SERRI Report 70015-004

RAPID PAVEMENT REPAIR GUIDANCE IN RESPONSE TO HURRICANE DAMAGE

SERRI Project: *Increasing Community Disaster Resilience Through Targeted Strengthening of Critical Infrastructure*

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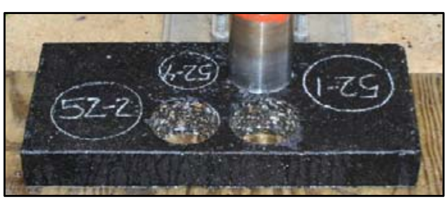

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16. **Abstract**

This report provides guidance for rapid repair of pavements immediately after a natural disaster such as a hurricane. The methods discussed in the report are to be implemented immediately after the disaster and are to provide up to 60 days of service life. The approaches are not intended to be permanent pavement repairs. The primary goal of the research was to enhance the preparedness of Emergency Management Agencies by developing protocols for quickly and accurately evaluating, prioritizing and repairing pavement networks post natural disaster for initial response operations.

The research first developed pavement damage categories to allow generalized identification of the type, severity, and extent of damage. Guidance was provided on prioritization of routes to the desired location. Using the damage categories and route prioritization guidance, applicable repair techniques were discussed and recommended as appropriate for the condition of interest. A substantial effort was also undertaken related to testing and analysis of hot mixed warm compacted asphalt incorporating warm mix additives. The results were that the approach appears viable for emergency construction applications.

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CHAPTER 1 – INTRODUCTION

1.1 Incorporation into the *National Response Framework*

The *National Response Framework* (*NRF*) is a document that guides the United States when conducting all-hazards response (response refers to immediate actions to save lives, protect property and the environment, and meet basic human needs). This framework is entailed in the NRF (2008), which has complimentary material found in print and online. The *NRF* is a continuation of previous federal level planning documents (e.g. Federal Response Plan of 1992), and serves as the state of the art in responding to disaster events. The following paragraphs summarize how the research conducted in Task Order 4000064719 could be applicable to the *NRF* and in what manner. The tone of the paragraphs assumes the reader is at least casually familiar with the *NRF* and supporting documentation.

The *Stafford Act* is a key piece of legislation regarding disaster response and recovery. Specifically, the *Stafford Act Public Assistance Program* provides disaster assistance to key responding units (e.g. states, local governments). Figure 1 was taken from the NRF (2008) to illustrate the overall disaster funding flowchart that summarizes *Stafford Act* support.

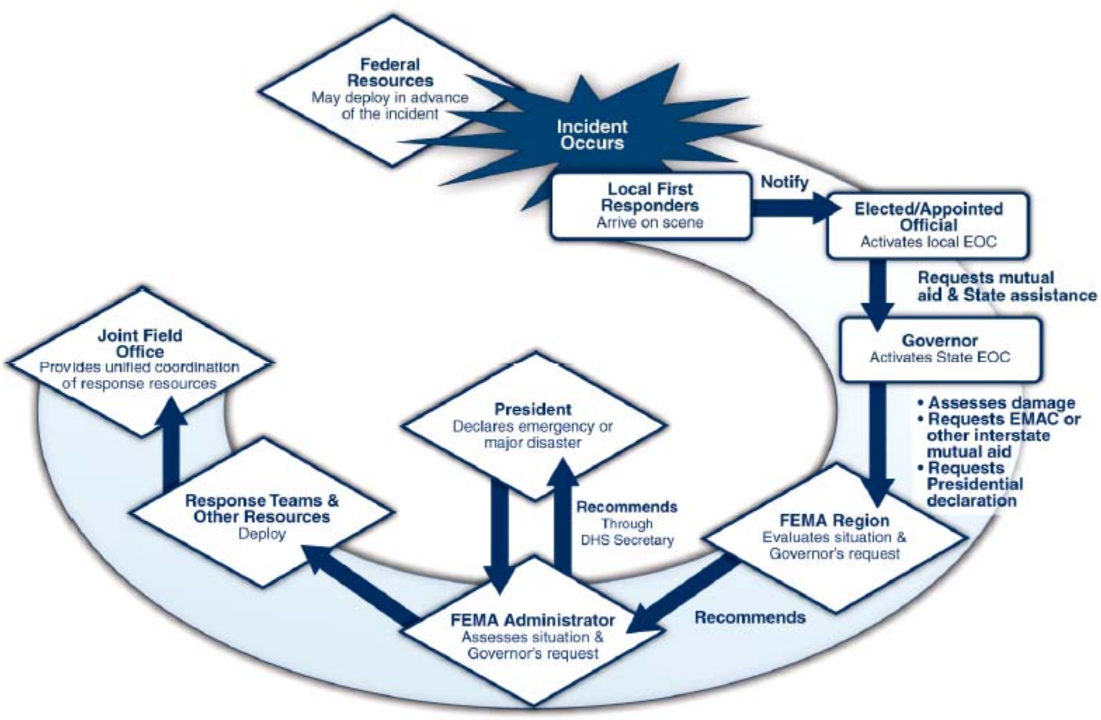

Figure 1: Stafford Act Summary from NRF (2008)

According to NRF (2008), "Resilient communities begin with prepared individuals and depend on the leadership and engagement of local government, nongovernmental organizations, and the private sector." The word "prepared" in the previous sentence is very powerful and could refer to numerous components. The current state of practice in emergency strengthening prior to a water based catastrophe and emergency construction after a water based catastrophe are areas where the authors feel the United States is not fully "prepared". To approach a state of readiness where the United States is "prepared" for these events, concepts need to be developed that are studied to reasonable resolution where design methods and materials are developed (primarily laboratory scale and analytical studies). These methods and materials then need to be demonstrated at full scale, and thereafter training needs to be performed to ensure construction responders can perform the needed tasks. In present day, this level of preparedness does not exist.

The *NRF* is primarily oriented toward implementing nationwide response policy and operational coordination for any domestic event. NRF (2008) focuses on responding to and recovering from incidents that do occur, which is one of four major parts of a larger *National Strategy for Homeland Security*. NRF (2008) states that although some risk may be unavoidable, first responders can effectively anticipate and manage risk through proper training and planning. An entire chapter of NRF (2008) addresses planning. One of the three principal benefits that is listed for planning is "it contributes to unity of effort by providing a common blueprint for activity in the event of an emergency. Planning is a foundational element of both preparedness and response and thus is an essential homeland security activity.

Neither training nor planning appears to be performed to any significant extent related to emergency design and construction for the purpose of rapidly strengthening and/or repairing civil infrastructure. Pre-disaster training programs that result in certifications to perform certain activities would expedite selection of qualified groups in the highly time sensitive environment of a disaster. Having known quantities of certified contractors in place would also be valuable during planning exercises. The end products of the work of Task Order 4000064719 would need to be further developed into full scale demonstrations. Contractors and design firms could then be certified to perform the tasks, if needed.

The response structure of NRF (2008) is based on the *National Incident Management System* (*NIMS*). Several key concepts are presented in the *NIMS*. First, leaders and staff are said to require initial and ongoing training on response principles. Second, classifying types of resources is said to be essential to ensure effectiveness. During a crisis it is stated that there will not be time to determine staff qualifications, and that all stakeholders should regularly exercise incident management and response capabilities. A system similar to this for emergency construction activities could prove useful.

The goals of the research conducted under Task Order 4000064719 align with the needs of the *Hurricane Liaison Team (HLT)*, whose goal is to enhance hurricane disaster response. Response was stated earlier to refer to immediate actions to save lives, protect property and the environment, and meet basic human needs. Task 4 is directly aligned with the stated mission of the *HLT*. All the aforementioned discussion also aligns with *Scenario 10: National Disaster-Major Hurricane* of the National Planning Scenarios that have been established in NRF (2008).

"**National Infrastructure Coordinating Center (NICC)**. The NICC monitors the Nation's critical infrastructure and key resources on an ongoing basis. During an incident, the NICC provides a coordinating forum to share information across infrastructure and key resources sectors through appropriate information-sharing entities such as the Information Sharing and Analysis Centers and the Sector Coordinating Councils." The NICC would benefit from the work performed in Task 4 in that it provides a method to monitor pavement infrastructure immediately after an incident. After observation of the pavement infrastructure in the vicinity of the disaster, information could be sent to responders in the form of direction as to which pavements to repair and how to repair them. The scope of Task 4 did not include the NICC, but the products produced could be reviewed for possible use in the future.

Response at the local level is organized within an *Incident Command System* (*ICS*). At the field level local responders use the *ICS*, which is led by an Incident Commander who has overall authority and responsibility at the incident site. An *Emergency Operations Center* (*EOC*) is a physical location established at the incident site. They can be organized by discipline (e.g. transportation), jurisdiction (e.g. city), Emergency Support Function (e.g. engineering), or a combination. A key *EOC* function is to ensure on scene responders have needed resources. The guidance and materials produced from this task would be a resource that could be provided through the Incident Commander.

Repeatedly preparedness is stated (directly or indirectly) as an essential precursor to response. The *RESPONSE ACTIONS* chapter of NRF (2008) show a circular preparedness cycle consisting of the following four categories: 1) plan; 2) organize, train, and equip; 3) exercise; and 4) evaluate and improve. Under the organize category, assembling well-qualified teams of paid and volunteer staff for essential response and recovery tasks is listed. Also under the organize category is discussion of *Pre-Scripted Mission Assignments*. They are used to assist in planning for and reduction in time necessary to deploy resources that can be tailored for training, development, and to exercise rosters of deployable resources. These assignments would need to be developed for Task 4 related to emergency pavement repair.

Advanced Readiness Contracting is used to ensure contracts are in place before an incident for often needed commodities (a list is provided that does not include construction materials). Geosynthetics, asphalt, and rapid set concrete are construction items that would need to be included in *Advanced Readiness Contracting*. This could be an essential step for some commodities (e.g. rapid set concrete). For example, in Mississippi typical road building materials were under state contract as of the time of this documents publication according to the *State Materials Engineer*. Materials such as geosynthetics and rapid set concrete are not usually set up ahead of time in terms of procurement.

Under the train category the following statement is made: "Professionalism and experience are the foundation upon which successful response is built. Rigorous, ongoing training is thus imperative." Under the *RESPOND* heading of the *RESPONSE ACTIONS* chapter of NRF (2008), response is broken into: 1) gain and maintain situational awareness; 2) activate and deploy resources and capabilities; 3) coordinate response actions. Providing correct and timely information is critical to situational awareness. With regard to activating and deploying resources, the text in the following paragraph is included in NRF (2008).

"**Identifying needs and pre-positioning resources**. When planning for heightened threats or in anticipation of large-scale incidents, local or tribal jurisdictions, states, or the Federal Government should anticipate resources and capabilities that may be needed. Based on asset availability, resources should be pre-positioned and resource teams and other support resources may be placed on alert or deployed to a staging area. As noted above, mobilization and deployment will be most effective when supported by planning that includes pre-scripted mission assignments, advance readiness contracting, and staged resources." This level of detail would be appropriate for the methods investigated in this research, but currently they are not in place.

As stated in NRF (2008), the emphasis on response will gradually transition to an emphasis on recovery. Short-term recovery is defined as immediate, it overlaps with response, and it lasts up to a few weeks. Long-term recovery is beyond the scope of NRF (2008). Long-term recovery can last for months to years, and includes some of the actions involved in short-term recovery. Quoting NRF (2008): "In the short term, recovery is an extension of the response phase in which basic services and functions are restored. In the long term, recovery is a restoration of both the personal lives of individuals and the livelihood of the community." The research in Task 4 is on short term recovery.

Fifteen Emergency Support Functions (ESF's) have been established under *FEMA* coordination. Of the fifteen ESF's, *ESF #1-Transportation*, and *ESF #3-Public Works and Engineering* are applicable to the research conducted under Task Order 4000064719. This research effort is primarily applicable to Regions IV (Atlanta headquarters) and VI (Denton headquarters) of the ten *FEMA* regions.

The primary agency tasked with ESF #1 is the Department of Transportation. Key items in the scope of ESF #1 as they apply to this research are to: 1) monitor and report the status of and damage to transportation systems and infrastructure; and 2) coordinate restoration and recovery of said systems. Quoting ESF #1: "**Monitor and report status of and damage to transportation systems and infrastructure as a result of an incident."** DOT provides this information (via the CMC) to the NOC, NRCC, and NICC, as well as the affected RRCCs and JFOs. Information is compiled from a variety of sources, including ESF #1 supporting agencies, each of DOT's Operating Administrators (through more than 300 field offices nationwide), and key transportation associations and transportation providers. Reports include specific damages sustained, ongoing recovery efforts, alternatives planned or implemented by others, and assessments of the impact." ESF #1 would benefit from the efforts of Task 4.

ESF #3 has a primary coordinator of the *USACE*. The *USACE* is tasked as a support agency for multiple functions including restoring transportation infrastructure. ESF #3 includes: 1) conducting pre-incident and post-incident public works and infrastructure assessments; 2) providing technical and engineering expertise including repair of damaged public infrastructure; 3) construction management; and 4) other scenarios outside the scope of this research.

State, tribal, and local governments are responsible for their own public works and infrastructures. Private sector entities, though, either own or operate a significant portion of the nation's infrastructure and must be included in response and recovery. *DHS/FEMA* are the leads for providing ESF #3 recovery resources, which includes assistance under the *Stafford Act Public Assistance Program*. The *USACE* and *DOD* are ESF #3 coordinators, and are the primary agencies for response. Response and short term recovery overlap in very early stages, thereafter recovery becomes an extension of response.

Support agencies identified within ESF #3 tasked with functions applicable to the current research are discussed as follows. "**Unified Coordination Group:** For a flooding event or other incident where *DOD/USACE* has jurisdictional authority and/or responsibilities for directing or managing major aspects of the response, *DOD/USACE* may be requested to provide a senior official to participate in the Unified Coordination Group." The Unified Coordination Group is field level support for ESF #3. Activities within ESF #3 include but are not limited to: 1) coordination and support of infrastructure risk and vulnerability assessments; 2) participation in pre-incident activities such as assessment team positioning and deploying advance support elements; 3) participation in post-incident assessments of infrastructure; and 4) execution of emergency contracting support for life-saving services that include providing potable drinking water.

The US Department of Agriculture (USDA) provides, if applicable, engineering personnel and equipment to assist with functions including temporary protection of roads and bridges. The Department of the Interior through the Bureau of Reclamation provides engineering support for damage evaluation of water control systems (e.g. dams and levees). Additionally, assistance is provided in damage assessment, structural inspections, and similar. The Department of the Interior through the Office of Wildland Fire Coordination provides assistance, if applicable, in engineering personnel and equipment for assistance with functions including repair of roads and bridges. The Department of Transportation provides technical expertise and repair assistance for restoration of all transportation infrastructure, which includes providing engineering personnel and support to assist with items including damage assessment, structural inspection, and transportation infrastructure restoration. In general, all the aforementioned discussion related to ESF #3 has applicability to this research; Task 4 relates directly to repair of roads.

Responsibility to respond to natural events (e.g. hurricane) is initiated at the local level, particularly with elected officials. Key responsibilities of these officials include: 1) establishing strong working relationships with vital public and private sector entities; 2) training with local partners in advance of an incident; 3) leading and encouraging local leaders to focus on preparedness by participating in planning, training, and exercises. With regard to coordinating response actions, catastrophic events with little to no notice are a precedent for state and federal governments to take proactive measures to mobilize and deploy assets in anticipation of formal requests for assistance. During this period, manufacture or procurement of the paving materials discussed in this report could be performed.

As stated in NRF (2008), government works with private sector groups as partners in emergency management; examples include businesses involved in transportation and civil infrastructure. Clearly defining the role of private sector in disaster response is significant. *Critical Infrastructure and Key Resources* (*CIKR*) are grouped into 18 sections that provide essential functions and services. The research team consisted of private sector groups to ensure they were represented and involved in the research.

1.2 Problem Statement and Objective

There are three primary modes of transportation that can be used during response operations after a natural disaster: land, air and water. Of these, land operations are the most efficient at supplying personnel, equipment and supplies to assist in response. Land transportation routes are comprised of streets, roads, highways and interstates. Each of these is vitally important to the operations required during response operations. A wide variety of vehicles (emergency vehicles, tractor-trailers, recovery equipment, etc.) use these routes to reach the affected area. However, after many natural disasters, such as *Hurricane Katrina*, many of the land transportation routes may be rendered impassable.

During natural disasters (e.g. floods and hurricanes) pavement structures are routinely damaged. Damage can result from the action of waves, tidal surge, water currents or simply flooding of the pavement structure. Resulting from these actions, sections of pavements can be completely destroyed or sufficiently damaged to hinder response operations.

