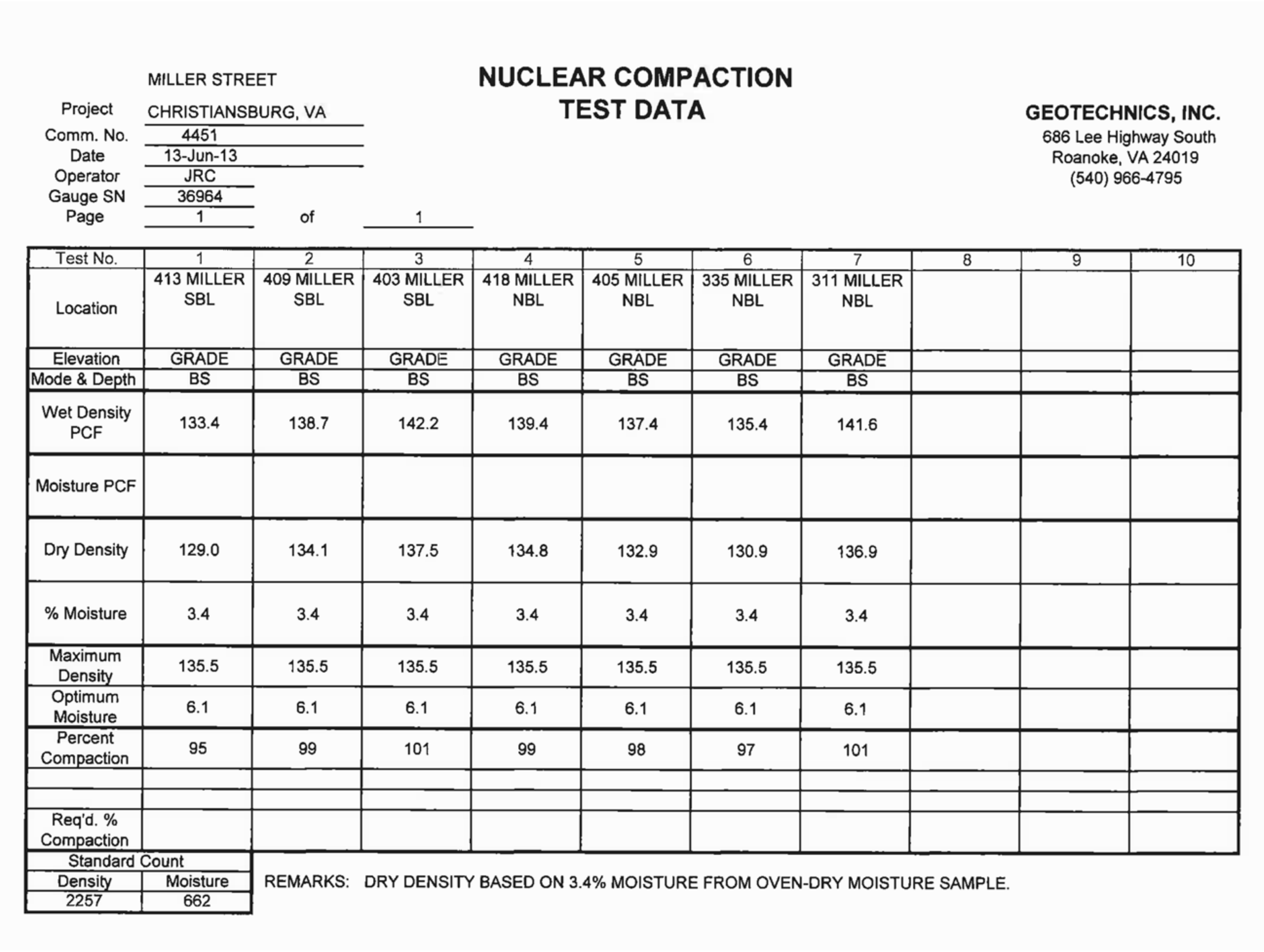
Test No.	11	12	13	14	15	16	17	18	19	20
Location	STA 21+75	STA 10								
Elevation	GRADE	GRADE								
Mode & Depth	BS	BS								
Wet Density PCF	128.0	130.4								
Moisture PCF										
Dry Density	123.2	125.5								
% Moisture	3.9	3.9								
Maximum Density	137.5	137.5								
Optimum Moisture	5.4	5.4								
Percent Compaction	90	91								
Req'd. % Compaction										

Standard Count	
Density	Moisture
2256	678

REMARKS:

Figure 66. Nuclear Compaction Test: Independence Boulevard – 3, Photo from Todd Walters, 2014, Used with Permission

Miller Street



MILLER STREET
Project CHRISTIANSBURG, VA
Comm. No. 4451
Date 13-Jun-13
Operator JRC
Gauge SN 36964
Page 1 of 1

NUCLEAR COMPACTION TEST DATA

GEOTECHNICS, INC.
686 Lee Highway South
Roanoke, VA 24019
(540) 966-4795

Test No.	1	2	3	4	5	6	7	8	9	10
Location	413 MILLER SBL	409 MILLER SBL	403 MILLER SBL	418 MILLER NBL	405 MILLER NBL	335 MILLER NBL	311 MILLER NBL			
Elevation	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE	GRADE			
Mode & Depth	BS	BS	BS	BS	BS	BS	BS			
Wet Density PCF	133.4	138.7	142.2	139.4	137.4	135.4	141.6			
Moisture PCF										
Dry Density	129.0	134.1	137.5	134.8	132.9	130.9	136.9			
% Moisture	3.4	3.4	3.4	3.4	3.4	3.4	3.4			
Maximum Density	135.5	135.5	135.5	135.5	135.5	135.5	135.5			
Optimum Moisture	6.1	6.1	6.1	6.1	6.1	6.1	6.1			
Percent Compaction	95	99	101	99	98	97	101			
Req'd. % Compaction										

Standard Count	
Density	Moisture
2257	662

REMARKS: DRY DENSITY BASED ON 3.4% MOISTURE FROM OVEN-DRY MOISTURE SAMPLE.