The objective of Task 4 was to develop protocols for quickly and accurately evaluating and prioritizing pavement networks post natural disaster for initial response operations. Protocols, methods and techniques developed within this project were developed to be easily deployable during and immediately after a natural disaster. They should provide the required information to make informed decisions on the pavement sections needing repairs as well as techniques that can be utilized to repair the pavement damage. The intent was not to permanently correct all pavement damage; rather, the intent was to develop protocols, methods and techniques needed to evaluate, prioritize and repair pavement networks for efficiently initiating and maintaining response operations. Figure 2 presents the

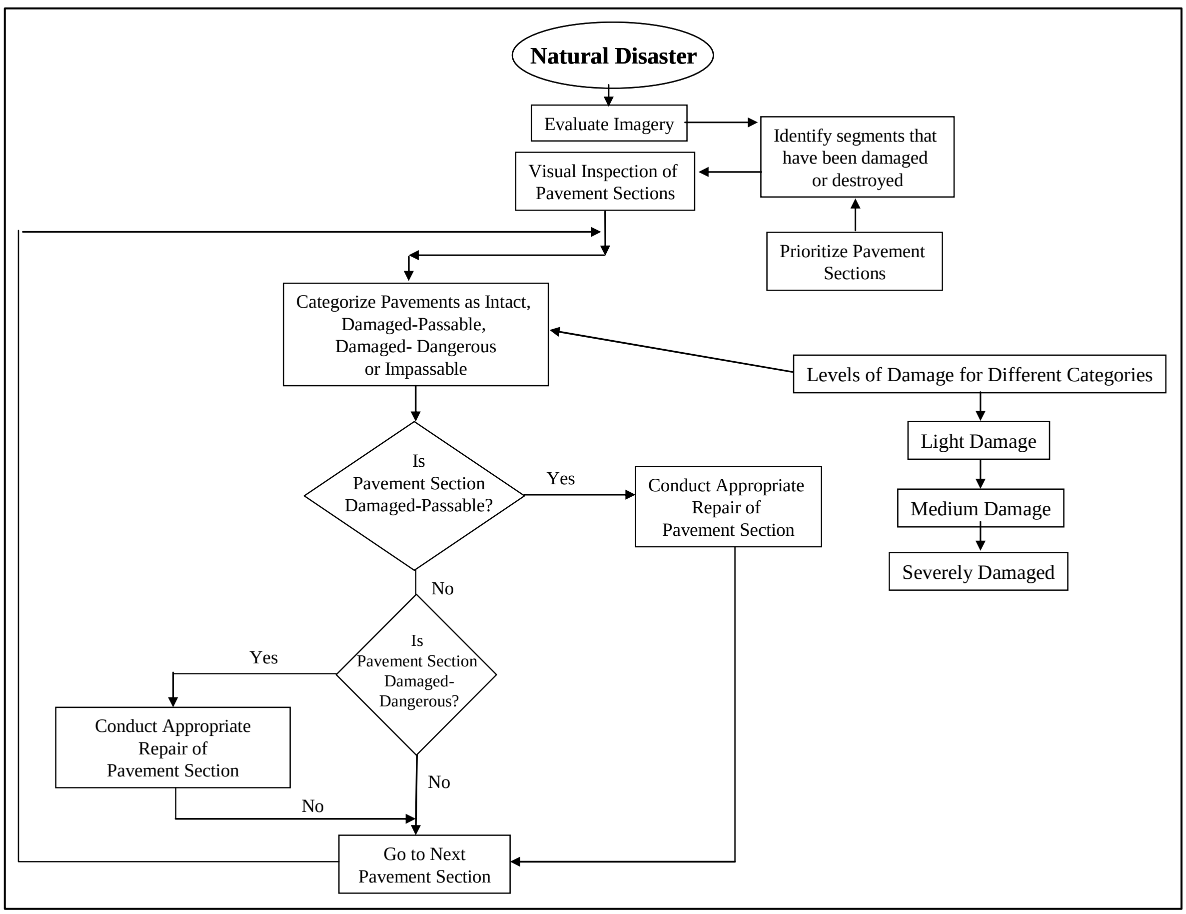

Figure 2: Overall Concept for Rapid Repair of Pavement Sections

overall concept for developing the protocols. Protocols, methods and techniques derived from this research are specifically intended to initiate response activities and will likely be performed during the first few days post disaster. Again, the intention of the methods and techniques is not to provide permanent repairs, but to provide repairs that will perform satisfactorily until permanent repairs can be made. A target performance timeline of 60 days or less was established.

1.3 Scope

This report fully addresses Task 4 of Task Order No. 4000064719 dated 9 September 2008. This report (*SERRI Report 70015-004*) is one of a series of reports performed for the task order. Task 4 included four subtasks as described in the following paragraphs.

Subtask 4a was to develop a method for evaluating/incorporating imagery and to provide an initial assessment of the pavement condition within the affected areas. Both satellite and images from aircraft were considered. The premise of this subtask was that the imagery could be utilized to quickly identify pavement segments that have been damaged or destroyed. Also of importance would be bridges, boxes, or large culverts which were destroyed during the disaster. Bridges, boxes, or large culverts that have been destroyed will need to be bypassed for initial response activities. This information was deemed important to prioritizing pavement repairs.

During Subtask 4b, the researchers developed methods and guidance for visual evaluations of pavements. Four categories of damage were defined: *Intact, Damaged-Passable, Damaged-Dangerous,* and *Impassable*. Categorization of damaged pavement is needed to assist in prioritizing pavement repair as well as selecting appropriate repair strategies.

Subtask 4c involved researching methods, techniques, and/or materials that could be utilized to repair pavements categorized as *Intact, Damaged-Passable* or *Damaged-Dangerous*. Pavements categorized as *Impassable* must be reconstructed instead of repaired.

The final subtask, 4d, was utilized to develop protocols for fast and efficient characterization and repair of pavements immediately following a natural disaster. Providing passable land transportation routes should save lives during initial response and provide the personnel, equipment and supplies needed for early recovery operations.

1.4 Report Format

This report contains seven chapters and eight supporting appendices. The first chapter of this report provides an introduction to the project including discussion of the NRF (2008), the problem statement from which the objective was derived, and the scope of the project. Chapter 2 provides definitions of the four categories of damage: *Intact, Damaged-Passable, Damaged-Dangerous,* and *Impassable*. The third chapter describes the use of imagery and how imagery can be utilized to assist in the prioritization of which roads need to be repaired during initial response operations. Prioritization of pavement repairs is discussed within Chapter 4 of the report. Chapter 5 provides methods and materials that can be utilized for pavement repairs. Chapter 6 discusses selection of repair techniques and Chapter 7 provides conclusions and recommendations.

CHAPTER 2 – CATEGORIZATION OF PAVEMENT DAMAGE

2.1 Introduction

Following the occurrence of a natural disaster, infrastructure can be damaged. Specific to this project, pavement structures can be damaged such that response actions can be hindered. Within the context of this project, the term “response” is defined as in NRF (2008) discussed in Chapter 1 as immediate action to save lives, protect property and the environment, and meet basic human needs. Based upon information accumulated during this project, damage to pavement structures can take many forms; from minor damage to total loss of the pavement structure.

In order to accomplish the overall objective of Task 4 and develop a protocol for evaluating, prioritizing and repairing pavement networks for response actions, a significant effort was expended on defining the types of pavement damage that could be encountered after a natural disaster. Accurate defining of pavement damage is vital to developing and utilizing protocols for repairing the pavement structures to allow effective response actions.

Pavement conditions can vary widely post natural disasters. Therefore, the categorization of pavement damage is tiered. Broadly, the four primary categories of pavement condition include: *Intact, Damaged-Passable, Damaged-Dangerous*, and *Impassable*.

2.2 Intact Pavements

An *Intact* pavement structure is one that was not damaged or has very minimal damage; however, actions may still be needed in order to carry out response operations. Damage to *Intact* pavements may include small potholes or scarring of the pavement surface due to debris passing over the pavement. In many instances, and possibly most, pavements remain *Intact* except debris makes them impassable. Debris can come in the form of wood from damaged buildings or telephone poles, fallen trees, boats or barges, facades of buildings, signs, etc. (Figures 3, 4 and 5). These occurrences are outside the scope of this particular task but will require bulldozers or other material movers to clear. The ability to get the material movers to the appropriate location could be pertinent to this task if damaged pavements exist nearby.

Figure 3: Typical Debris Making Road Impassable

Figure 4: Debris Making Road Near Impassable

Figure 5: A Beached Watercraft Making Road Impassable

2.3 *Damaged-Passable* Pavements

The category of *Damaged-Passable* includes pavements that have been damaged but response personnel can still travel the roadway once debris is cleared. Distresses within the *Damaged-Passable* category could entail potholes or small areas in which the pavement substructure has been eroded. These distresses will generally be caused by wave action prior to the passing of the eye or due to the water flowing back toward the ocean, receding after the passing of the eye (Douglas et al 2004). From a severity standpoint, pavements categorized as *Damaged-Passable* can have varying degrees of damage. For this reason, two severity levels have been developed in order to enhance the ability for selecting the appropriate pavement repair strategy and prioritizing routes. The first severity level is termed *Light Damage*. The *Light Damage* severity level is defined as pavement areas in which the damaged areas are less than 2 to 4 m^2. These types of damaged areas may include relatively small areas of pavement that have washed away near a pavement edge due to the actions of waves or water receding; small areas near bridge abutments or culverts that have washed away (Figure 6); or small areas where the pavement has been damaged due to debris passing overtop of the pavement. Generally, damaged pavements that fall into the *Light Damage* severity level do not extend an entire lane width and do not hinder response activities in other lanes; if available.

Figure 6: Example of *Light Damage* from *Damaged-Passable* Category

The second severity level associated with the *Damaged-Passable* category is *Medium-Damage*. Pavements that fall into this severity level are damaged at least one lane width leaving at least one lane width for travel. These types of damaged areas are generally the result of scour caused by wave action or water receding toward the ocean (Figure 7).

Figure 7: Example of *Medium-Damage* Severity from *Damaged-Passable* Category

2.4 *Damaged-Dangerous* Pavements

The third category of pavement damage is *Damaged-Dangerous*. Damage associated with this category will generally be the result of wave actions or the receding of water and include the scouring away of the underlying pavement structure (Figure 8). In some instances, damage may be in the form of buckled concrete slabs caused by the washing away of subgrade soils near joints. Asphalt pavements may also break apart and appear similar to buckled concrete slabs as subgrade soils are eroded away and the actions of waves reorient the broken pieces (Figure 9). Similar to the *Damaged-Passable* category, the *Damaged-Dangerous* category has two severity levels though they are labeled to signify the heightened need for repair: *Medium-Damage* and *Severely-Damaged*. The *Medium-Damage* severity level encompasses damage that is generally a single lane width. In many instances, the roadbed (or pavement substructure) has been eroded from underneath the pavement surface and the passage of response vehicles near the edge of the damaged area could result in additional pavement damage; hence the dangerous part of the category.

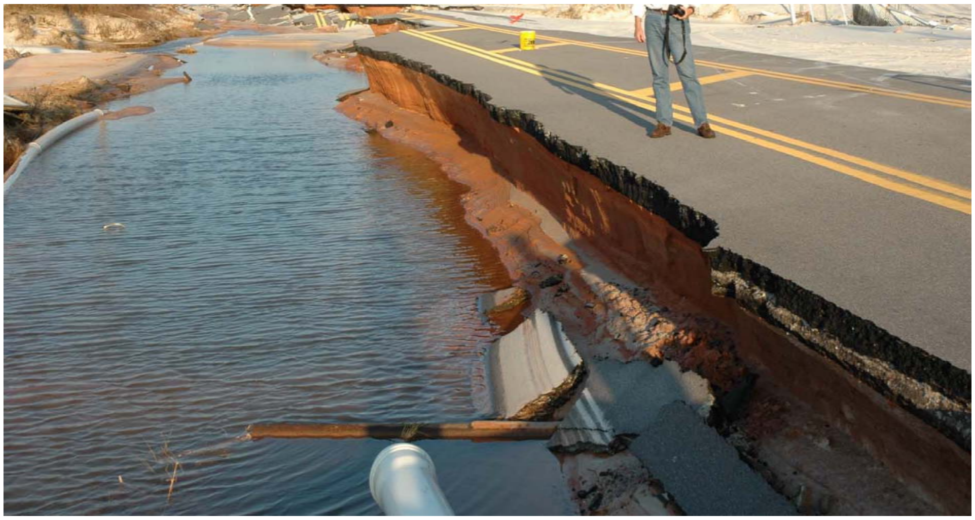

Figure 8: Example of *Medium-Damage* from *Damaged-Dangerous* Category

Figure 9: Example of *Medium-Damage* from *Damaged-Dangerous* Category

The second severity level within the *Damaged-Dangerous* category is *Severely-Damaged*. These pavements have been damaged across all travel lanes; however, response vehicles can pass over the pavements in extreme cases if all-terrain vehicles are utilized. Pavements that fall within this severity level may include full sections of roadway that have been broken apart and the broken pieces reoriented due to tidal surge (Figure 10).

Figure 10: Example of *Severely-Damaged* from *Damaged-Dangerous* Category

2.5 *Impassable* Pavements

The final category of pavement damage is *Impassable*. Pavements that fall into this category have been totally destroyed and may not be traveled in vehicles. In many instances, these pavements have been eroded away totally by the actions of waves or the receding of water back to the ocean (Figure 11).

Figure 11: Example of *Impassable* Damage

2.6 Summary

In the context of rapid pavement repair, pavement damage has been assigned four categories: *Intact*, *Damaged-Passable*, *Damaged-Dangerous*, and *Impassable*. These categories and their associated definitions were developed to assist in prioritizing which pavement segments should be repaired. Figure 12 illustrates the hierarchy of these categories. As pavement damage increases, it will be more difficult to repair the pavement.

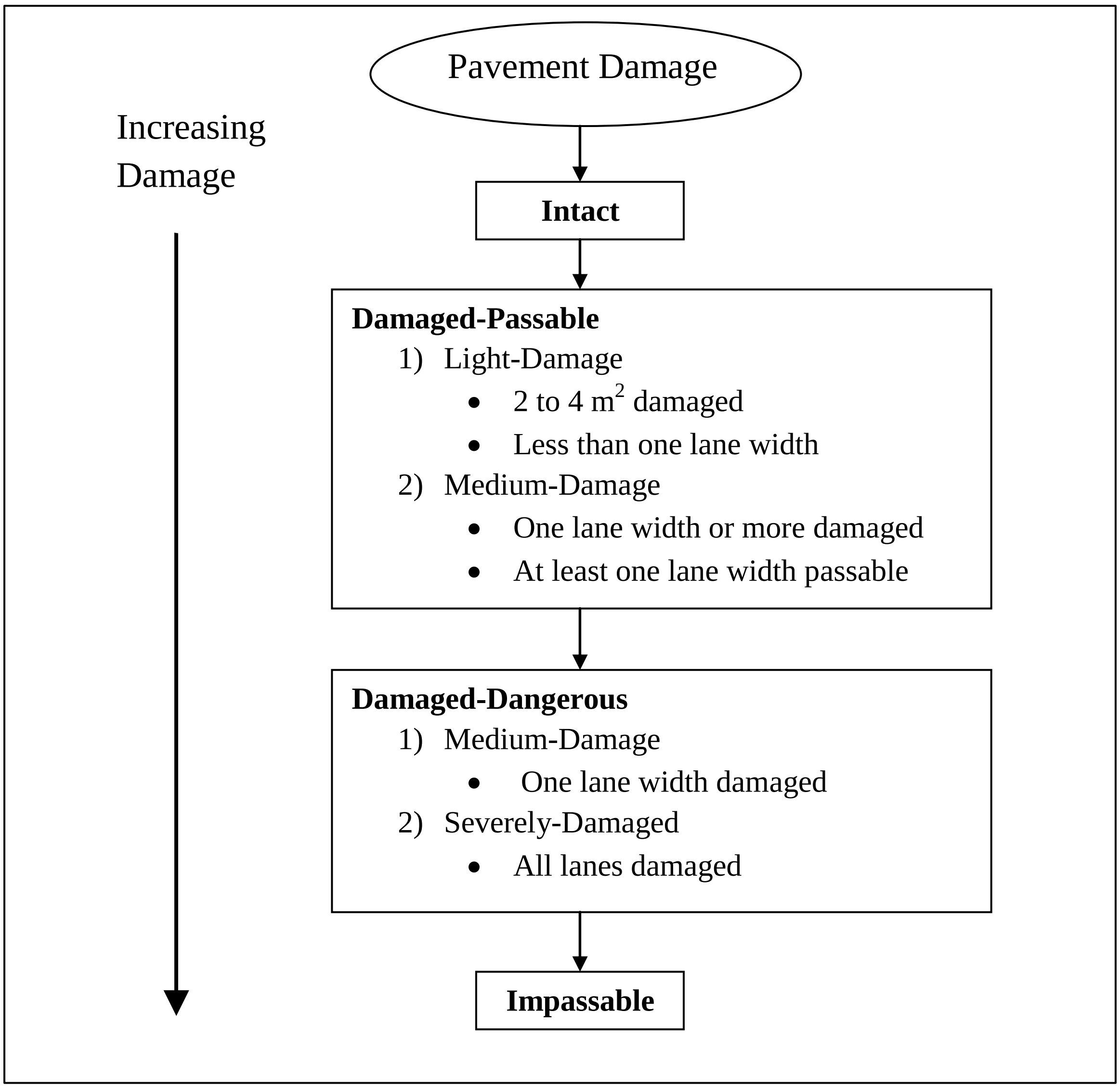

Figure 12: Hierarchy of Pavement Damage

CHAPTER 3 - IMAGERY

3.1 Introduction

As will be described within Chapter 4 of this report, a vital part of prioritizing and conducting rapid repair of pavement sections after a natural disaster is reconnaissance. Reconnaissance is the gathering of data or information about infrastructure such that informed decisions can be made toward the prioritization of routes to initiate response activities. Within this report, two forms of reconnaissance have been recommended: 1) on-site human reconnaissance, and 2) imagery. Imagery generally is obtained from two different sources: satellite and aerial.

3.2 Satellite Imagery

Satellites used for this purpose may be government owned or commercial. There are several issues that must be considered with satellite imagery. First, satellite imagery is limited by the location of the satellite. If satellites are not in an appropriate position following a natural disaster, imagery would not be available. Another possible issue is cloud cover. Cloud cover will remain after the occurrence of a natural disaster for some time period. Satellite images will not be available as long as the cloud cover remains. Typical resolution for satellite imagery is 60 to 180 cm. Some commercial satellites will take images with a 40 cm resolution. For the purpose of reconnaissance, the resolution should be such that enough detail is available to distinguish pavement structures that are impassable due to debris or pavement damage. These resolutions should be sufficient to provide reconnaissance information for prioritizing rapid pavement repair.

3.3 Aerial Imagery

Aerial imagery infers photos or videos taken of the earth’s surface using an airplane or helicopter, generally airplanes. Aerial imagery can be obtained from a variety of altitudes. Aerial mapping is a common technology utilized to chart the horizontal and vertical features of a large area. In order to chart the location of images, Geographic Information System (GIS) data can accompany the images. Cloud cover can hinder aerial mapping; however, in emergency situations, the planes can fly under the cloud cover. When this occurs it will be important that GIS technology be utilized as the image will be of a smaller area and may not include identifiable landmarks. Aerial imagery can collect data to a resolution down to 7 cm. The resolution should be such that enough detail is available to distinguish pavement structures that are impassable due to debris or pavement damage; 7 cm is more than adequate to do so. One potential hindrance to aerial imagery is that planes collecting images may be sharing airspace with aircraft on critical life saving missions. Another potential problem with aerial imagery is high winds. After a disaster such as a hurricane, wind speeds can remain excessive even after landfall. Aerial imagery will not be feasible until conditions become safe.

3.4 Discussion of Imagery Use

Both methods of imagery should be utilized as they become available to aid in prioritization of pavement repairs as the needed resolution for this application can be achieved with either application. As described above, both methods have advantages and disadvantages. Of the two methods, the aerial imagery method may provide more rapid access to images depending upon how soon the cloud cover and high winds decrease. Government agencies have capabilities to conduct both kinds of imagery techniques. Likewise commercial avenues are available for both types of imagery.