Figure 67. Nuclear Compaction Test: Miller Street, Photo from Todd Walters, 2014, Used with Permission

APPENDIX D: FWD AND GPR DATA IMAGERY FOR CHRISTIANSBURG, VA

Screenshot samples of the GPR data are included in this appendix. The software producing the images of the samples was RADAN 7.0.

South Franklin Street

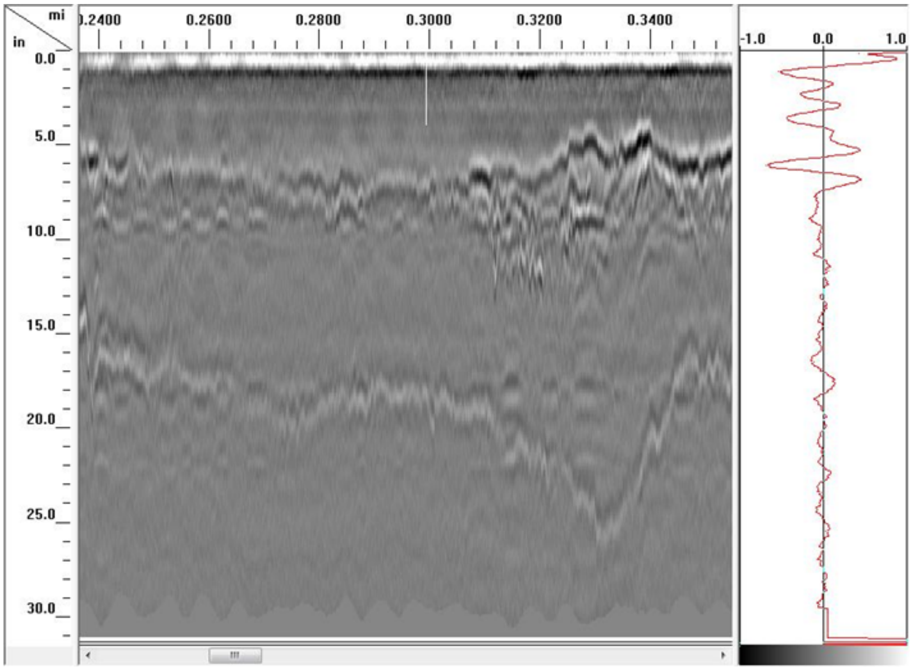


Figure 68. GPR Imagery: South Franklin Street 0.24 – 0.34 mi (starting near Route 615)

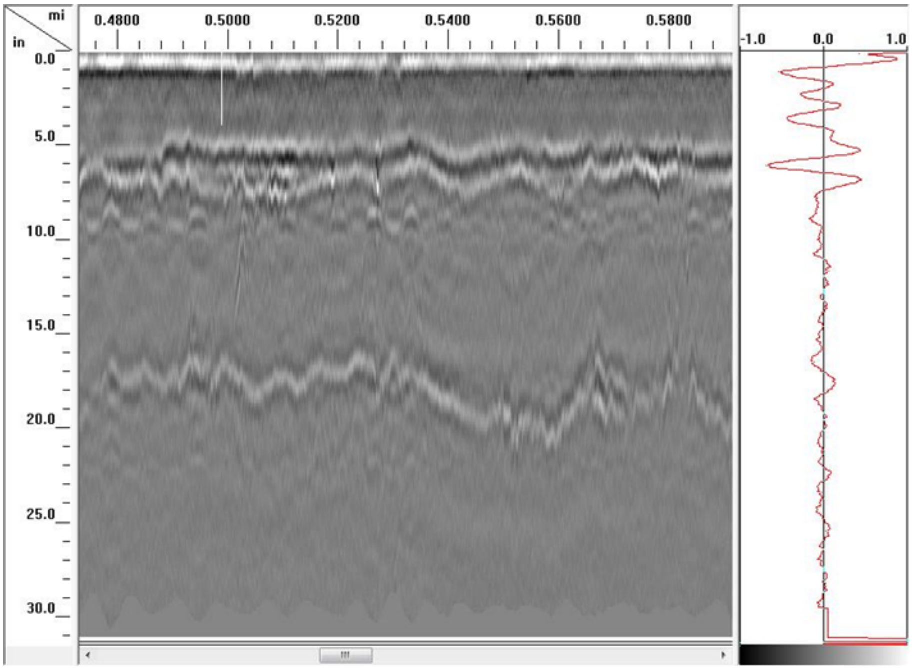


Figure 69. GPR Imagery: South Franklin Street 0.48 – 0.58 mi

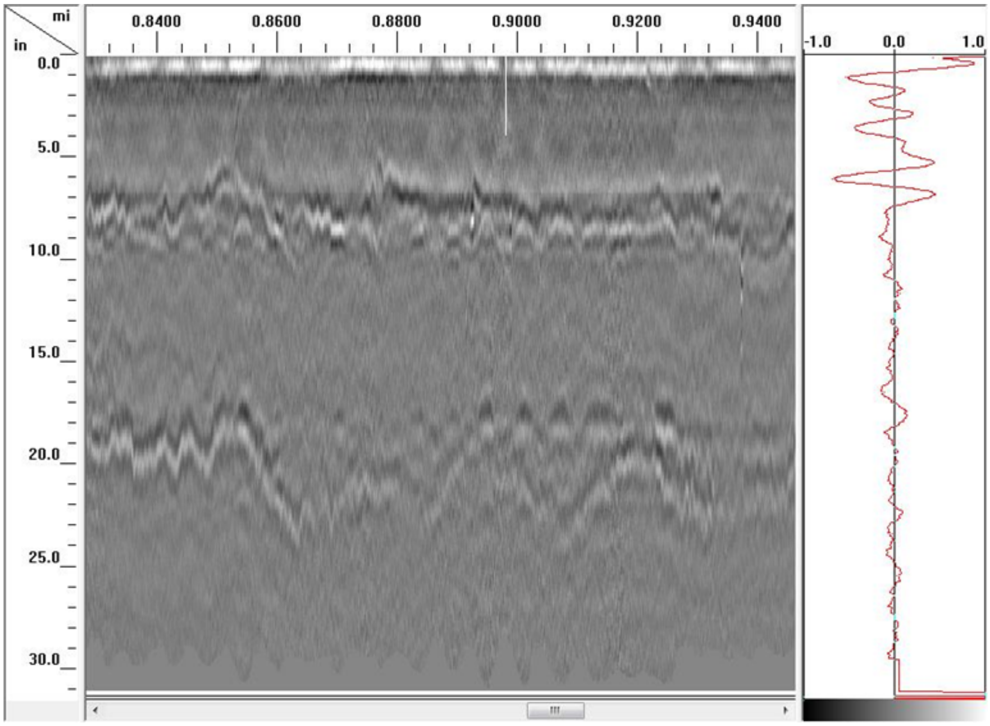


Figure 70. GPR Imagery: South Franklin Street 0.84 – 0.94 mi

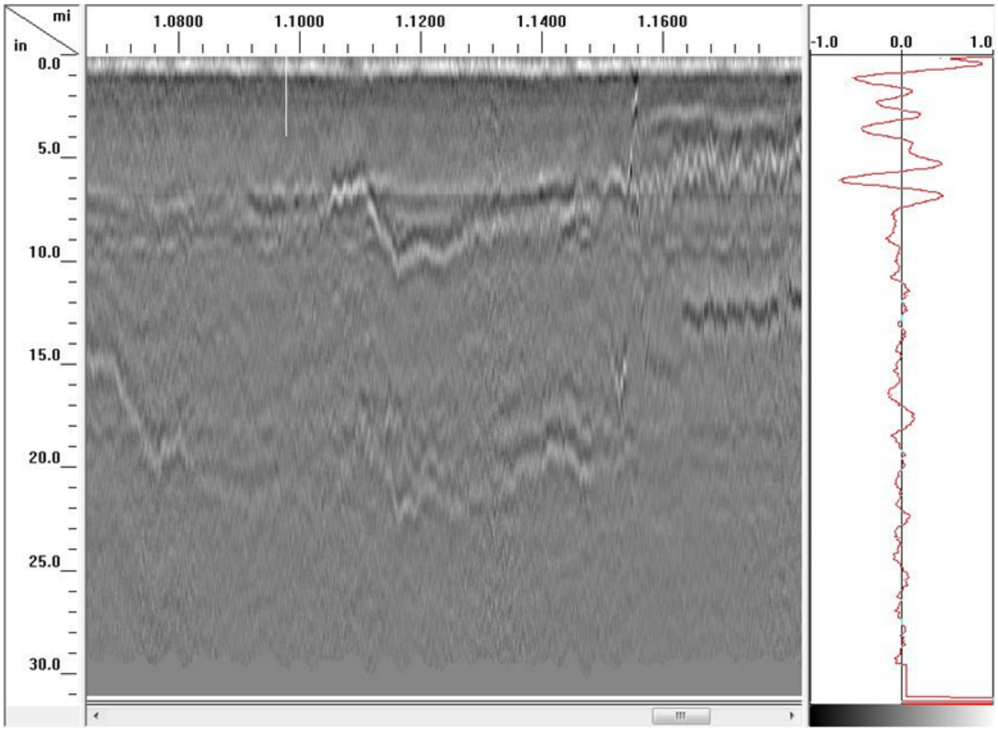


Figure 71. GPR Imagery: 1.08 – 1.15 mi (I-81 Overpass starts at 1.15 mi)

George Edward Via

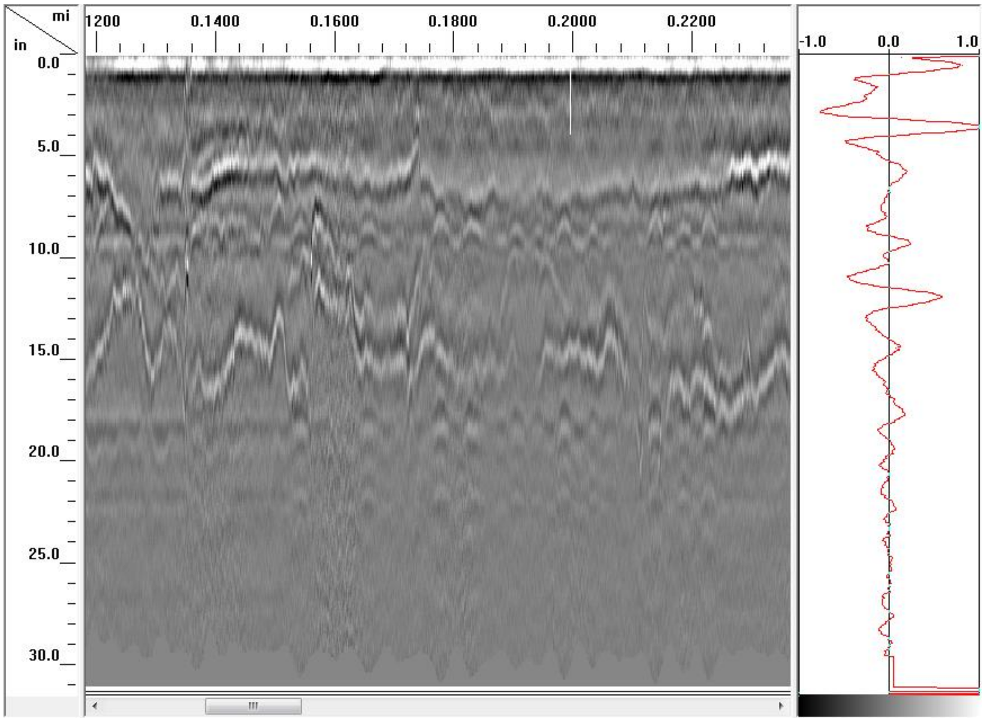


Figure 72. GPR Imagery: George Edward Via 0.12 – 0.22 mi (Starting at Cul-de-Sac)