Commercial companies should be identified by local Emergency Management Agencies as part of a preparedness plan. It may be prudent to have contracts or memorandums of understanding set up in anticipation of natural disasters. As will be discussed in Chapter 4, proper use of imagery will be a beneficial tool to assist in prioritization of pavement repair. Identification of bridges or culverts that have been destroyed, pavements that have been destroyed, and pavements rendered impassable due to debris will save time prioritizing pavement repairs for response activities. The aforementioned activities are the anticipated uses of imagery. Identification of smaller distresses will be performed with ground reconnaissance rather than imagery.

Images from the National Geospatial-Intelligence Agency (NGA), National Oceanic and Atmospheric Administration (NOAA), or commercial entities could be used in emergency pavement repair. The NGA provided the first comprehensive overview (satellite images) of the damage along the Gulf Coast resulting from *Hurricane Katrina* (The White House 2006). Figure 13 provides example imagery photos taken by NOAA after *Hurricane Katrina*. The approximate ground sample distance (GSD) for each pixel is 37 cm and the images have a 60% forward overlap.

(a) Photo 1 of 4

(b) Photo 2 of 4

(c) Photo 3 of 4

(d) Photo 4 of 4

Figure 13: Example Aerial Imagery Post *Hurricane Katrina* (from NOAA)

CHAPTER 4 – PRIORITIZATION OF PAVEMENTS

4.1 Pavement Functional Systems

In order to describe the prioritization of pavement sections for rapid repairs, it is necessary to first describe the classifications of roads. According to the Federal Highway Administration (FHWA), there are three basic functional systems for traveled roads: 1) rural areas, 2) urbanized areas and 3) small urban areas. The information in the remainder of this section was taken from FHWA (1989). Table 1 presents the categories for each of these functional systems.

Table 1: Hierarchy of Functional Systems from FHWA (1989)

Rural Areas	Urbanized Areas	Small Urban Areas
Principal Arterials	Principal Arterials	Principal Arterials
Minor Arterial Roads	Minor Arterial Streets	Minor Arterial Streets
Collector Roads	Collector Streets	Collector Streets
Local Roads	Local Streets	Local Streets

Rural areas are those outside of small urban and urbanized areas. Typically rural areas will include county or state owned roads connecting urban areas or networks within very small communities. According to the FHWA, rural principal arterials will have the following characteristics: 1) serve corridor movements indicative of substantial statewide or interstate travel; 2) facilitate movements between all, or virtually all, urban areas with populations above 50,000 or a larger majority of urban areas with populations above 25,000; and 3) provide an integrated network without stub connections (except where unusual geographic or traffic flow conditions dictate). In most states the rural principal arterial system will include rural freeways (interstates) or major state highways.

Rural minor arterials work with rural principal arterials to provide the following characteristics: 1) link cities and larger towns to provide interstate and inter-county service; 2) be spaced such that all developed areas of the state are within a reasonable distance to an arterial highway; and 3) provide service to corridors with trip lengths and travel density greater than rural collectors or rural local roads.

Rural collector roads will generally serve intra-county travel rather than statewide. Rural collectors can be divided further into major collectors and minor collectors. Major rural collectors provide service to county seats and link county seats to other nearby towns. Minor rural collectors provide travel to remaining small towns. Rural local roads primarily provide access to adjacent land or service over relatively short distances. These types of roads will generally be narrow and two-laned.

As suggested by the name, urbanized areas are those areas heavily populated. Similar to the rural areas, there are four categories of pavements within urbanized areas. An urban principal arterial system serves the major centers of activity within the city, includes the highest traffic volume corridors and should include the majority of traffic. Urban principal arterials will carry the majority of trips entering and leaving urban areas, as well as movement to bypass the central part of the city. Additionally, a significant part of intra-area travel will be served by the urban arterial system. Based upon these characteristics, urban principal arterials will include freeways, major highways and other types of roads.

Urban minor arterial streets interconnect and augment the urban principal arterial system. The minor arterial streets distribute movement to geographic areas smaller than those included in the urban principal arterial systems. Urban minor arterial distribute movement intra-community.

Urban collector street systems provide land access and traffic movement within residential, commercial and industrial areas. Conversely, urban collector streets collect traffic from local streets and channel the traffic to the arterial system.

Urban local streets comprise all pavements not included in the higher functional classifications. This system primarily provides access to land and other higher systems. Neighborhood streets would be an example of urban local streets.

Small urban areas are towns/small cities that generally have less than 50,000 people. Again, there are four categories within the small urban system. The small urban principal arterial system is the network of streets and highways that serve the major centers of activity and the highest traffic volume corridors. This system will also include most major routes into and out of an area, including interstates and major state highways.

Small urban minor arterials interconnect with and augment the principal arterial system. Within small urbanized areas, minor arterials provide intra-community travel and connections to rural collectors.

The small urban collector system provides land access and routes within neighborhoods, commercial and industrial areas. Collectors also collect traffic from local streets and channels it to arterials. The final category is small urban streets. These routes are streets not included within the higher volume facilities and will generally provide access to residences.

4.2 Concepts for Prioritization

Now that the different types of pavement functional classes have been discussed, concepts about the important aspects of prioritizing transportation related pavement repairs will be discussed. As defined in the National Response Framework (NRF 2008), response includes immediate actions to save lives, protect property and the environment, and meet basic human needs. These components of response must be considered when developing the protocols for prioritizing rapid pavement repair.

The NRF contains two Emergency Support Function (ESF) Annexes that deal directly with pavements or transportation infrastructure, ESF #1 – Transportation and ESF #3 – Public Works and Engineering. ESF #1 describes the Department of Transportation’s role during a disaster which is to monitor and report status of and damage to the transportation system and coordinate the restoration and recovery of the infrastructure. ESF #3 describes the activities to be conducted by the Department of Defense/US Army Corps of Engineers which includes post incident assessments of infrastructure and providing emergency repair of damaged public infrastructure. Prioritization of pavement repairs likely falls under the scope of ESF #3 as the assessments help to determine critical needs.

As stated above, the NRF has three primary objectives for response: save lives, protect property and the environment, and meet basic human needs. Though all three of these objectives are very important, each must be treated separately when prioritizing pavements for repair immediately after a natural disaster. Of the three objectives, saving lives must be considered the single most important objective followed, in order, by providing basic human needs and protecting property and the environment.

Because saving lives immediately post a natural disaster is considered the most important objective of response operations, there are a number of issues that must be considered when developing the protocol for prioritization of pavement repairs. The first issue is location. Obviously, high priority should be given to areas which have received the most damage.

Something that must be considered near the location most affected by the natural disaster is the existence of bridges. Bridges that are damaged by the natural disaster and are impassable result in a travel route that can not be rapidly repaired. Bridges take time to repair or rebuild and, therefore, their repair is not considered herein. However, knowing where damaged bridges exist will allow a more efficient prioritization of pavement repairs. Imagery is key to identifying damaged bridges

A second issue that must be considered is population density. Even though every life is equally important, initial priority should likely go to areas having higher population densities. Higher population densities mean a higher number of people that could be harmed.

Another issue that should be considered is pavement functional classification. As described previously, there are three basic functional systems of travel roads, each having different classifications. The number of lanes available to traffic will be influenced by the classification of the road. Arterials (principal or minor) will generally have multiple lanes of traffic in both directions. The number of lanes is important because a single pathway for response vehicles to traverse to and from one location to another may be more likely on multilane facilities. In other words, a response vehicle may be able to bypass small pavement damage if multiple lanes are available. If the road contains only two-lanes, both lanes may be damaged and impassable. Another reason multilane facilities are important is that they are generally located in higher population densities and/or provide travel between population hubs, which means basic needs can be transported to these hubs.

Immediately following a natural disaster, it is common that other states or organizations will mobilize assistance to the location of the natural disaster. In most instances these agencies or organizations send supplies to provide basic human needs or personnel to assist in response. Therefore, another issue to be considered must be the maintaining of a way for these agencies or organizations to reach the affected area. In many cases this will be interstates.

The final issue that must be considered is the most typical impedance to traveling a road network within an affected area. According to a report prepared post *Hurricane Katrina* (DesRoches 2006), the major impedance to travel post incidence was debris. Removal of debris is outside the scope of this project; however, the ability to get material movers to the debris because of damaged pavements would be within the scope of this project. Also, within the prioritization process, it would be important to know which roadways are totally impassable because of debris and whether there are alternate routes around the debris. Imagery would be the key to this knowledge.

Prior to a natural disaster, local Emergency Management Agencies have developed plans should a natural disaster occur. Within these plans are the identification of shelters (e.g. hospitals, gymnasiums, etc) for persons to utilize post disaster. These shelters are generally utilized post disaster to administer food, medical treatment, and basic human needs. Shelters are also generally selected based upon population density, i.e., more shelters are needed in higher population areas. Knowledge of the locations of these shelters prior to the natural disaster will be important to the implementation of the protocols set forth in this chapter.

Another concept that is important to the implementation of the protocols set forth within this report is that of hierarchy of decisions. The term hierarchy infers that decisions have to be made by many individuals and that there is a tiered approach to the decisions that must be made to accomplish all goals and objectives. For instance, within a given State, the Governor of the State must make decisions that are carried out by different State agencies. Likewise, the Head of each State agency makes decisions that carry out the Governor's directions and are carried out by underlying employees. An illustration of this hierarchy is a pyramid. More and more decisions must be made as the base of the pyramid becomes larger. As more and more decisions are made, more people must make the decisions.

Because of the hierarchal decision making process, it is assumed that a single person or small group of people will have responsibility for the rapid repair of pavements for a given area (termed *Decision Maker* herein). The area of responsibility may be a small town, a portion of a larger town, or a non-urban area; however, the area should be defined. Defining these areas should be conducted as the disaster becomes imminent and may be altered as information becomes available as the disaster approaches. It is further assumed that under the direction of the *Decision Maker* will be a group or groups of personnel that are assigned to conduct information gathering, conduct pavement evaluations, conduct cleanup activities, and conduct pavement repairs. The *Decision Maker* will likely be located at an *Emergency Operations Center* (*EOC*).

4.3 Prioritization of Rapid Pavement Repairs

Based upon the above paragraphs, a number of issues and concepts were discussed that must be considered when prioritizing pavements that need to be repaired immediately post occurrence of a natural disaster. The following paragraphs describe the protocol for prioritizing rapid pavement repair.

Figure 14 illustrates the protocol for prioritization of rapid pavement repair post natural disaster. The first step post natural disaster is for the *Decision Maker* (person or persons in charge of prioritization) to deploy the group or groups of workers (hereafter termed *Team(s)*) to their designated location or staging area. These designated locations in most instances will be major intersections inland from the disaster area. For example post *Hurricane Katrina*, a designated location could have been the intersection of Highway 49 and Interstate 10 in Gulfport, Mississippi.

Upon arrival to the designated location, the *Team(s)* will begin reconnaissance as to the amount of damage in their area as well as the amount and location of debris. Information derived from the reconnaissance will be communicated to the *Decision Maker*. As soon as possible post disaster, imagery operations should also begin. This data will also be communicated to the *Decision Maker*. As the *Team(s)* begin initial clean up and repair operations, data will be continuously communicated to the *Decision Maker*.

Reconnaissance information important to the *Decision Maker* can take many forms. It will be important to know routes near the designated location that are passable, areas that are not passable due to debris, areas that are not passable due to pavement damage, and roadways which have bridges/culverts that have been destroyed. Roadways that are impassable due to debris or a bridge/culvert being out are vitally important. It is assumed that these on-site *Team(s)* will have some type of vehicle, whether SUV, truck or ATV, that can be utilized. It will be important that these first responders can maneuver off road in order to gather reconnaissance data for the *Decision Maker*. The *Decision Maker* must use all this information to select appropriate routes for the *Team(s)* to reach their objective(s).

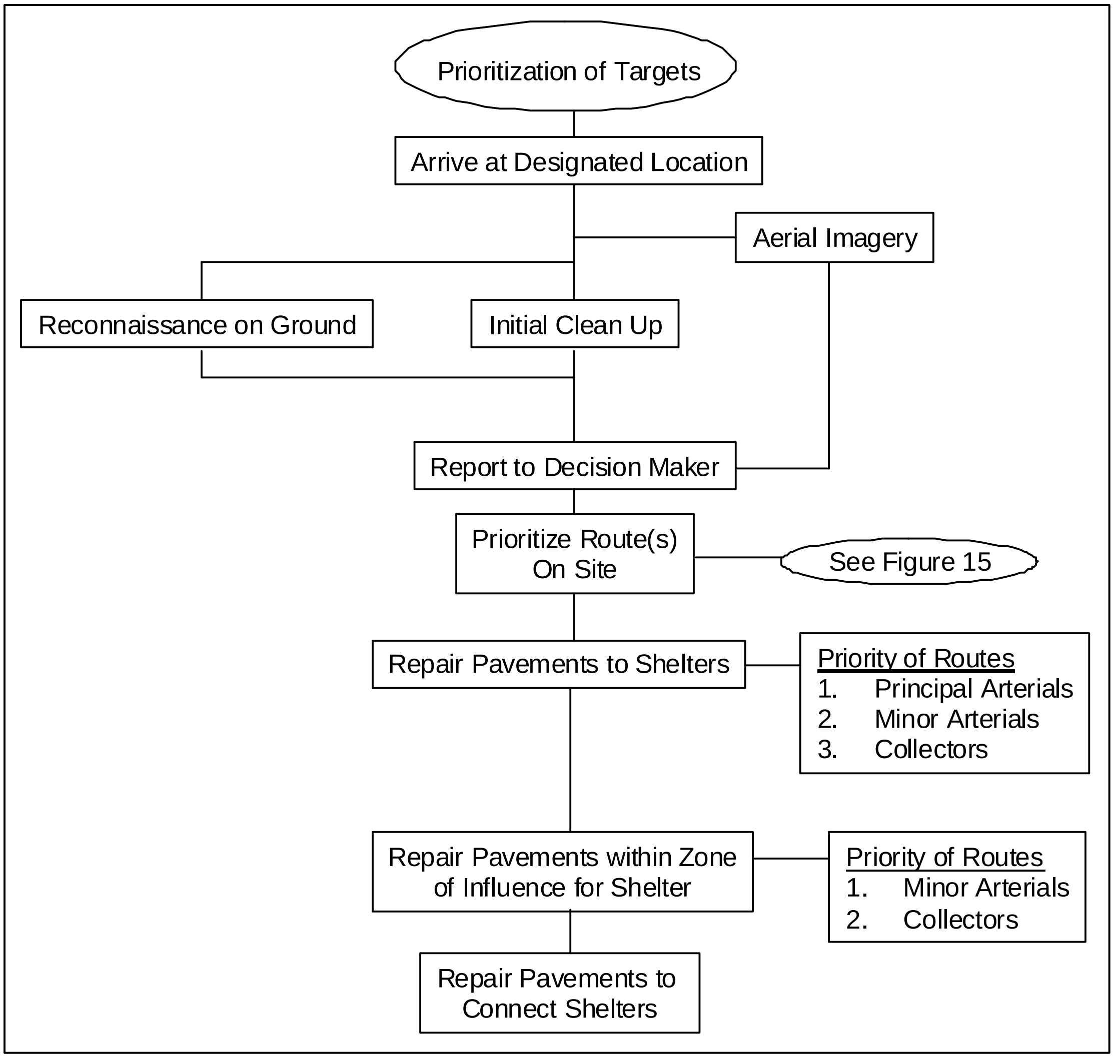

Figure 14: Flow Diagram Showing Protocol for Prioritizing Pavement Repair

Once initial reconnaissance operations are conducted, this information should be communicated to the *Decision Maker*. The *Decision Maker* must then decide on the routes the *Team(s)* takes to their designated target. As soon as possible, aerial imagery operations should be initiated and this data communicated to the *Decision Maker*. The aerial imagery can be used to evaluate areas in which the on-site *Team(s)* could not reach. Again, important information to be obtained from the aerial imagery will be to identify routes that are passable, areas not passable due to debris, areas that are not passable due to pavement damage, and roadways in which bridges/culverts are impassable.

As shown in Figure 14, the initial targets for the on-site *Team(s)* will be to provide a transportation route to their target shelter. It will be important to provide a travel route to the target shelter so that emergency personnel, medical supplies, food, water, etc. can be transported to the shelter. It will be important that the on-site *Team(s)* understand that the transportation route to the shelter be repaired such that tractor-trailers can utilize the route. The *Decision Maker* should set the following priority to the selection of pavement classifications for the route to get to the shelter: principal arterials, minor arterials, and collectors, respectively.

Principal arterials should be provided the highest priority because these pavement types will generally be multi-lane. Being multi-lane, a route within the principal arterial in which a tractor-trailer can traverse toward the target shelter should be easier found. The second priority route should be minor arterials. These pavement types may or may not be multi-lane. Minor arterials will generally have more pavement structure than lower classified roadways and, therefore, be able to withstand the weights of tractor-trailers more efficiently. Third priority should be given to collectors. These pavement types may or may not be multi-lane. At times, collector roads will be the final leg to shelters.

In some instances, the prioritized route selected by the *Decision Maker* may encompass principal arterials, minor arterials and collectors. One of the goals that the *Decision Maker* must understand when selecting the route is to provide an immediate path to the intended target(s) for response operations. Traversing different pavement classifications should not be considered detrimental. As such, the *Decision Maker* should consider the type of pavement damage from the gathered reconnaissance information. Figure 15 illustrates the priority of pavement damage the *Decision Maker* should use in setting priority of routes. The first priority should be given to *Intact* pavements. These pavements will require only minimal, if any, repairs prior to being utilized for response activities. Next, the *Decision Maker* should identify pavements categorized as *Damaged-Passable, Light-Damage. Damaged-Passable, Medium-Damage* would be the next category to identify. If at all possible, routes should avoid pavements categorized as *Damaged-Dangerous*. Repair techniques for this damage category will require more time and effort. However, when unavoidable, the *Decision Maker* should select pavements within the *Damaged-Dangerous, Medium-Damage* over pavement categorized as *Damaged-Dangerous*, *Severely-Damaged*.