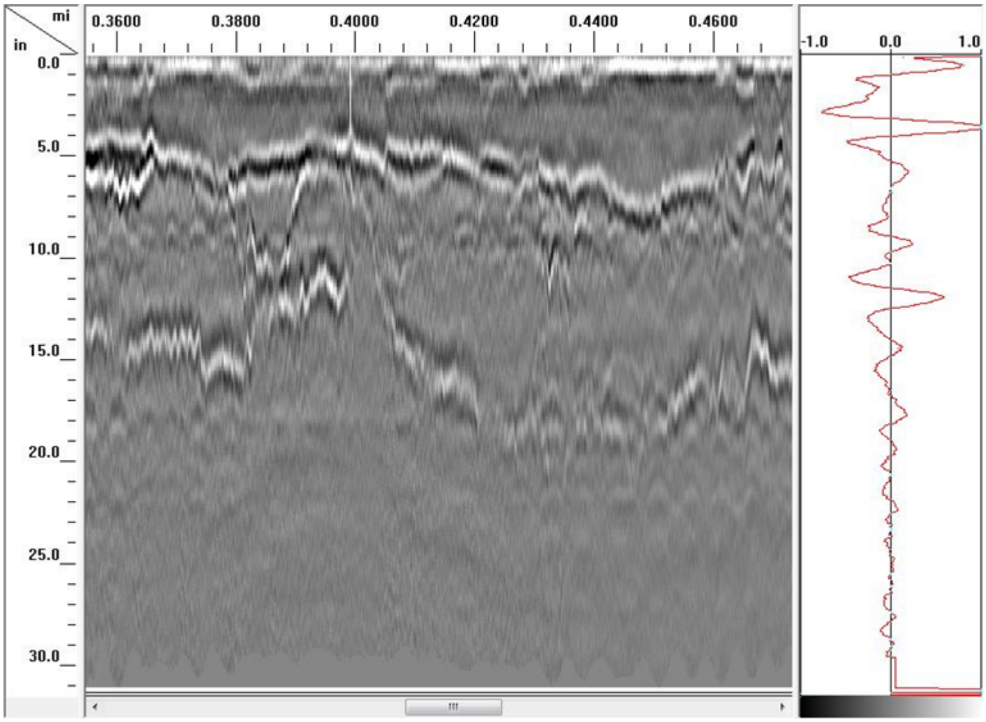


Figure 73. GPR Imagery: George Edward Via 0.35 – 0.46 mi

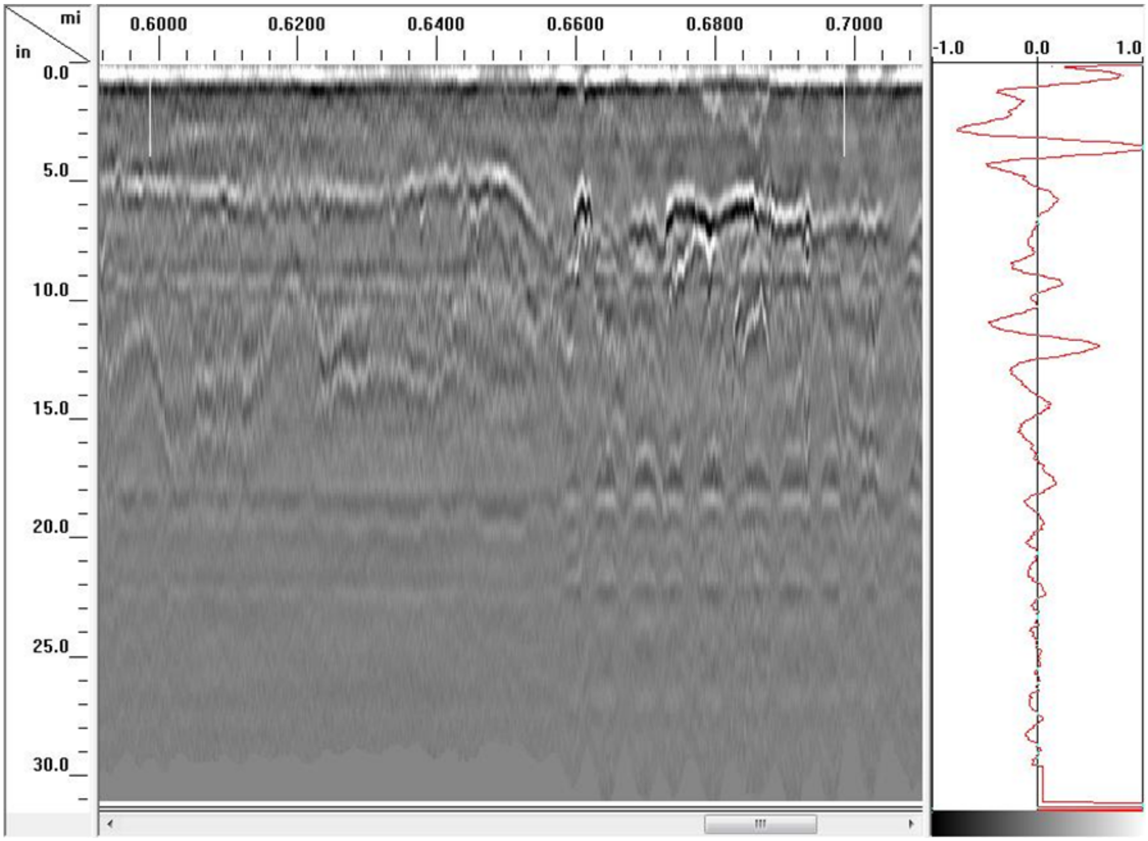


Figure 74. GPR Imagery: George Edward Via 0.60 – 0.70 mi

Independence Boulevard

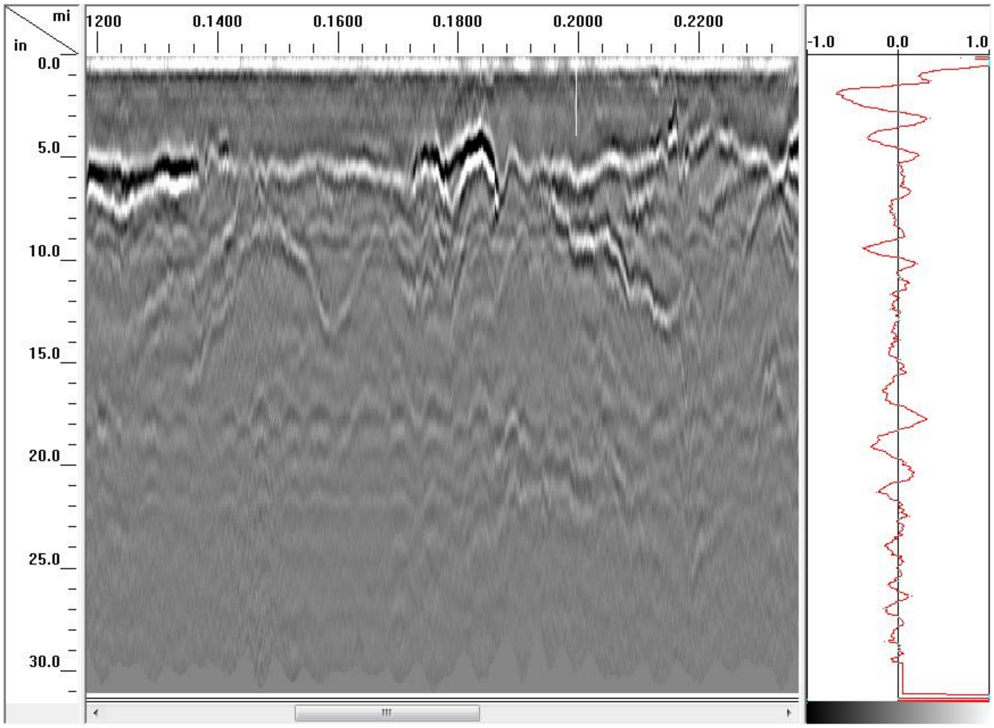


Figure 75. GPR Imagery: Independence Boulevard 0.12 – 0.22mi (Starting near High School entrance)