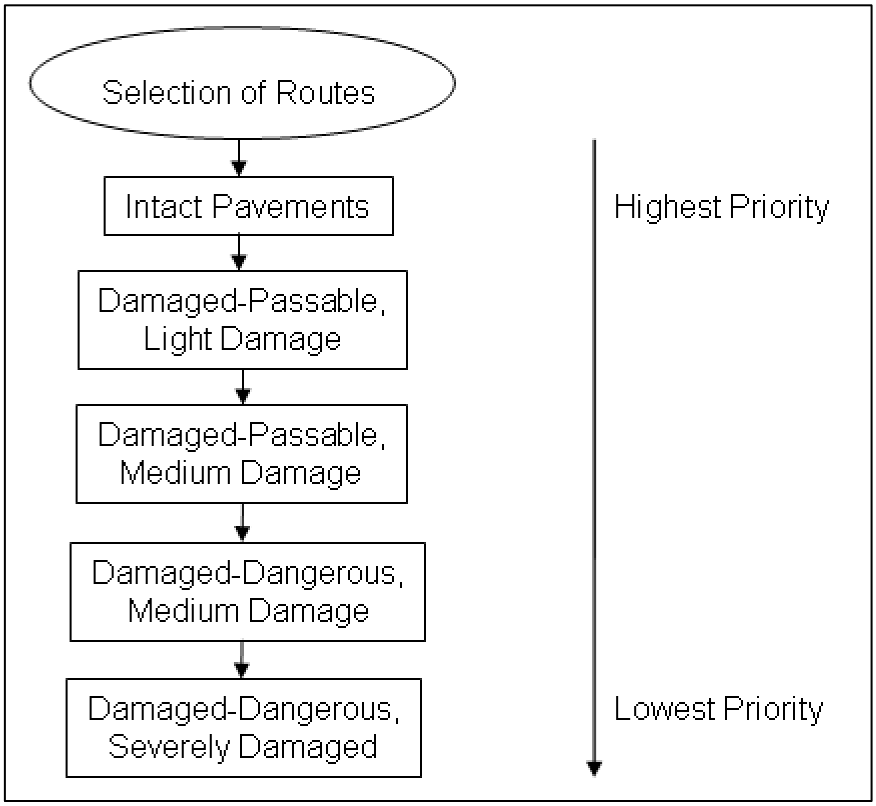

Figure 15: Priority of Pavement Damage

As shown in Figure 14, after a route has been made passable to the target shelter(s), the next course of action is to provide passable routes within the zone of influence for the shelter. The term "zone of influence" refers to the areas surrounding the shelter in which the shelter is designated to provide assistance. It is anticipated that passable routes within the zone of influence will fill two primary objectives of response operations: 1) response personnel will be able to begin life saving operations; and 2) supplies to meet basic human needs will become available to those in need. The routes made passable within the zone of influence will allow response personnel to reach neighborhoods where people may be hurt and will also allow routes for people that remained during the disaster to reach the shelter.

The final step in prioritizing pavements for repair will be to connect shelters. This final step will indirectly be accomplished as routes are made passable within each shelter's zone of influence. However, it will be important that routes be made passable between shelters so that medical personnel and supplies can be transported between shelters.

CHAPTER 5 – REPAIR TECHNIQUES

5.1 Introduction

Damage that occurs to a pavement during a natural disaster can vary widely as seen in Chapter 2 of this report. As such, the researchers evaluated a number of pavement repair techniques that are applicable to small and/or large areas. During the evaluation of each of the various techniques, there were several items deemed important. One item of interest for each of the evaluated repair techniques was shelf life. Techniques or products that have a long shelf life would allow for storage of materials for long periods of time. In other words, long shelf lives would allow for the stockpiling of materials prior to the occurrence of a natural disaster should an agency elect to do so.

Another item of interest for each technology is construction. Each manufacturer of the various technologies has recommended construction methodologies. A quick overview of construction considerations are also provided. Chapter 6 will provide recommendations for various repair techniques based upon the pavement damage categories. However, within the discussions on the various repair techniques, general comments are provided on the relative size of areas that the technique will repair.

The final comment on the various repair techniques is on the expected performance life. In most cases, local DOT's will be able to mobilize within a week after a large natural disaster. However, the DOT will have to prioritize pavement rehabilitation. For the purposes of this project, a performance life of up to 60 days was selected. This time period should allow for the DOT to mobilize and conduct all pavement repairs.

5.2 Geotextile and Aggregate

Many damaged areas or areas that have been washed out can be made temporarily passable by placing a geotextile and a compacted dense-graded aggregate. This repair option is useful for medium to large areas of pavement damage. When selecting a geotextile for this repair technique, it is important to select a product that is designed for reinforcement (typically a high density product). Some geotextiles are designed for other purposes and are not desirable in reinforcement applications. The degree of compaction and aggregate stability will dictate what type and volume of traffic that can utilize this repair.

AASHTO M 288 procedures should be followed if possible for material selection and construction guidance. General construction guidance is provided in Figure 16. Depending on the size of the repair, the geotextile should be pulled relatively tight and secured to the subgrade. Construction traffic should not be allowed to drive directly on the geotextile. Aggregate meeting local standards should be back-dumped onto the geotextile and advanced by a dozer or equivalent. In general, aggregate should be advanced on the outside edges ahead of the center in a U shape to tension the geosynthetic during compaction (15 to 20 cm lifts are typical). Equipment required includes haul trucks and a spreader to place the aggregate. The trucks hauling aggregates could possibly provide adequate compactive effort, but a compaction roller would be more efficient, effective, and consistent. This technique may also utilize repairs in the following sections as the aggregate may be a base layer topped by asphalt, rapid set concrete, precast concrete, or paving mats. The shelf life of the aggregate and geotextile is indefinite.   Appendix A provides data for acceptable geotextiles.

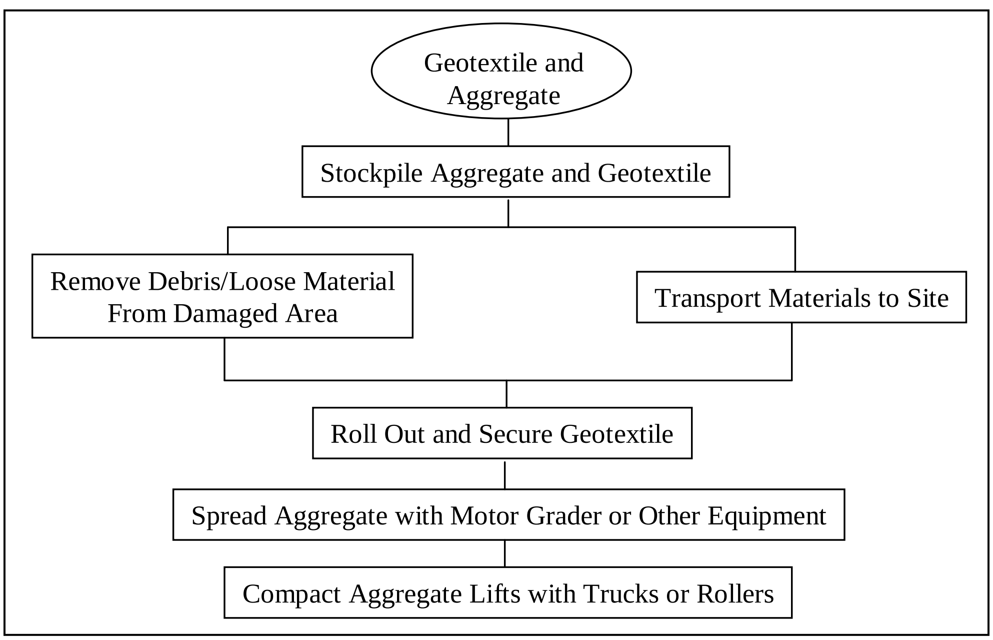

Figure 16: General Construction Method for Geotextiles and Aggregates

Design of the unpaved section of the roadway can be performed according to the procedure of Giroud and Noiray (1981). The method is used to design unpaved roads reinforced with geotextiles. The approach is applicable to cohesive subgrade soils where less than 10,000 passes of vehicular traffic are to occur. The method can be utilized in a matter of hours, so the design could be performed while materials are being delivered to the site.

5.3 Flowable Asphalt

Flowable asphalt is a bituminous based epoxy-like material. Generally, all components required to make flowable asphalt are supplied within a 19 L bucket. The components will be polymers and topping materials (sand). Figure 17 provides general guidance for using flowable asphalt. Flowable asphalt repair can be used to patch small areas of distress. Generally, the area of repair will range from 0.1 to 5 m^2. The smaller areas would include pothole repairs and the larger areas would typically be resurfacing projects. This is a low skill repair option, as the repair team needs only follow the instruction on the repair kit. Construction with flowable asphalt includes mixing the material with a power drill, cleaning the area and spreading the material for thin lift applications. For pothole filling applications, all steps are the same except the flowable asphalt is poured directly into

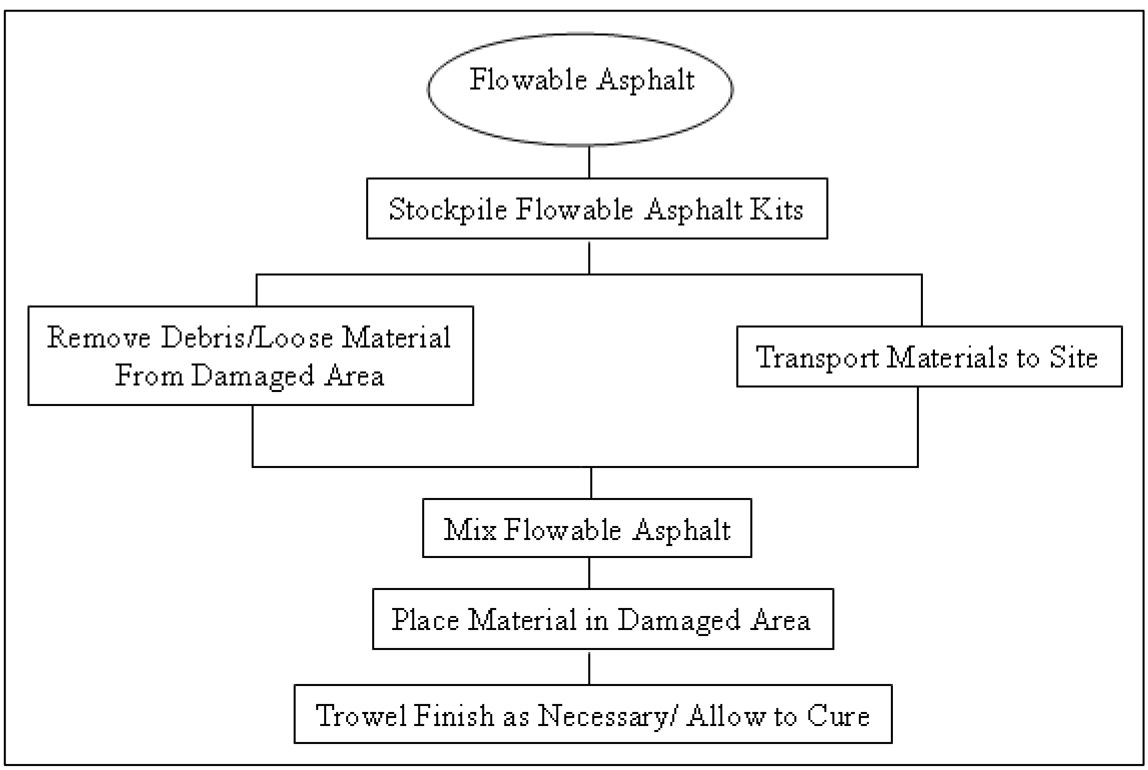

Figure 17: General Construction Method for Flowable Asphalt

the pothole, where it will cure into a hard surface in about 1 hour. Suppliers of flowable asphalt indicate the approximate cost of the material is around $20 a square meter. Flowable asphalt has a shelf life of one year if kept indoors in a dry environment. For small repair areas, repairs made with flowable asphalt may be utilized as permanent repairs. Appendix B provides additional information about flowable asphalt.

5.4 Cold Patch Asphalt

Cold Patch Asphalt is a blend of aggregates and asphalt binder. The asphalt binder has additives which allow the cold patch asphalt to be compacted without heating. Cold Patch Asphalt repair can be used to repair small areas of distress. Figure 18 provides general construction guidance. Generally the area will be 0.1 to 1 m^2. If the patched area is much larger it may take some time for the patch to cure so that it will not shove under loading. Larger areas can be repaired with cold patch asphalt, but the patched area may be unstable until the mixture can cure because of the lack of close confinement. Cold patch asphalt repair is a simple repair option and requires very little skill. The distressed area to be repaired needs to be moderately dry (no pooled water). The cold patch is then placed in the

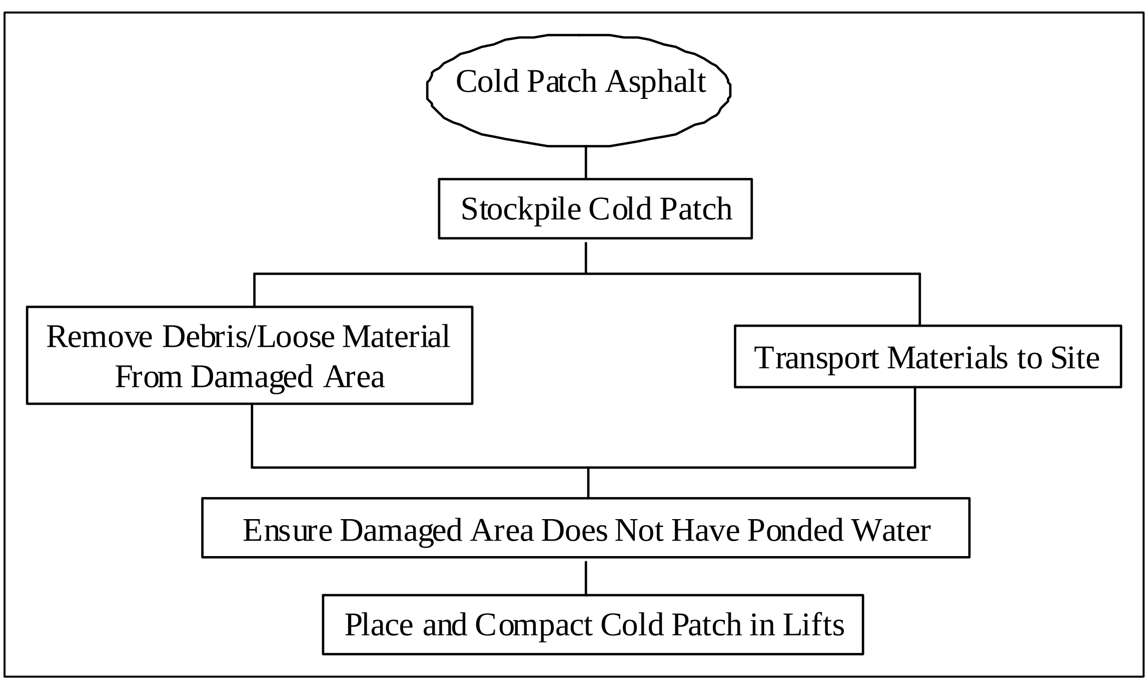

Figure 18: General Construction Methods for Cold Patch Asphalt

distressed area in lifts and compacted with a hand tamp or other suitable device. The cost of cold patch is around $75 a square meter (5 cm deep). The shelf life of most cold patch sealed in bags is 1-2 years. Stockpiled cold patch material can last 6 months to a year. Appendix C provides more information about cold patch asphalt.

5.5 Rapid Set Concrete

Rapid set concrete is a hydraulic cement based product that is specifically designed to set rapidly. The rapid set cement, when combined with aggregates, can provide a hard driving surface. Rapid Set Concrete can be used to repair small potholes to entire roadways. Conventional concrete could also be used if available. Figure 19 provides general construction guidance for use of rapid set concrete. As the repair area increases in size, the equipment required will also increase. If used to fill potholes or smaller distress area, a small concrete mixer or even a wheelbarrow and a technician with a shovel could be utilized to mix the material and place into the repair area. A hand trowel or float would be necessary to smooth out the concrete surfaces. If the area to be repaired does not have a suitable construction platform, one must be created likely using the geotextile and aggregate repair discussed in Section 5.2. If filling a depressed area, the edges of the depression would act as confinement for the rapid set concrete. If an entire section of roadway requires repair, a form will have to be built, mixing will need to be accomplished in a concrete truck and larger finishing equipment will be required. The skill required for the repair also significantly increases as the area increases. Depending on the type of rapid set concrete used, the shelf life can range from 1 year to much more. The cementitious portions of the concrete will need to be stored in a dry location. Because of the wide range of areas that can be repaired with rapid set concrete, the approximate price varies significantly as well. Appendix D provides more information about rapid set concrete products.

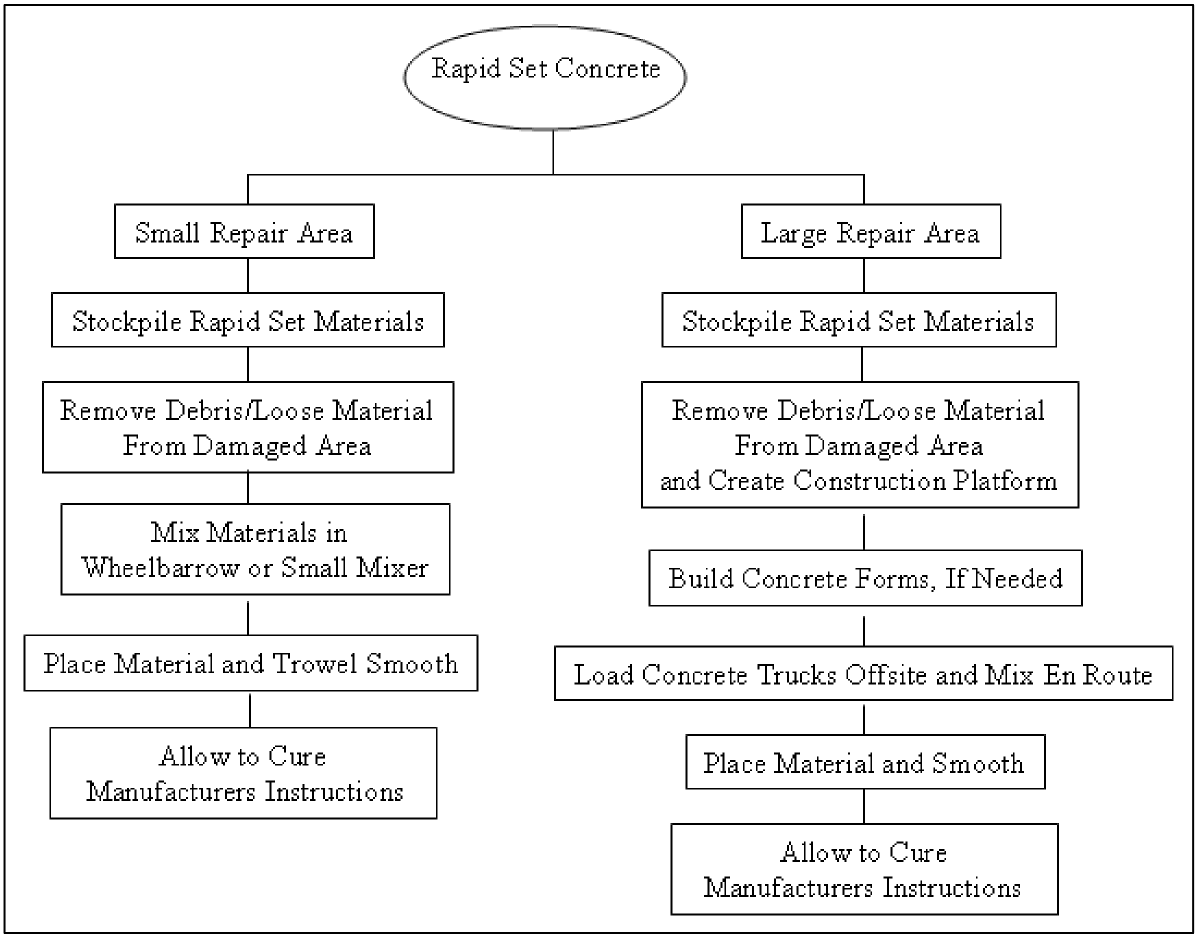

Figure 19: General Construction Methods for Rapid Set Concrete

5.6 Paving Mats

There are several different types of paving mats available. Generally, these mats can be used to bridge a distress or replace a washed out roadway. A paving mat can cover a wide range of areas (e.g. 1 to 17 m^2 per mat). They can be connected together to produce a repair of any desired area. Several options exist for paving mats including Pierced Steel Plank (PSP), small hardened steel (JR), Folded Fiberglass Mat (FFM), Fiber Reinforced Polymer, Wood, and Precast Concrete. No matter the type of mat used, a stable base on which to lay the mat will be required, though the stability required varies with mat type. This can be accomplished with stone, sand, or chemically stabilized soil. The remainder of this section describes paving mat options. Figure 20 summarizes the use of paving mats, while Appendix E provides more information about paving mats.

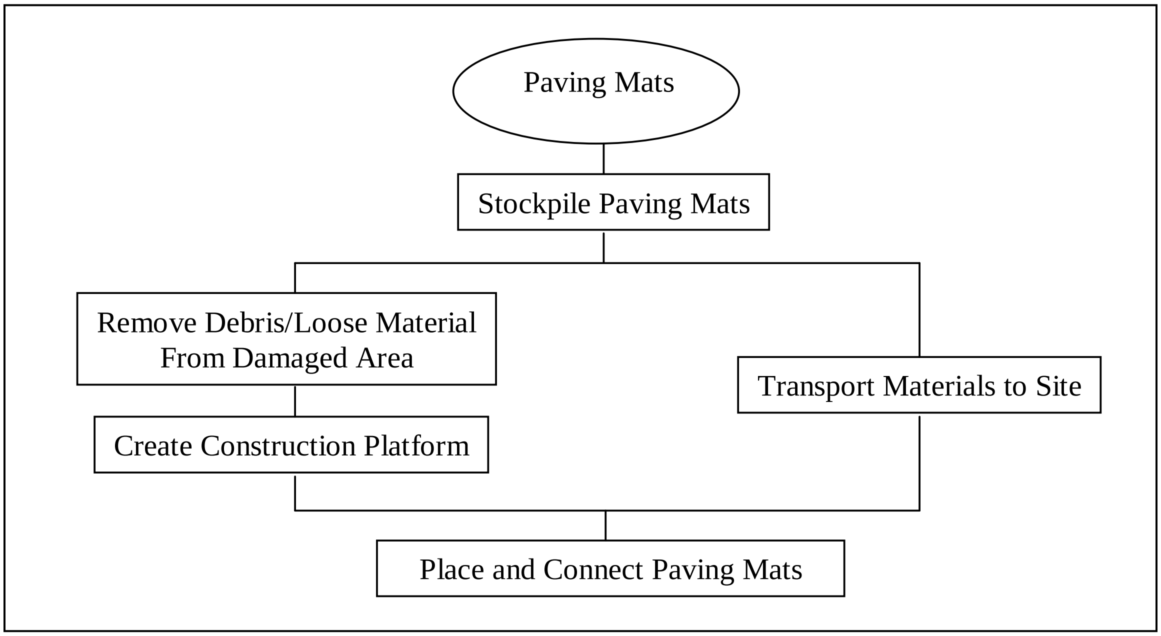

Figure 20: General Construction Methods for Paving Mats

The PSP and JR mats are World War II surplus mats, but are generally available because of quantities produced during the war. These mats can be placed and connected by hand. They weigh approximately 30 kg per mat; therefore, heavy equipment would be required to move several of the mats at once. Costs for these mats could be on the order of \$30 to \$40 per m^2. These mats can be stored outdoors indefinitely and can be reused.

FFM mats are generally broken into panels on the order of 1.8 by 9.1 m. Each panel weighs on the order of 150 kg and can be placed by several workers. Again, multiple mats will require heavy equipment to haul these mats to the distressed area. These mats are often utilized by the military to repair airfields, so kits put together by the manufacturer provide all the necessary equipment to place FFMs. The construction of these mats is relatively simple, but prior training is required. FFMs can be stored indefinitely.

Precast concrete panels are available through a number of contractors that can make them to whatever size is deemed most beneficial. Typical sizes include 3 m by 3 m or 3.7 m by 3.7 m. Precast panels are typically the most durable of all the repair options and can often be left in place permanently, if the underlayment is properly prepared. Precast concrete panels, though, are also likely the most costly. Once the base for these panels is prepared, heavy equipment is required to transport the slabs to the site and a crane is required to place them. Short sections can be placed in a 5 hour span with experienced personnel. This is a relatively high skill operation with specific equipment required for placement. The precast panels can be stored indefinitely.

Wooden construction platforms are also a viable option for temporary applications such as emergency pavement repair. These mats are manufactured on a large scale by multiple companies. Conceptually, they are used in the same manner as the aforementioned matting types.

Fiber reinforced polymer mats (and similar mats produced with modern materials) are available. The *US Army Corps of Engineers (USACE)* through its *Engineer Research and Development Center (ERDC)* conducted a sustained research effort referred to as the *Joint Rapid Airfield Construction (JRAC)* program beginning in 2002. The objectives of the program were fairly unique; one of the objectives was rapid mobilization of forces. The majority of the *JRAC* efforts were related to *C-130* and *C-17* aircraft, with some efforts devoted to items such as helipads. On the order of 30 projects were performed as part of the *JRAC* program. The information related to the use of matting systems has direct applicability to this research. *ERD*C also has tested matting systems in the presence of vehicular traffic for temporary applications. A summary of this research has been presented in Appendix E to demonstrate the viability of the technology.

5.7 Slab Jacking

Typically slab jacking is performed on intact sections of concrete pavement that have lost subgrade material because of rapid water movement in or around the subgrade and have consequently sunken from their original grade. Slab jacking should only be performed if the differential movement of the concrete pavement is only a few centimeters (e.g. 15). This technology will vary in the square footage repaired, but generally the areas will be less than 20 square meters. Figure 21 provides general construction guidance for slab jacking. The standard process is to drill holes into the slab and inject expanding foam into the void below until the slab returns to its original elevation. Slab jacking with foam is a proprietary process that usually is performed by highly skilled workers with very specialized equipment. The cost of slab jacking is around $110 per square meter and the material can be stored for 1 to 3 years out of extreme temperatures. Appendix F provides more information on slab jacking.

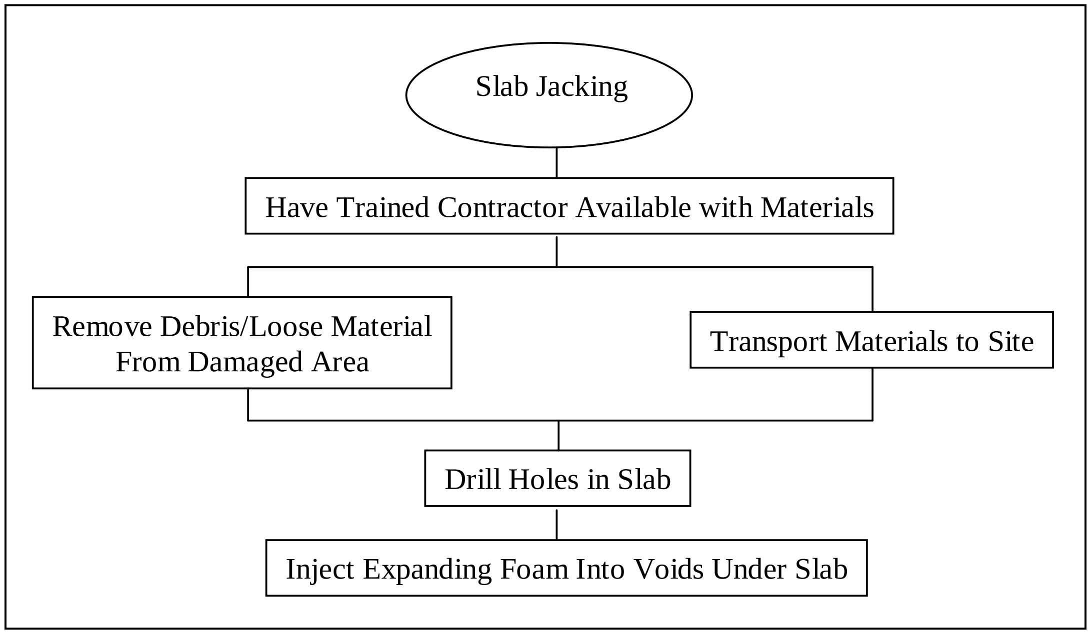

Figure 21: General Construction Methods for Slab Jacking (Concrete Only)

5.8 Hot Mix Asphalt

Hot mix asphalt (HMA) is a blend of asphalt binder and aggregates that have been processed at temperatures around 150 C in an HMA production facility. Hot mix asphalt can be used to repair any size area, from very small to entire roadways. Generally, construction with hot mix asphalt will require a construction platform. This platform may be an aggregate base material or a compacted subgrade. During response operations, HMA will have to be trucked in, laid, and compacted. The skill level to place HMA is high, but many contractors are experienced with placing HMA. Specialized heavy equipment and a plant to produce the HMA are also required. This is typically readily available in a pre-natural disaster scenario. If nearby plants are damaged HMA can be trucked in from longer distances. If the distance is too great, warm mix asphalt (WMA) technologies should be considered. The cost of HMA repair varies significantly depending on the amount of work required before placement and the thickness of the asphalt. The components required to blend HMA in a plant can be stored for long periods of time. Figure 22 provides general HMA construction guidance.

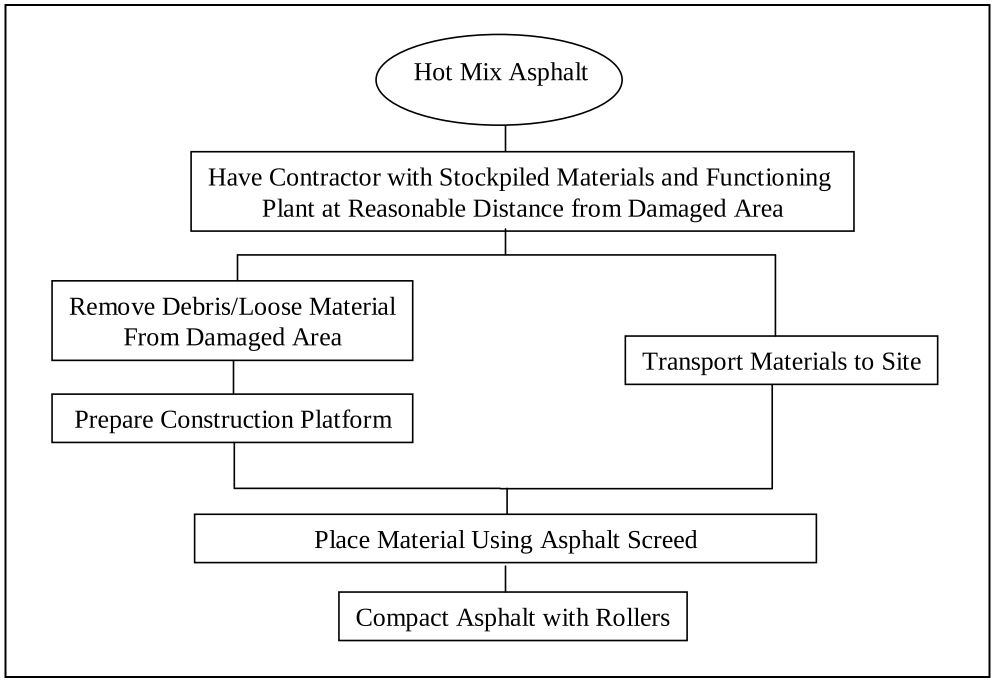

Figure 22: General Construction Method for Hot Mix Asphalt

5.9 Warm Mix or Hot Mix Warm Compacted Asphalt

Warm Mix Asphalt (WMA) is similar to HMA but utilizes a process or asphalt binder additive that allows it to be compacted to proper density at lower temperatures. The benefit of this lower temperature compaction is that it can be trucked in from greater distances than HMA if the plants that are more local are damaged by the natural disaster and/or are without power. The major difference in WMA and HMA occurs at the plant where an additive or foam is added to the asphalt binder in order to ensure a compactable mixture at lower temperatures. Appendix G provides more information on different types of WMA technologies. Hot mix warm compacted asphalt would combine HMA and WMA. The mixing temperature is that of HMA but the WMA additives allow warm compaction extending the haul distance. This technology is relatively new, so many asphalt plants are not equipped to produce WMA. The cost for WMA could be higher than HMA.

Appendix H provides the results of an extensive laboratory study conducted as part of Task 4 to evaluate hot mixed warm compacted asphalt with WMA additives for rapid pavement repair. Based upon this research, hot mixed warm compacted asphalt can be placed successfully a number of hours after production, possibly up to six hours. This finding is significant. Because of this extended time for being able to construct with the material, it can be hauled from greater distances.

Figure 23 presents a map of the Gulf Coast region. Also included on this map are circles having a radius of 80, 160, 240 and 320 km centered on Mobile, Alabama. The rings of various distances represent different haul times in which WMA could be transported. The 80 km ring represents an approximate 1 hour haul time and the 320 km ring represents an approximate 4 hour haul time. According to Appendix H, a 4 hour haul time would still allow approximately 2 hours of time to construct a pavement repair. This statement assumes the aging protocols match field conditions which have yet to be verified. As shown on Figure 23, hot mixed warm compacted asphalt could be hauled to Mobile from as far as Birmingham, Alabama; Jackson, Mississippi; and Columbus, Georgia. These locations are far enough inland that HMA production facilities should be operational. Figure 24 provides general construction methods for WMA and/or hot mixed warm compacted asphalt.