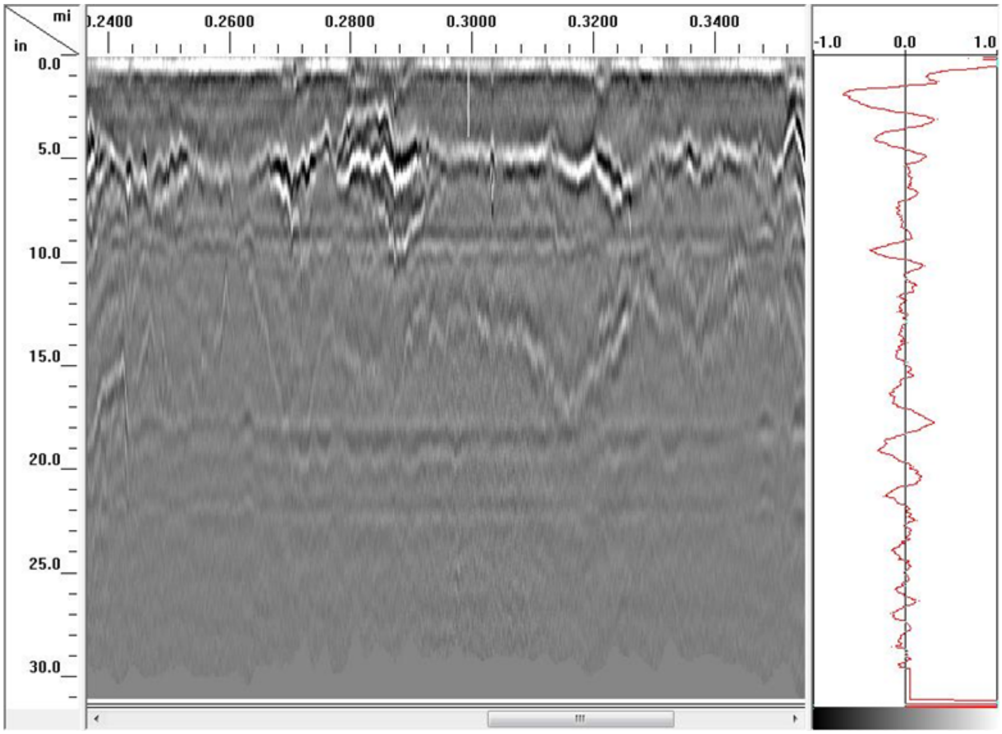


Figure 76. GPR Imagery: Independence Boulevard 0.24 – 0.34 mi

Miller Street

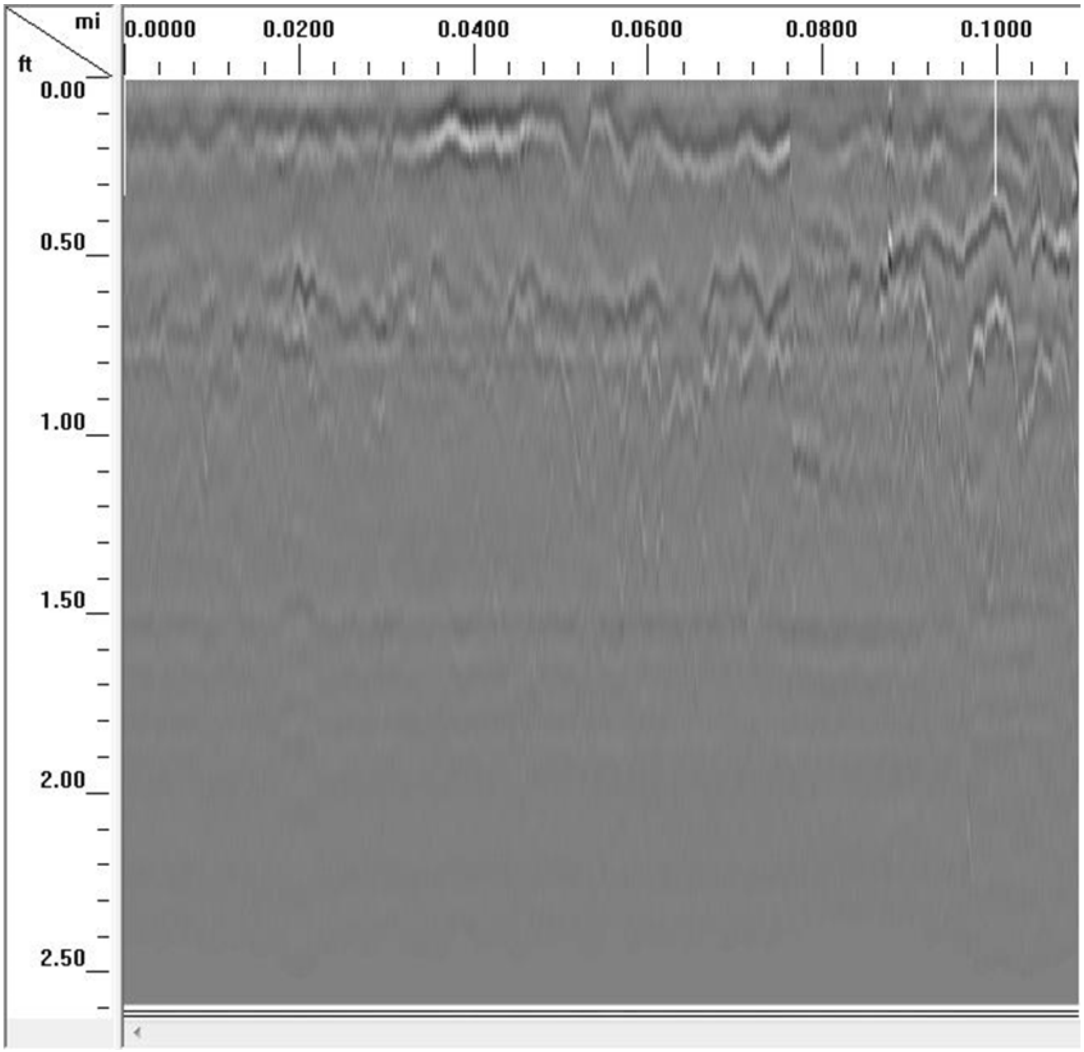


Figure 77. GPR Imagery: Miller Street 0.00 – 0.10 mi

APPENDIX E: FWD AND GPR DATA ANALYSIS FOR CHRISTIANSBURG, VA