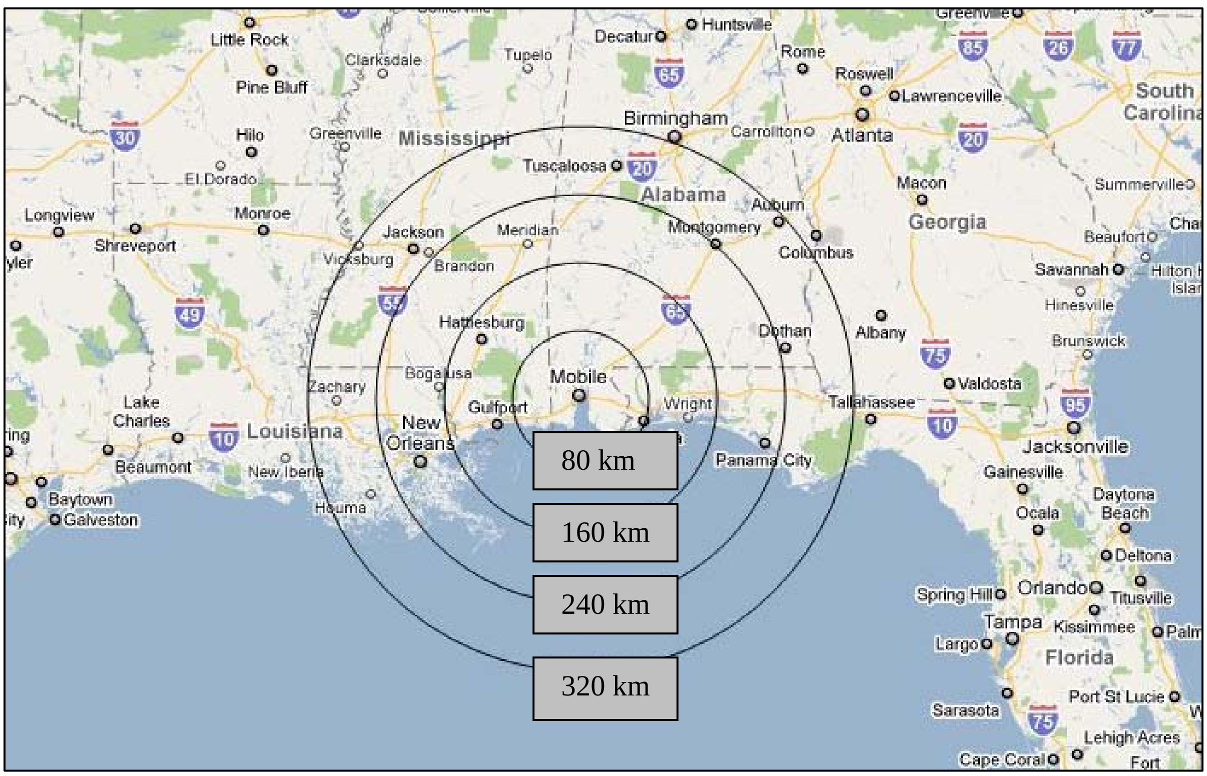

Figure 23: Potential Haul Distances from Mobile, Alabama

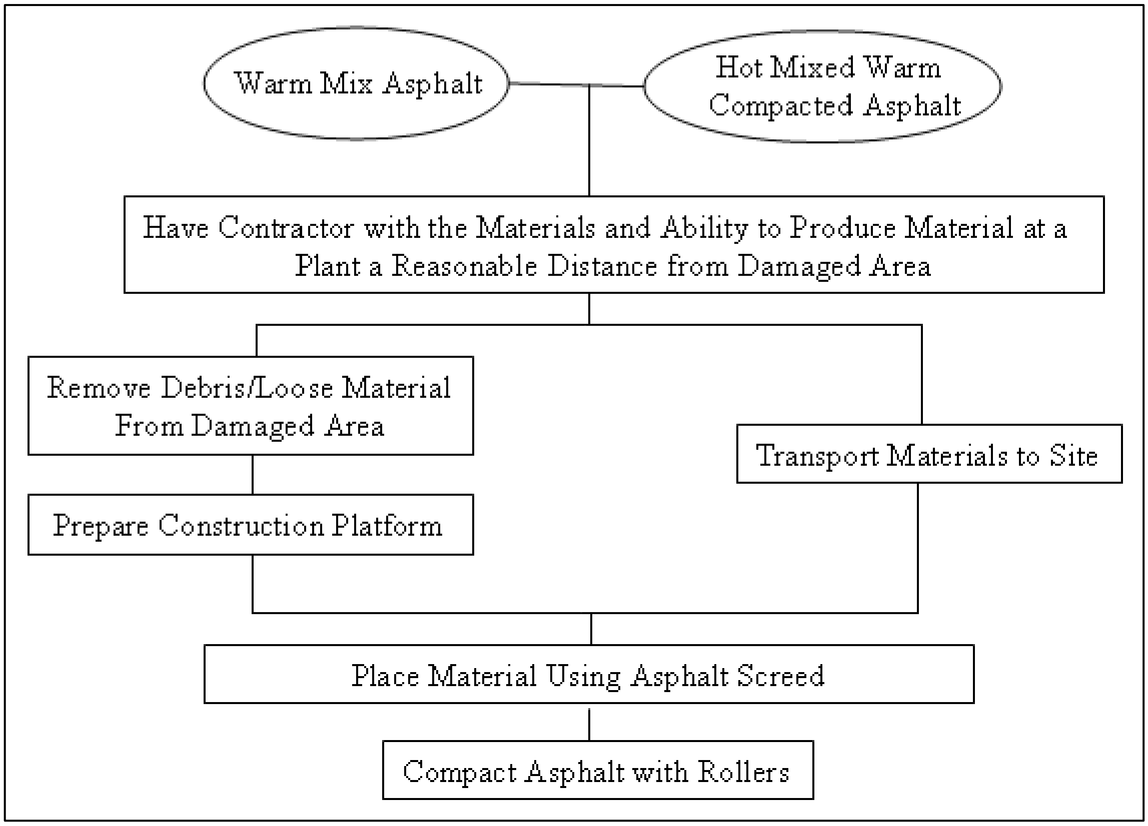

Figure 24: General Construction Methods for Asphalt with WMA

It should be noted that all WMA technologies are not equal. WMA produced with foaming technology generally cannot be compacted at temperatures as low as some of the WMA additives on the market. Also, the use of hot mixed warm compacted asphalt would not be possible with some additives due to maximum plant temperature requirements and similar.

CHAPTER 6 – SELECTION OF REPAIR TECHNIQUES

6.1 Introduction

Chapter 4 of this report provided protocols for selecting pavements for rapid repair. Chapter 5 provided descriptions of different technologies that can be utilized for rapid repair. This chapter of the report provides decision trees that can be utilized by the *Decision Maker* and *Team(s)* to select the appropriate repair technique. The decision trees are based on the different categories of pavement damage.

6.2 Intact

Damage to *Intact* pavements would be minimal. However, small potholes or other relatively small surface distresses may require repair. Figure 25 presents the most applicable repair strategies for *Intact* pavements. These repair strategies: flowable asphalt, cold patch and rapid set concrete are generally designed for small damaged areas. However, if a truck containing hot mix asphalt or warm mix asphalt is readily available, they can also be utilized.

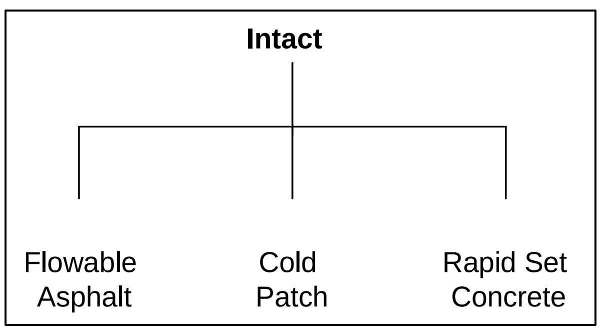

Figure 25: Decision Tree for *Intact* Pavements

6.3 *Damaged-Passable, Light Damage*

This damage category entails relatively small areas; i.e. less than about 2 to 4 square meters. Figure 26 presents repair strategies that are applicable for *Damaged-Passable* and *Light Damage* categories. As shown in this figure, flowable asphalt, cold patch asphalt, rapid set concrete, hot mix asphalt, and warm mix asphalt are all applicable. Another potential strategy would simply entail filling an area with a dense-graded aggregate. However, use of a dense-graded aggregate requires that the placed aggregates be confined on all sides.

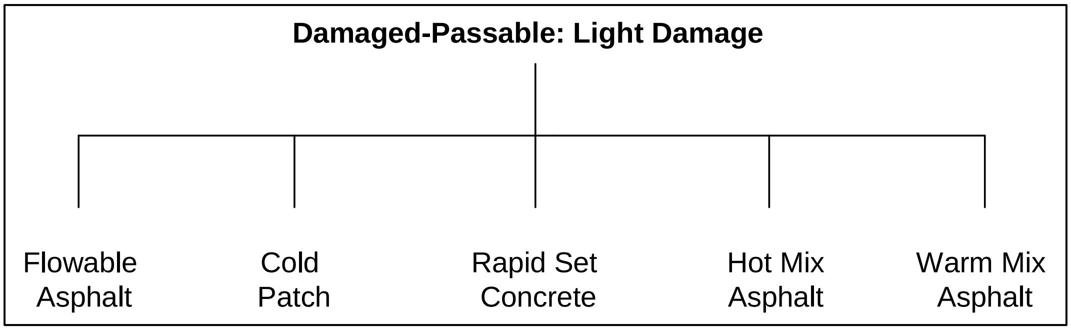

Figure 26: Decision Tree for *Damaged-Passable, Light Damage* Pavements

6.4 Damaged-Passable, Medium Damage

As defined in Chapter 2, the *Medium Damage* severity level encompasses damage that is one lane width. As such, flowable asphalt and cold patch are not as applicable. As shown in Figure 27, repair strategies applicable to this damage category includes geotextile and aggregates, rapid set concrete, slab jacking, paving mats, hot mix asphalt, warm mix asphalt, and hot mix warm compacted asphalt.

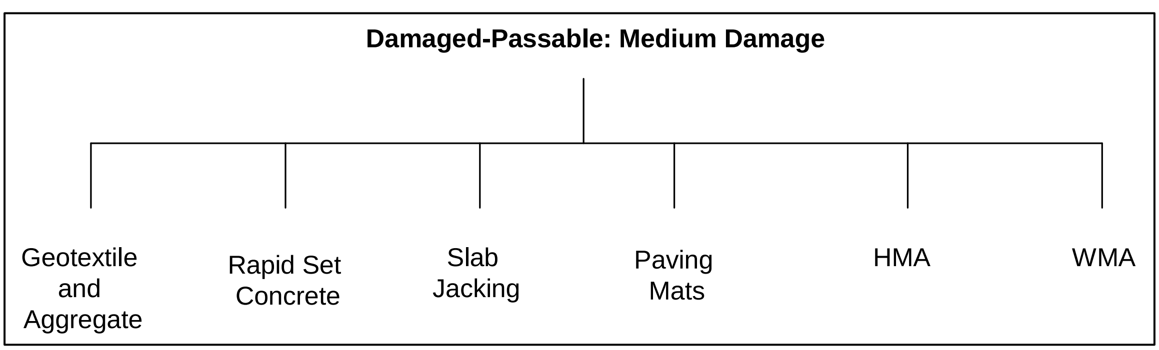

Figure 27: Decision Tree for *Damaged-Passable, Medium Damage* Pavements

6.5 Damaged-Dangerous, Medium Damage

The breadth of damage contained within this category will generally be larger than the categories mentioned previously. Also, the depth of the damage may be high. Therefore, the repair strategies selected for this damage category will generally be bulky. Figure 28, presents the repair strategies for *Damaged-Dangerous, Medium Damage* areas and includes geotextiles and aggregates, slab jacking, paving mats, hot mix asphalt, warm mix asphalt, and hot mixed warm compacted asphalt. Damage that is very deep may require the placement of dense-graded aggregates to provide a construction platform for the repair strategy.

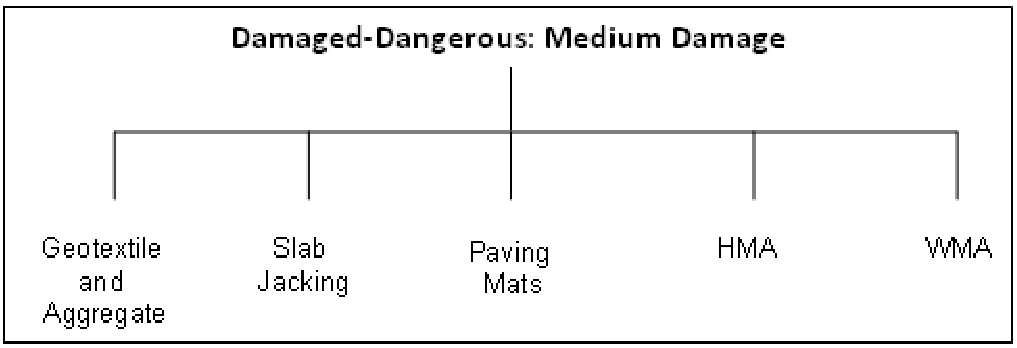

Figure 28: Decision Tree for *Damaged-Dangerous, Medium Damage* Pavements

6.6 Damaged-Dangerous, Severely Damaged

Damage within this category encompasses all lanes and may be deep. Figure 29 presents the applicable repair strategies for this category and severity level. Repair strategies included within this figure are geotextile and aggregate, slab jacking, paving mats, hot mix asphalt, warm mix asphalt, and hot mixed warm compacted asphalt. If the damage is deep, a dense-graded aggregate may be required to produce a construction platform.

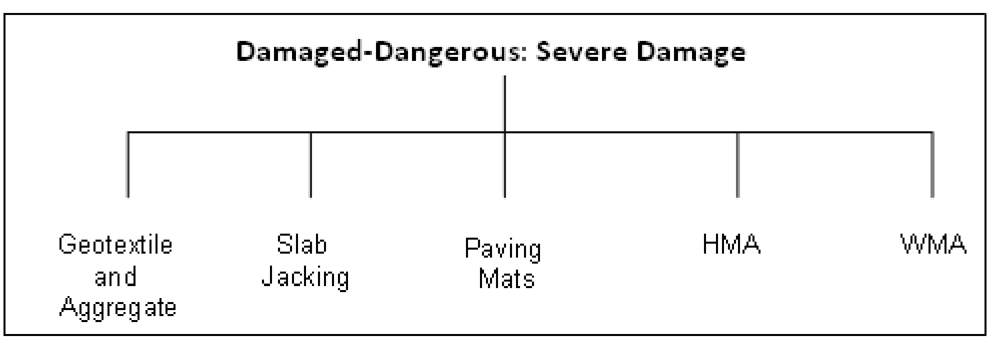

Figure 29: Decision Tree for *Damaged-Dangerous, Medium Damage* Pavements

CHAPTER 7 – SUMMARY AND CONCLUSIONS

7.1 Summary

Emergency Activities encompass a number of concepts. The first concept within *Emergency Activities* is preparedness. Preparedness includes the pre-planning of tasks and activities needed to respond and recover from an incident. Measures included within preparedness include the development of plans, protocols, and training and exercises. Once an incident occurs, the second concept is response. Response includes the immediate activities to save lives, protect property and meet basic human needs. The final *Emergency Activity*, recovery, is the process of restoring and rebuilding community lives, property and economy.

Task 4 of Task Order 400064719 was conducted to enhance the preparedness of Emergency Management Agencies by developing protocols for quickly and accurately evaluating, prioritizing, and repairing pavement networks post natural disaster for initial response operations. Protocols, methods and techniques described within this report were developed to be easily deployable during and immediately after a natural disaster, such as a hurricane.

The overall concept presented within this report for the rapid repair of pavements involves evaluating the condition of pavements, prioritizing the pavements to be repaired and then conducting rapid repair techniques. Because the underlying objective of this project was to repair the pavements such that response operations could be initiated, the repair techniques provided should not be deemed as permanent repairs. Rather, the authors detailed repair techniques recommended for use up to 60 days, or until permanent repairs could be performed as part of recovery.

An important part of prioritizing the pavements for repair is a characterization of pavement damage that occurs during the natural disaster. Four categories of pavement damage were developed during this project and include: *Intact, Damaged-Passable, Damaged-Dangerous and Impassable.* Within the categories of *Damaged-Passable* and *Damaged Dangerous,* severity levels were also developed.

Prioritization of routes includes the concept of a *Decision Maker*, a *Team(s)* and a specific target (shelter). Immediately after a natural disaster, the *Team(s)* will arrive at a designated location and begin reconnaissance. Also, aerial or satellite imagery will be utilized to identify bridges and/or culverts that have been destroyed or entire pavement sections that have been made *Impassable*. The *Decision Maker* will use the reconnaissance data and the selected target to prioritize the route(s) which will be initially repaired. The authors developed a protocol for selecting the targets of rapid pavement repairs. The first step would be for the repair of pavements to a target shelter. Shelters were selected as the target because they are utilized to administer food, medical supplies and other basic human needs. Once the route has been prioritized and rapid repairs made to the target shelter, the next course of action will be to prioritize and repair pavements within the zone of influence around the shelter. The final prioritization of pavement repairs will be to connect shelters.

Rapid repair techniques utilized will be based upon the type of damage that has occurred. The authors described a number of repair technologies that could be utilized post natural disaster. Decision trees were developed that were based upon the category and severity level of pavement damage. For each category and severity level of pavement damage, several repair technologies were provided.

7.2 Conclusions

The protocols and methodologies provided within this report are new and innovative. As such, training and exercises will be needed as part of the preparedness concept of *Emergency Activities*. Training and exercises conducted as part of preparedness will allow these protocols and methodologies to be effectively utilized during response operations.

The approach outlined in this report is feasible and should improve emergency pavement repair after a disaster. Many of the resources to respond are in place, and needed to be assembled into a single document describing how they might be used as was performed in this research. A report of this nature could not be identified in literature.

The work related to hot mixed warm compacted asphalt provided a notable contribution to the material characterization knowledge base as testing of the magnitude and nature performed was not found in literature. Testing demonstrated that material haul distances and compaction conditions could be extended beyond current practice for short term use. This finding is significant as it allows the asphalt industry to respond to disasters much more effectively.

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Note: All references for the appendices also appear in the following list.

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APPENDIX A

ACCEPTABLE GEOTEXTILES

Geotextiles

AASHTO M 288: Geotextile Specifications for Highway Applications is a key document for this research. It establishes properties that must be met to classify a geotextile in a given manner. *Class 1* geotextiles represent products most suited for harsh installation conditions as would be common after a disaster. *Class 1* geotextiles are recommended for this application when available, but *Class 2* might also be used depending on availability and the situation. *M 288* provides a table of properties related primarily to installation damage that qualify a product as *Class 1*, *Class 2*, or *Class 3*. Pavement reinforcement is stated to be a site specific design issue. Stabilization, which often accompanies reinforcement but is not required to, is stated to be applicable for *CBR* values of 1 to 3; shear strengths on the order of 30 to 90 kPa.

A variety of geotextiles could be used for the applications of interest in this research. This appendix is not intended to provide a comprehensive list of materials available for the research, nor should exclusion of a product from this appendix be taken to mean the product is not suitable for the application as it may or may not be. The intent is to provide a range of example products and corresponding key properties. The *Industrial Fabrics Association International* (*IFAI*) annually produces the *Geosynthetics Specifier's Guide* to provide a comprehensive source of geosynthetic products, of which geotextiles would be one. Information in this appendix was obtained from Volume 27 Number 6 (December 2009 January 2010 edition) of the guide unless noted otherwise.

Nineteen companies were listed as providing some type of geotextile; some of the products would not be suitable for paving reinforcement. *TenCate Geosynthetics* was the largest supplier of geosynthetics at the time this document was written. Table A-1 provides select properties from the *Geosynthetics Specifier's Guide* that could be applicable to the current research. The products provided represent a very small percentage of the products available.

Table A-1. Example Properties of Candidate Geotextiles for Paving Reinforcement

				ASTM D 4595	
Product	**Supplier**	**Contact**	***M 288*** **Class**	***MD***	***XD***
GT300/300	ACE Geosynthetics	www.geoace.com	1	50	89
P105.105	Huesker	www.hueskerinc.com	1, 2, 3	50	55
2 x 2HF	Propex Geosynthetics	www.geotextile.com	1, 2, 3	11	21
4 x 4	Propex Geosynthetics	www.geotextile.com	1, 2, 3	21	38
HP 270	TenCate Geosynthetics	www.mirafi.com	2, 3	18	20
HP 370	TenCate Geosynthetics	www.mirafi.com	2, 3	22	23
HP 570	TenCate Geosynthetics	www.mirafi.com	1, 2, 3	35	39

ASTM D 4595 properties provided are the strength at 5% strain in units of kN/m.
MD refers to the warp or machine direction while XD refers to the fill or cross machine direction (width of roll).
All products listed have M 288 application ratings for separation (SP).
All products listed have manufacturer recommended applications of stabilization (ST) and reinforcement (R).