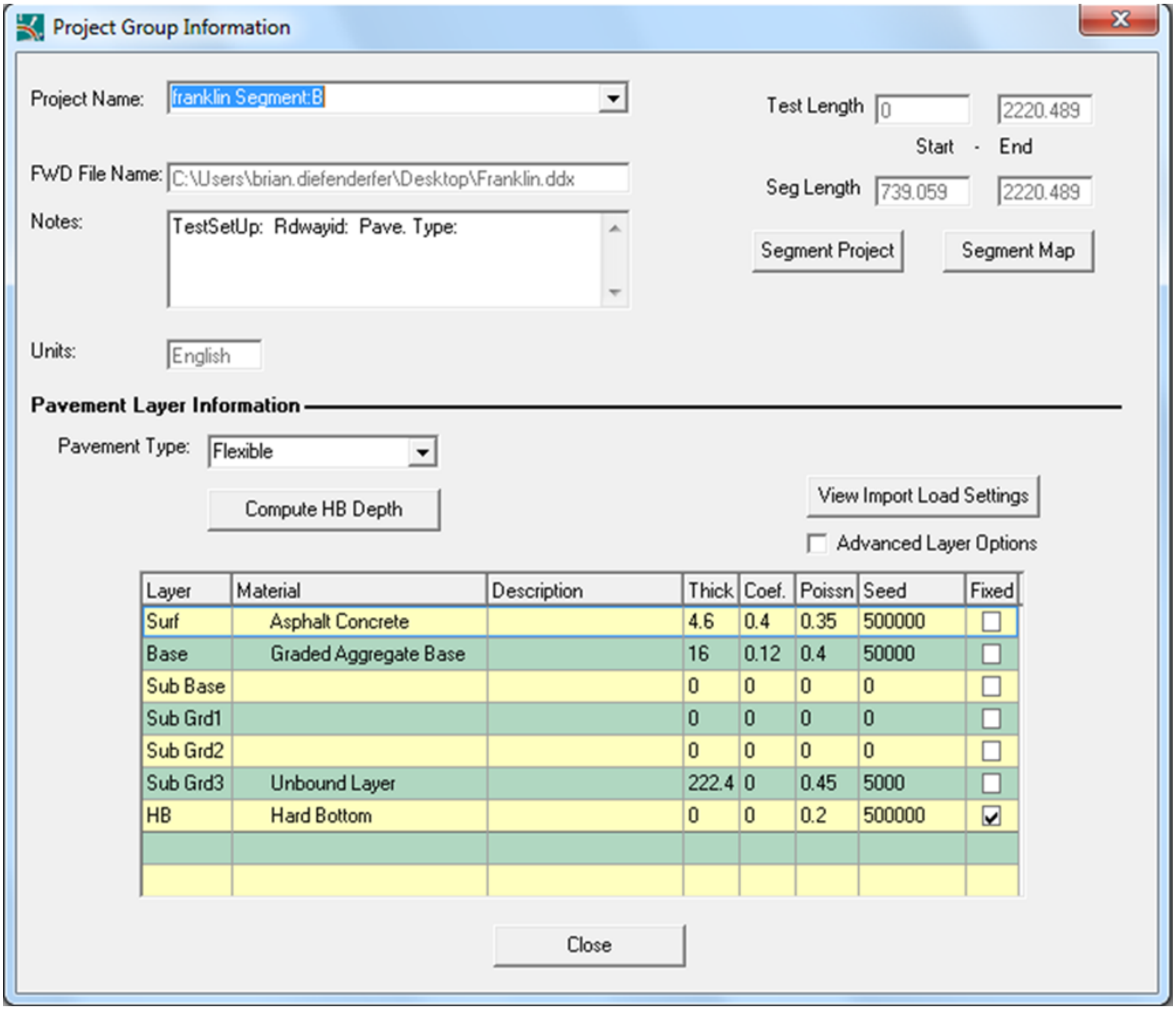
After the layer interfaces were identified in RADAN 7.0 software, the data was exported into Microsoft Excel. A running average of the layer depth was taken for every 0.1 miles. These values can be found in the tables below.