APPENDIX B

FLOWABLE ASPHALT PRODUCTS

Flowable Asphalt Patching Materials

Flowable asphalt patching materials differ from traditional asphalt cold patching materials in that they do not cure due to evaporation of hydrocarbons; instead, flowable asphalt materials incorporate epoxies, plastics, rubber compounds, or other proprietary chemical components that allow the material to cure once placed. Like typical cold patch asphalt materials, flowable asphalt does not require heat for placement. Flowable asphalt products may or may not require aggregate, those that require aggregate may or may not be premixed with aggregate. Some flowable asphalt products have two components that must be mixed in the field before use and others come pre-mixed and ready to use. Due to the wide range of proprietary additives and formulations, no standard specifications or requirements are available for flowable asphalt patching materials. Example properties of a few flowable asphalt materials are given in Table B-1.

Table B-1. Example Properties of Flowable Asphalt Patching Products

Product	Supplier	Contact	Curing	Shelf Life
EnviRoad PACHR	Envirotex	www.envirotx.com	None	1- 2 years[1]
Perma-Patch®	Nat. Paving & Contracting	permapatch.net	None	1 - 2 years[2]
FloMix	PTI	www.pavepatch.com	60 min	NA
4 Seasons™	PTI	www.pavepatch.com	40 min	indefinite

1) Shelf life 1 year when stored in bags and up to2 years stockpiled in bulk.

2) Shelf life minimum 1 year when stockpiled in bulk and minimum 2 years in bags or pails.

APPENDIX C

COLD PATCH ASPHALT

General

Cold asphalt patching materials are combinations of aggregate and asphalt binder that can be stored for a period of time after mixing, up to several months, and then used as needed at ambient temperatures. They do not require heat for placement and are often compacted by hand or some other method using a relatively low compactive effort. Most state *DOT*s have specifications, approved/qualified products lists or both for cold asphalt materials. An excellent manual of best practices for use of cold asphalt patching material is Wilson and Romine (1999); it includes proper installation procedures for cold asphalt patches. Several research reports relevant to cold asphalt patching materials are briefly summarized in the following sections. The reader is directed to the full documents detailing each research effort for further particulars; each report is readily available in the public domain.

Strategic Highway Research Program Cold Asphalt Patch Material Evaluation

As part of the *Strategic Highway Research Program* (*SHRP*), a study of available pavement surface patching equipment and materials was made in Project H-105 that included a survey of state departments of transportation (Smith et al. 1991). A follow on project, H-106, was conducted that included an extensive laboratory and field evaluation of asphalt patching materials and equipment identified in H-105. The research included 1,250 individual patches placed in the field at eight locations in North America (Wilson and Romine, 1993). The field locations were monitored for performance at regular intervals for 18 months following installation. Eight cold asphalt patching materials were evaluated; laboratory testing of material properties was also conducted as part of the evaluation.

Over the course of the study a large number of the patches failed; however, the failure rate for patches was very dependent on geographic location of the patches. Patches performed at the same time in the same locations according to local maintenance practice for patching were used as control patches. In most cases, the seven study materials performed better than the control patches. No statistical correlations were found between laboratory measured properties and field performance of the patching materials. Wilson and Romine (1993) recommended that the best quality materials be used for patching instead of cheaper, poorer quality materials due to the increased cost associated with re-patching when the lower quality materials failed relatively quickly.

State Departments of Transportation Cold Asphalt Patch Material Evaluations

Prowell and Franklin (1996) evaluated thirteen cold patching materials in Virginia. Both laboratory and field testing was performed. The field testing consisted of placement of approximately 80 pothole patches and monitoring their performance for 12 months. The potholes were artificially created with 380 mm diameter, 50 to 75 mm depth and a flat bottom; one half of the potholes were partially filled with water before patching. Based on all of the results, the researchers stated that laboratory tests are insufficient to distinguish between high or low quality patching materials and that field testing was necessary to discern the best performing materials. Based on their superior performance, use of high quality patching materials was recommended.

Berlin and Hunt (2001) evaluated ten asphalt cold patching materials in Oregon. The bituminous material types included were six cutback asphalts, two emulsions, one natural tar sand, and one unspecified material. Patches were applied in the field to both natural potholes and to artificial potholes created with a jackhammer for purposes of the study. The artificial potholes were approximately 410 mm in diameter and ranged from 38 to 64 mm in depth (Berlin and Hunt, 2001). Field performance of the patches was monitored for six months. A few of the products failed prematurely due to causes that could not be determined while the rest of the patched locations were still performing well at the end of evaluation. Laboratory testing of material properties was also conducted for all of the materials tested. Based on the study results, Berlin and Hunt (2001) recommended that less than 5% passing the 0.075 mm sieve be permitted on gradation.

A study performed in New Jersey in 2001 (Maher et. al. 2001) evaluated six asphalt cold patching materials. The evaluation included laboratory testing of material properties and field evaluations of patch performance six months after installation. Based on the results, all of the patching materials tested performed well after six months in-service and no specific recommendations could be made except that the lowest cost material should be selected. This is contrary to the recommendations of the previous studies cited.

Cold Patch Testing at *ERDC*

Shoenberger et al. (2005) evaluated cold patch asphalt and rapid set (i.e. rapid hardening) concrete material for patching roadways. Laboratory and field testing was performed on a variety of materials. A listing of materials in addition to that tested was also provided in the report. Laboratory testing was performed to characterize key material properties, and field testing was performed primarily to provide information related to placement, handling, and performance under traffic. The portion of the work related to cold patch asphalt is summarized in this section while Appendix D summarizes the work related to rapid set concrete.

Twelve cold patch products were tested in the laboratory consisting of nine cutback binders and three emulsions. All materials were packaged in small containers (e.g. 19 L buckets). Five cold patch products were evaluated in a full scale test. Areas measuring 10 cm thick, 50 cm wide, and 90 cm long in a flexible pavement were patched with the bituminous materials over a two day period where high temperatures were approximately 35 C. The materials were placed into dry and wet (four of the five products) patches to evaluate effect of moisture on patch properties. All five propriety products were relatively easy to handle, place, and compact. Traffic was placed with a dual axle military truck that would be a candidate for use in emergency response. Performance of all products was similar as each experienced additional compaction during trafficking but the level of densification was not reported to be excessive. All products were reported to perform well; long term performance evaluation was not made. The four products that were compacted in wet and dry patches were reported to perform essentially the same in either condition. The researchers noted that a large number of propriety repair products were available.

Example Off-the-Shelf Asphalt Cold Patch Materials

All Weather™ Blacktop Patch (www.packagepavement.com) is produced by the Package Pavement Company of Stormville, NY. It is available in 36.3 kg bags. It is recommended to be installed in approximately 12 mm thick lifts; each lift should be compacted before placing any additional lifts. Two to three days are recommended for the material surface to cure before traffic to turn on the patched area.

Quikrete Commercial Grade Permanent Black Top Repair (www.quikrete.com) is produced by the Quikrete Companies of Atlanta Georgia. It is available in 27.3 kg bags or 15.9 kg pails. It is recommended for patching areas no more than approximately 900 by 900 mm. It should be applied in lifts about 25 mm thick. Traffic can be placed on mix once the repair is complete.

U. S. Cold Patch® (www.uscoldpatch.com) is produced by the YK Products of Everett, WA. It is available in 22.7 kg bags. Manufacturer’s recommended installation is 25 to 50 mm thick lifts. It can be driven on as soon as patching is complete.

APPENDIX D

RAPID SET CONCRETE

Rapid Set Concrete Testing at *ERDC*

Shoenberger et al. (2005) evaluated cold patch asphalt and rapid set (i.e. rapid hardening) concrete material for patching roadways. Laboratory and field testing was performed on a variety of materials. A listing of materials in addition to that tested was also provided in the report. Laboratory testing was performed to characterize key material properties, and field testing was performed primarily to provide information related to placement, handling, and performance under traffic. The portion of the work related to rapid set concrete is summarized in this section while Appendix C summarizes the work related to cold patch asphalt.

Four rapid set concrete products were tested at full scale. Rapid set products are available in 19 L pails, and/or in bulk in some instances. Areas measuring 10 cm thick, 50 cm wide, and 90 cm long in a flexible pavement were patched with the concrete materials over a two day period where high temperatures were approximately 35 C. Traffic was placed with a dual axle military truck that would be a candidate for use in emergency response. The overall performance of the rigid repairs was very good; no distresses were observed after traffic. The researchers noted that a large number of propriety repair products were available. The performance of the products in this research is one example of the viability of using raid set concrete for emergency construction after a disaster.

Example Products

Example rapid set concrete products are provided in this section. Significant numbers of additional products are available. *FlexSet* (www.pavepatch.com) is marketed in 19 L pails and is stated to be ready for traffic in one hour. Uses have varied from potholes to driveways to bridges.

Rapid Set® Cement and *Rapid Set® DOT Repair Mix* are products from *CTS Cement* in Cypress, CA (www.ctscement.com). Note that *Rapid Set® Cement* is also being tested in Task 5 of this research. *Rapid Set® Cement* is hydraulic in nature and has been used since the 1960's. It can be used as a repair material for most concrete applications, and could be used for all pavement repairs related to Task 4. It is typically packaged in 23 to 40 kg bags but is available in bulk in some locations. Typical mortar cube compressive strengths according to *ASTM C 109 (Mod.)* reported by the manufacturer are 176, 352, 458, and 563 kg/cm^2 at 1.5 hr, 3 hr, 24 hr, and 28 days, respectively. The initial set of the material is in 15 minutes and the final set is in 35 minutes. Generally recommended proportions are one bag (40 kg) of *Rapid Set® Cement*, 80 kg sand, 80 kg of aggregate (9.5 to 19 mm), and approximately 15 liters of potable water (*w/c* ratio of approximately 0.40). The material can be mixed in a conventional fashion and is then water cured. Set control additives are available from the manufacturer.

The rapid set technology discussed in the previous paragraph can also be modified using latex, thus producing *Rapid Set® Latex Modified Concrete*. The key ingredients are: *Rapid Set® Cement*, clean sand conforming to *ASTM C 33*, coarse aggregate conforming to *AASHTO M 80*, latex emulsion manufactured by DOW Chemical Company (e.g. styrene butadiene polymeric emulsion), water free from salt, acid, oil, organic matter, or similar substance, and possibly an admixture to lengthen working time (e.g. *Set Control®* or food grade citric acid). A typical mix design using the material would be: 700 kg of *Rapid Set® Cement*, 94.5 kg of styrene butadiene polymeric emulsion, 775 kg of fine aggregate, 590 kg of coarse aggregate, and 73 kg of water. Continuous mixers are required with available fluid tanks to separate the water, latex, and any admixtures used while providing positive flow control. The mixer must be able to allow accurate proportioning. When placing, a thin layer of the material should be brushed into the moist substrate just ahead of the main pour. Vibration is permissible and water curing should be performed. During periods of hot weather (e.g. above 27 C), the mixture may need to be supplemented with citric acid to extend the working time (in a disaster environment this will likely be needed).

Rapid Set® DOT Repair Mix is a mixture of sand and *Rapid Set® Cement* that can be trafficked two hours after placement. It is suitable for all pavement repairs applicable to this research. The material comes in 25 kg bags that produce compressive strengths of 232, 338, 458, and 669 kg/cm^2 at 1 hr, 3 hr, 24 hr, and 28 days, respectively when mixed with approximately 3 to 4.5 liters of water. The material can be extended by 100% using a clean and uniformly sized aggregate. Strengths resulting from this extension should remain acceptable for emergency pavement applications. The working time for the material is 10 to 20 minutes at 21 C; working time will increase as the temperature decreases and vice versa. The material can be mixed in a conventional fashion and is then water cured. Set control additives are available from the manufacturer.

QUIKRETE® Cement & Concrete Products™ (www.quikrete.com) manufactures products applicable to rapid repair of pavements in disaster environments. An example product is *QUIKRETE® Rapid Road Repair® #1242*. The material is applicable to all rapid set pavement repairs related to Task 4. Traffic can resume in many conditions in approximately one hour. The material is supplied in 22.7 and 30.4 kg bags, which contain specialty blended cements, graded aggregate, and glass fibers (in some cases). Initial set of the material is typically 17 to 25 minutes and final set is typically 25 to 45 minutes. Compressive strength of *ASTM C 109* mortar cubes as reported by the manufacturer are 210, 240, 366, 570, and 589 at 1 hr, 3 hr, 1 day, 7 days, and 28 days, respectively. The water required for use is 2.8 liters for the 22.7 kg bag and 3.8 liters for the 30.4 kg bag. Mixing and placement follow customary approaches. The manufacturer recommends ambient rather than moist curing conditions. The product can also be extended with aggregates.

APPENDIX E

PAVING MATS

General

Currently available matting can be obtained in rolls, folded, and in panels. Matting systems are often developed with rapid constructability in mind. Mat connections include tongue and groove; locking rails; threaded bolt and bushing; locking pins; overlap and underlap sections that are pin connected; and built-in cam pins. Table E-1 provides general information of four products that were part of a contingency helipad demonstration led by *ERDC* at Fort Campbell, KY to allow a generalized view of key construction parameters.

Table E-1. Properties of Mats Tested in Anderton and Gartrell (2005)

Product	**Installation (m^2/person hr)[a]**	**Density (kg/m^2)**	**Unit Cost ($/mm^2)[b]**
Deschamps Mobi-Mat®	47	1.9	150
DURA-BASE®	28	42.6	169
SUPA-TRAC®	56	7.5	104
MP Fiberglass Matting	28	11.8	85

a: Assuming a typical crew of five people.
b: Cost in 2002.

Anderton et al. (2008) performed a *JRAC* demonstration in Australia in 2007, which was the conclusion of a six year research and development cycle. The *JRAC* training program could be an example for rapid infrastructure programs to investigate; rapid pavement repair would be a candidate. The program reduced time for construction of military airfields in a contingency setting, with the construction activities reducing the durations by intervals measured in days while still requiring times measured in days. The success of the program demonstrates the viability of using matting systems for rapid pavement repair after a disaster such as a hurricane.

Folded Fiberglass Mat

One product specifically mentioned in the body of the report was a Folded Fiberglass Mat (FFM). Colt® Rapid Mat™ (www.rapidmat.com) is one source for such a material. The panels are connected using elastomer hinges that are approximately 7.5 cm wide. The total weight of a nine panel system is on the order of 1,350 kg with each panel being approximately 1.8 m wide, 9.1 m long, and 1 cm thick. Equipment needed to use products of this nature is commercially available and can be provided by the manufacturer of the specific product.

Wooden Mats

Stroble (2009) provides detailed testing and analysis of wooden construction platforms. The work shows the products as a viable rapid repair option. Multiple vendors are available for these types of products including *Anthony Hardwood Composites* and *MODUMAT*. The *USACE* through *ERDC* has also tested wooden matting systems in the presence of vehicular traffic. The literature review of Stroble (2009) provides detailed information.

Matting for Expeditionary Roads

Rushing et al. (2007) and Rushing et al. (2009) provide detailed testing of matting systems for expedient road construction. Rushing et al. (2007) provides data regarding nine commercially available matting systems tested at traffic intervals up to 2,000 passes with a 6,350 kg military truck: *ROLLAROAD™ MKIII, RoverDeck™, Fast Composite Roadway (FCR), Plastic hexagonal mat, Aluminum hexagonal mat, BRAVO®, ACE-Mat™, DuraDeck*, and *Mobi-Mat® A2X*. Rushing et al. (2009) provides evaluation of a single matting system (*Supa-Trac*) with a fully loaded 6,350 kg military truck with up to 3,500 passes. The results of the various configurations have been omitted for brevity as these reports are publically available. For purposes of this report, the significant parameter is that products are commercially available that have demonstrated performance in full scale testing.

Matting for Airfields

The information presented in this section is a summary of the research performed by Anderton and Gartrell (2005) and Gartrell (2007). Table E-2 is a series of matting options tested for aircraft loading. They were tested in conjunction with five soil support conditions varying from CBR of 3 to CBR of 50 in the presence of *C-130* and *C-17* aircraft loading. Depending on the support, mat, and aircraft combination, failure of the matting systems occurred as early as prior to 100 passes or did not occur after 2,000 passes. Note aircraft loading (especially *C-17* loading) is more severe than truck traffic in most instances. This research also demonstrates viability of using matting systems in temporary pavement repair in disaster applications.

Table E-2. Example Matting Properties: Anderton and Gartrell (2005)

Mat	Material	W_T (m)	L_T (m)	W_E (m)	L_E (m)	D (cm)	Density (kg/m^2)	E_c^{NJ} (MPa)	E_c^{J} (MPa)
1	Fiberglass	9.10	16.50	9.10	16.50	0.64	9	---	---
2	Polymer	2.40	15.30	2.40	15.30	2.54	43	---	---
3	HDPE	1.22	1.22	1.08	1.08	6.40	14	182	119
4	Fiberglass	2.04	2.04	1.83	1.83	0.95	12	16,960	11,700
5	HDPE	2.44	4.27	2.13	3.96	10.8	46	321	462

W_T and L_T are total dimensions of one panel, W_E and L_E are effective dimensions, and D is mat thickness.
E_c^J and E_c^{NJ} are elastic modulus properties of the mats with and without joints, respectively
Mat1: Folded Fiberglass Mat (FFM)
Mat 2: Rolla Road Mark III®
Mat 3: SP-12 Mat (aka BRAVO®)
Mat 4: Multi-Purpose (MP) Mat (5-ply)
Mat 5: DURA-BASE®

APPENDIX F

SLAB JACKING

Overview

Deep injection methods can be candidates for slab jacking during a disaster environment. *URETEK* (www.uretekusa.com) is one example of a company who provides such a service. In that this is a service and a product rather than a product alone, less detail has been provided as experienced personnel will be performing the process. The process is applicable to concrete slabs.

The material injected is hydro insensitive, which means no appreciable water infiltration and no breakdown when exposed to water. It is also lightweight so as to minimize settlement and is chemically stable. *URETEK* company literature indicates a significant portion of the strength is generated within minutes of the application. The technology has been used on Department of Transportation projects; New Mexico is an example where the technology was used on I-25 near Albuquerque.

A key material used is *URETEK 486* polymer, which is a high density expanding resin. Application of the material can be measured in hours. Injection holes (on the order of 19 mm) are drilled into the pavement to allow the polymer resin to be placed. The number of holes required depends on the footprint of the area to be treated.