South Franklin Street

Table 28. RADAN Outputs: South Franklin Street

Dist. (mi)	Average Layer (in)
0.10	4.86
0.20	5.49
0.30	4.39
0.40	4.04
0.40	4.55
0.50	4.20
0.60	4.54
0.70	4.59

After the average depth of the layers in South Franklin Street were determined, this data was used as inputs in ModTag software with the FWD data.



Project Name: franklin Segment:B

FWD File Name: C:\Users\brian.diefenderfer\Desktop\Franklin.ddx

Notes: TestSetUp: Rdwayid: Pave. Type:

Units: English

Test Length 0 2220.489

Start - End

Seg Length 739.059 2220.489

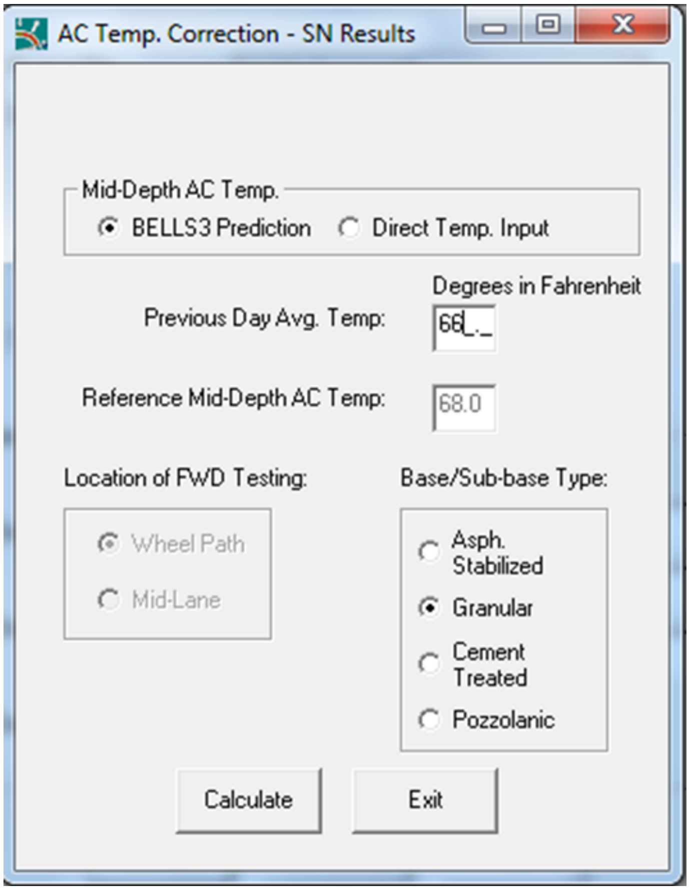
Pavement Layer Information

Pavement Type: Flexible

☐ Advanced Layer Options

Layer	Material	Description	Thick	Coef.	Poissn	Seed	Fixed
Surf	Asphalt Concrete		4.6	0.4	0.35	500000	☐
Base	Graded Aggregate Base		16	0.12	0.4	50000	☐
Sub Base			0	0	0	0	☐
Sub Grd1			0	0	0	0	☐
Sub Grd2			0	0	0	0	☐
Sub Grd3	Unbound Layer		222.4	0	0.45	5000	☐
HB	Hard Bottom		0	0	0.2	500000	☑

Figure 78. ModTag Inputs: South Franklin Street, Hard Bottom Depth and Layer Assumptions



AC Temp. Correction - SN Results

Mid-Depth AC Temp.

● BELLS3 Prediction ○ Direct Temp. Input

Degrees in Fahrenheit

Previous Day Avg. Temp: 66_._

Reference Mid-Depth AC Temp: 68.0

Location of FWD Testing:

● Wheel Path

○ Mid-Lane

Base/Sub-base Type:

○ Asph. Stabilized

● Granular

○ Cement Treated

○ Pozzolanic

Figure 79. ModTag Inputs: South Franklin Street, Temperature Correction

George Edward Via

Table 29. RADAN Outputs: George Edward Via

Dist. (mi)	Average Layer 1 (in)	Average Layer 2 (in)
0.00	4.63	7.25
0.10	4.75	6.90
0.20	4.33	7.09
0.30	3.61	7.11
0.40	4.55	7.59
0.50	4.20	6.87
0.60	4.54	7.30
0.70	4.59	7.10

Independence Boulevard

Table 30. RADAN Outputs: Independence Boulevard

Dist. (mi)	Average Layer 1 (in)	Average Layer 2 (in)
0.00	3.51	6.25
0.10	3.66	6.12
0.20	3.31	6.15
0.30	3.69	6.28
0.40	3.71	6.41

Miller Street

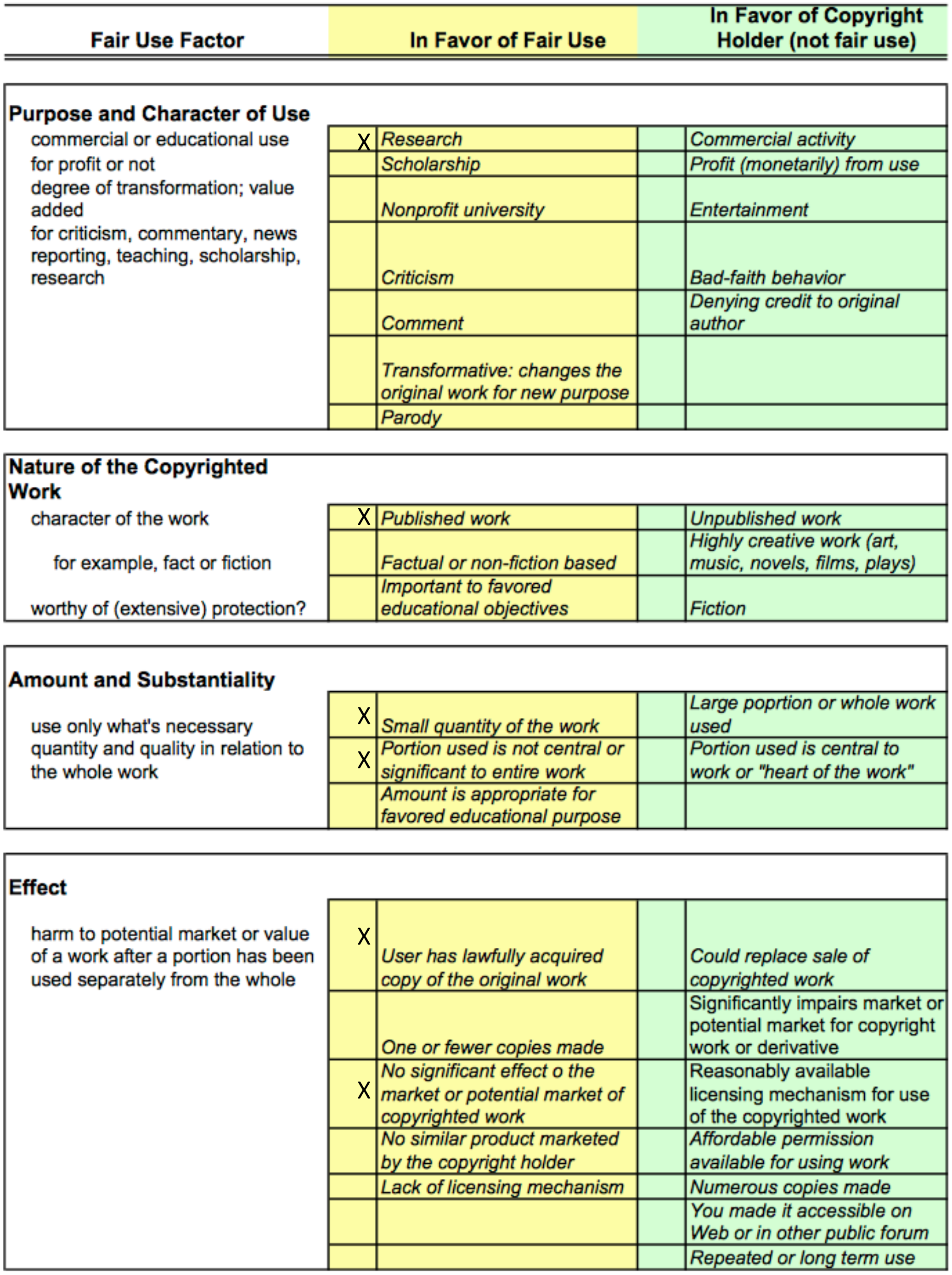
Table 31. RADAN Outputs: Miller Street

Dist. (mi)	Average Layer 1 (in)	Average Layer 2 (in)
0.00	2.25	6.34
0.05	2.64	5.72
0.10	2.43	5.24

APPENDIX F: FAIR USE

As a test of fair use in ETDs at Virginia Tech:

Stroup-Gardiner, M. (2011). "NCHRP Synthesis 421: Recycling and Reclamation of Asphalt Pavements Using In-Place Methods," Transportation Research Board of the National Academies, Washington, D.C.



Fair Use Factor		In Favor of Fair Use		In Favor of Copyright Holder (not fair use)
Purpose and Character of Use				
commercial or educational use	X	*Research*		*Commercial activity*
for profit or not		*Scholarship*		*Profit (monetarily) from use*
degree of transformation; value added		*Nonprofit university*		*Entertainment*
for criticism, commentary, news reporting, teaching, scholarship, research		*Criticism*		*Bad-faith behavior*
		Comment		*Denying credit to original author*
		Transformative: changes the original work for new purpose		
		Parody		
Nature of the Copyrighted Work				
character of the work	X	*Published work*		*Unpublished work*
for example, fact or fiction		*Factual or non-fiction based*		*Highly creative work (art, music, novels, films, plays)*
worthy of (extensive) protection?		*Important to favored educational objectives*		*Fiction*
Amount and Substantiality				
use only what's necessary	X	*Small quantity of the work*		*Large poprtion or whole work used*
quantity and quality in relation to the whole work	X	*Portion used is not central or significant to entire work*		*Portion used is central to work or "heart of the work"*
		Amount is appropriate for favored educational purpose		
Effect				
harm to potential market or value of a work after a portion has been used separately from the whole	X	*User has lawfully acquired copy of the original work*		*Could replace sale of copyrighted work*
		One or fewer copies made		Significantly impairs market or potential market for copyright work or derivative
	X	*No significant effect o the market or potential market of copyrighted work*		Reasonably available licensing mechanism for use of the copyrighted work
		No similar product marketed by the copyright holder		*Affordable permission available for using work*
		Lack of licensing mechanism		*Numerous copies made*
				You made it accessible on Web or in other public forum
				Repeated or long term use