APPENDIX G

WMA FOR RAPID PAVEMENT REPAIR

General

Warm mix asphalt is composed of the same components as HMA, only it is produced and compacted at lower temperatures. To allow for the reductions in mixing and compaction temperature, a variety of production processes, specialized equipment, or additives are used. New warm mix technologies are regularly being developed and brought to market and it is outside the scope of this report to identify all of them. An excellent resource for information on warm mix asphalt and the latest warm mix technologies is www.warmmixasphalt.com, which is maintained by the National Asphalt Pavement Association, an industry-wide organization. For the purposes of this discussion, these various warm mix technologies will be broadly broken into two categories: those that incorporate some type of binder foaming, and those that do not. Each of these categories will be discussed in the following sections.

Foaming Equipment and Additives

A number of warm mix asphalt technologies utilize binder foaming in one form or another to improve the coating of aggregate at reduced mixing temperatures and improve compaction. The foam is produced by introducing small amounts of water into the binder in such a way that it is quickly converted to steam. The steam expands very quickly to produce asphalt binder foam with very small bubbles of binder. Many of these technologies require asphalt plant modifications for injection nozzles to introduce water for steam generation. A few additives are available that introduce moisture into the binder; the zeolites which they are composed of contain relatively large moisture contents. Table G-1 summarizes several of these foaming warm mix technologies currently available commercially. The foam produced by these technologies is transient in nature and has a relatively short half life. The effect of the foamed binder will potentially not remain for the extent of the extended haul times proposed in Appendix H of this report. For the application of hot mixed warm compacted asphalt as presented in this report, foaming warm mix technologies are not considered to be appropriate.

Table G-1. Foaming Warm Mix Technologies

Name	Manufacturer	Process Type
Aspha-min®	aspha-min GmbH	Foaming Additive
Advera®	PQ Corporation	Foaming Additive
Double Barrel Green™	Astec Industries	Foaming Equipment
Ultrafoam GX™	Gencor Industries	Foaming Equipment
AQUABlack®	MAXAM Equipment	Foaming Equipment
Aqua Foam WMA System	Meeker Equipment Corp.	Foaming Equipment
Accu-Shear™	Stansteel	Foaming Equipment
TEREX® WMA System	TEREX Roadbuilding	Foaming Equipment
LEA	LEA-CO / McConnaughay	Foaming Equip / Process

Chemical or Organic Additives

Non-foaming warm mix technologies include chemical and organic additives; these additives can be added in several different ways including pre-blending with binder at the asphalt terminal, blending with binder at the asphalt plant, and blending with the mixture at the asphalt plant. The primary advantage of non-foaming warm mix technologies in the context of hot mixed warm compacted asphalt as proposed elsewhere in this report is that their effect is not time sensitive. The additives will retain their effectiveness over time even for extended haul distances. Table G-2 summarizes several non-foaming warm mix additives. Two of them, namely Sasobit®, and Evotherm™ were utilized for experimental laboratory work for this report; details can be found in Appendix H.

Table G-2. Non-Foaming Warm Mix Technologies

Name	Manufacturer	Process Type
Sasobit®	Sasol Wax North America Corp.	Organic Wax Additive
Evotherm™	MEADWESTVACO	Chemical Additive
REDISET™ WMX	Akzo Nobel	Chemical Additive
Cecabase RT	Arkema Group	Chemical Additive

APPENDIX H

HOT MIXED WARM COMPACTED ASPHALT

Introduction

The recent advent of technologies and processes that facilitate production and placement of asphalt pavements at lower temperatures than typical hot mix asphalt (HMA) raised the possibility of increasing the distance over which mixes could be transported before lay down. This was due to the smaller temperature differential between the material and its surroundings resulting in slower cooling during transport as well as the ability to compact the mixtures at lower temperatures. This purported benefit of warm mix asphalt (WMA) to longer haul distances is frequently mentioned (D'Angelo et al. 2008; Prowell and Hurley 2007*)* but is difficult to quantify. In a disaster response environment where significant pavement infrastructure damage has occurred and paving materials are not readily available, such as after a major hurricane, there are potential advantages to importing asphalt mixture from less affected areas on a limited basis as temporary patching and paving material. This material would not be used long term. The material would have residual value as, for example, milled RAP or in full depth reclamation.

Producing asphalt mixtures at typical HMA temperatures and then compacting at WMA temperatures negates the energy savings associated with reducing the production temperature but will maximize the temperature differential and therefore the distance which material can be transported before compaction. The purpose of this research is to evaluate the potential for hot mixed and warm compacted asphalt to be used as temporary paving and patching material in a hurricane response environment; it includes a component to estimate the temperature of mixture upon arrival after significant transport distances. To accomplish this objective an experimental program was developed to evaluate the performance of three scenarios relative to a control under the anticipated conditions. Two of the scenarios were use of warm mix additives and the third was a sequential mixing method.

Aging of Asphalt Binder

Asphalt binder hardening occurs in two distinct stages: 1) short term aging during production, transport and placement principally due to volatilization and oxidation of the binder; and 2) long term aging after construction principally due to weather and environmental effects (Bell 1989; Bell et al. 1994a). The effects of short term aging are an important issue for hot mixed warm compacted asphalt especially in conjunction with the extended haul distances under consideration. Long term aging is of less concern for disaster recovery due to the short service life anticipated for hot mixed warm compacted asphalt.

Heat drives volatilization of lower molecular weight components of asphalt binder; elevated temperature also speeds the rate of oxidation. During production hot asphalt is mixed with aggregates and forms a thin film on their surface facilitating the volatilization process and exposing the binder to oxygen while at elevated temperature; the combined effects result in a higher viscosity, stiffer binder. In addition to volatilization the high temperature of construction causes asphalt to be absorbed into the pores of aggregate which affects the volumetric properties of the mixture. This is especially significant in mixtures made with large quantities of absorptive aggregate such as is common in Mississippi and many other hurricane prone areas.

During the development of Superpave by the *Strategic Highway Research Program (SHRP)* significant effort was devoted to quantifying the effects of short term aging of asphalt mixtures during production and construction. A state of practice and literature review conducted by Bell (1989) identified three potential methods to simulate short term aging in the laboratory and several prospective tests to evaluate the effect of laboratory aging. Bell (1989) also noted that almost no data was available to compare the performance of laboratory produced mixture to field produced mixture with respect to short term aging. Work by Von Quintus et.al. (1991) compared recovered binder viscosities of lab aged to field produced material. The necessary oven aging period required to approximate field produced results varied from 108 minutes to 486 minutes for different field projects. Subsequent laboratory work (Bell et al. 1994b) and field validation (Bell et al. 1994a) resulted in a recommendation of short term oven aging of loose asphalt mix at 135 C for 240 minutes. This recommendation was implemented in the first iteration of Superpave (Cominsky et al. 1994).

National Cooperative Highway Research Program (NCHRP) Project 9-26 was a study of absorptive aggregates that included a component investigating the effect of oven aging time of laboratory samples. Based on the data generated a maximum laboratory short term aging period of 240 minutes was recommended; however it was noted that "laboratory aging does not necessarily represent the aging that takes place in the field" (Arazietal et al. 2006).

Current Superpave recommendations for mix design are to short term oven age the loose asphalt mix for 120 minutes ± 5 minutes at the desired laboratory compaction temperature according to *AASHTO R 30-02: Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)*. The current *MDOT* volumetric mix design method requires 90 minutes of loose mix short term oven aging time at the compaction temperature (oven set 2.7 to 5.6 C above compaction temperature) (MDOT 2005).

Thermodynamics of Asphalt Transport

Once asphalt mix leaves the plant storage silo and enters a truck it begins to cool. The amount of heat lost depends on 9 factors (Brock and Jacob 1998); 1) mix temperature when loaded into truck; 2) ambient air temperature; 3) if the truck bed is insulated; 4) size of truck bed in relation to tons of mix hauled; 5) length of haul; 6) speed of travel; 7) waiting time at paver; 8) if the mix is covered; and 9) traffic delays. Heat is lost quickly to the air above the mass of asphalt in the truck and through the sides of the truck bed; however the relatively low thermal conductivity of asphalt mix slows the rate of heat transfer from the middle of the mass to the edges (Brock and Jacob 1998). An outer crust of mix relatively cooler than the center of the mix mass develops resulting in an insulating effect. Brock and Jakob (1998) present data collected with a thermal imaging camera of asphalt mix in the bed of a truck; the center of mass is above 116 C while the formation of a cooler outer crust on the order of 82 C is evident.

Brock and Jakob (1998) cite an instance in Australia where a mix was transported 240 km from the plant to the paving site; upon arrival the outside truck body temperature was 80 C, the mix exposed top was 96 C, and the center temperature of the mix mass was 152 C.

Several field trials of warm mix asphalt were conducted in Virginia in 2006. The trials are described in the literature by (Diefender et al. 2007). For field trial B of the report, relevant temperatures and average haul time was reported that is useful in estimating the cooling properties of asphalt mix being hauled for relatively long periods. An HMA control section and a WMA section were placed on consecutive days; August 14 and August 15,

2006. The paving location was in Highland County in northwestern Virginia. The data of interest is summarized in Table H-1. Due to local mountainous terrain between the plant and paving site the haul time was approximately 105 min over a distance of 72 km. This translates into an average speed of about 41 km per hour. The ambient conditions were taken from the nearest available weather stations to the plant and paving sites. For most parameters a range of temperatures was reported; when only one value was reported it was considered to be the median value.

Table H-1. Field Trial Temperatures as Reported in (Diefenderfer et al. 2007)

Parameter	High (C)	Low (C)	Median (C)	Comments (---)
HMA – 8/14/06				583 metric tons produced
Ambient Temp at Plant	32.8	15.6	24.2	sunny
Ambient Temp at Paving Site	30.0	20.0	25.0	sunny
Production Temp	165.6	162.8	164.2	
Temp of Mix at Arrival	---	---	148.9	
Temp of Mix Behind Screed	148.9	137.8	143.4	
WMA – 8/15/06				290 metric tons produced
Ambient Temp at Plant	30.0	20.0	25.0	overcast
Ambient Temp at Paving Site	22.2	20.0	21.1	overcast, drizzle
Production Temp	---	---	148.9	
Temp of Mix at Arrival	137.8	132.2	135.0	
Temp of Mix Behind Screed	135.0	121.1	128.1	

The type of mixture used was a typical Virginia DOT approved mixture and is concisely described by (Diefenderfer et al. 2007).

> *"The mixture used in this trial was an SM-12.5A mixture (12.5 mm nominal maximum surface mixture with PG 64-22 binder) containing 10% RAP with a design asphalt content of 5.3%. Hydrated lime was used in the mixture to prevent stripping. Sasobit was added at a rate of 1.5% by weight of binder. No other changes were made to the mix design during the production of WMA."*

No material transfer vehicle was used during the paving operation. Since the specific type of truck used to haul the mixture from plant to paving site was not stated it is assumed that it was a typical full size truck-trailer combination.

Newton's Law of Cooling states that the time rate of change in temperature of an object is proportional to the difference between its temperature and the ambient surroundings (*12*). This relationship can be expressed in the form of Equation H-1.

$$\frac{dT}{dt} \propto \left(T - T_a\right) \qquad \text{(H-1)}$$

T_a : ambient temperature

The relationship can also be expressed in terms of a proportionality constant in the form of Equation H-2.

$$\frac{dT}{dt} = -k\left(T - T_a\right) \qquad \text{(H-2)}$$
$$k: \text{ constant}, \quad k > 0$$

The general solution to this differential relation is as follows in Equation H-3. Its derivation can be found in many differential equations textbooks such as (Zill and Cullen 2005).

$$T\left(t\right) = T_a + \left(T_0 - T_a\right)e^{-kt} \qquad \text{(H-3)}$$
$$T_o: \text{ initial temperature of object}$$

Using the data from Table H-1 and the average 105 min haul time, cooling constants for the Virginia warm mix field trials were determined and are found in Table H-2. It is seen that the cooling constants for HMA and WMA are similar and have a low standard deviation.

Table H-2. Newton's Law of Cooling Parameters from Virginia Data

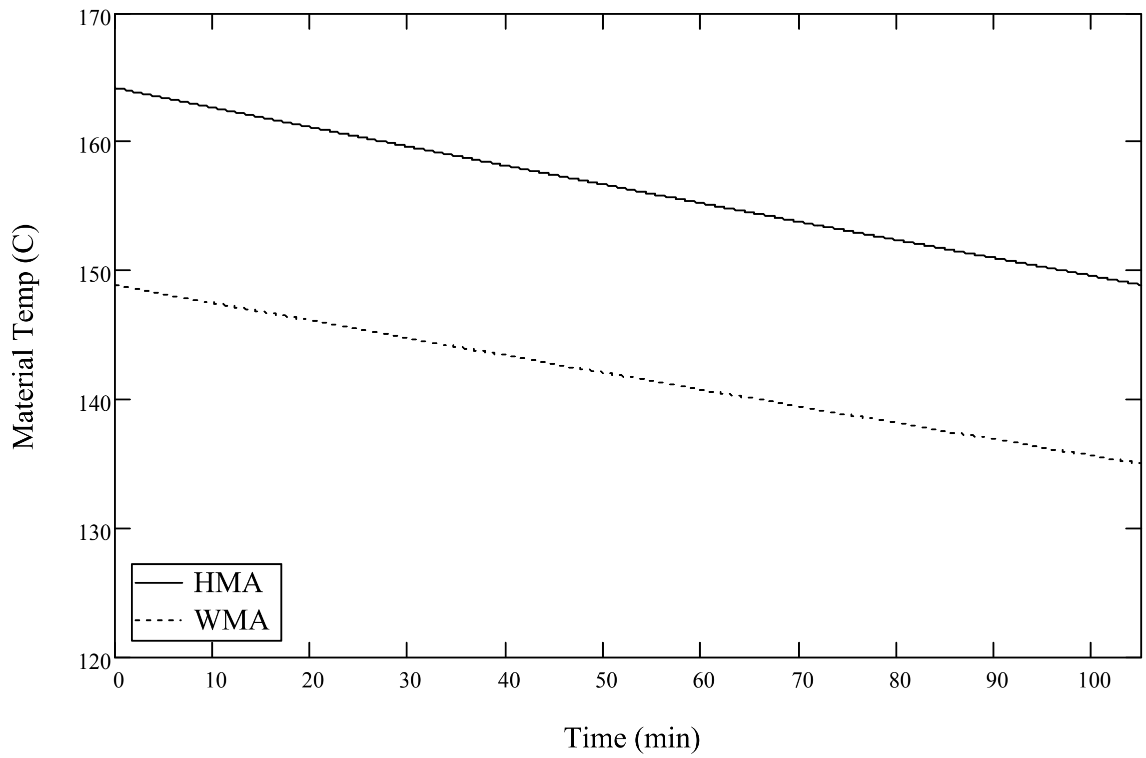
	T_0 **Production Temp[1]**	***T_a*** **Ambient Temp[2]**	***T(105)*** **Arrival Temp**	***k*** **cooling constant**
HMA	164.2	24.6	148.9	1106×10^{-6}
WMA	148.9	23.1	135.0	1115×10^{-6}
Average	**---**	**---**	**---**	**1111×10^{-6}**
Std. Dev.	---	---	---	68×10^{-6}

1. All temperatures in C and are median of values reported unless otherwise stated.
2. Ambient temperature taken as average of all high and low temperatures at plant and paving site.

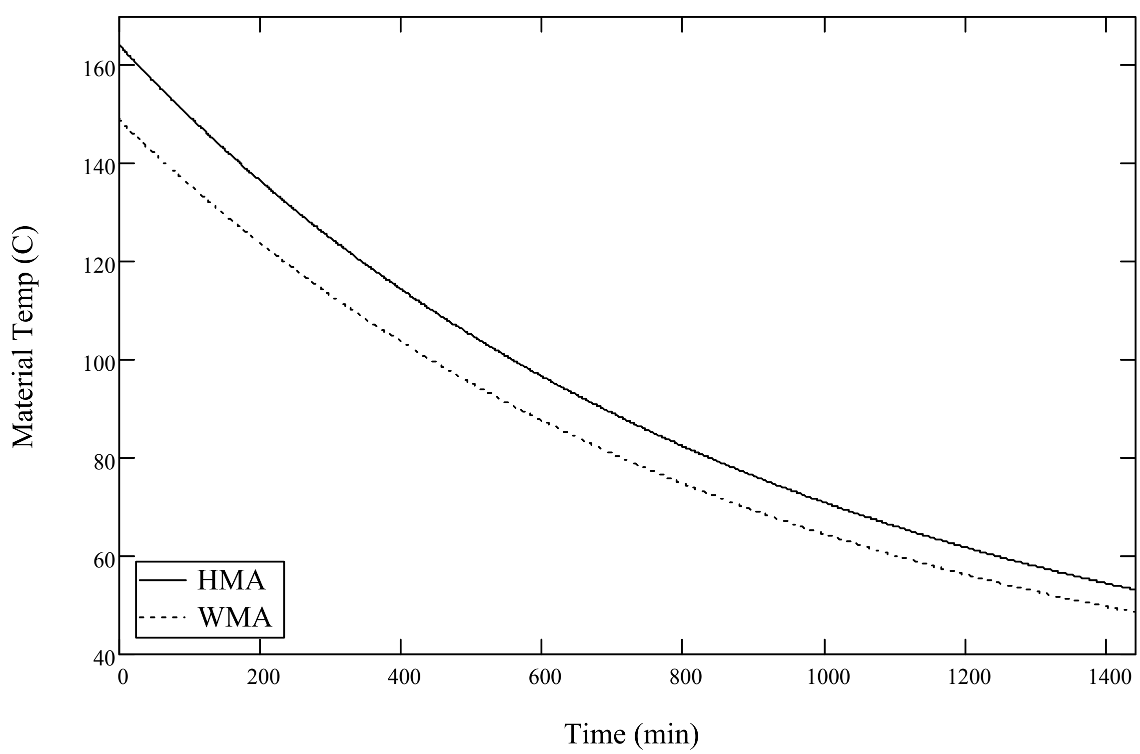
Equation H-3 and data from Table H-2 are plotted in Figure H-1a. The curves for HMA and WMA track each other consistently with the only major difference being the lower mix production temperature of the warm mix asphalt compared to the hot mix asphalt. The cooling rate is essentially linear over the 105 min haul time from the plant to the paving site. The same data is plotted again in Figure H-1b for a 1440 min period (24 hr). This would be the estimated cooling if the material were left in the truck for 24 hours after production (it wouldn't be and is only shown for illustration). The final temperatures of the HMA and WMA after 24 hours of cooling in a truck would be in the vicinity of 50 C. Obviously this would never be performed in practice but it demonstrates how the relatively large mass of material in a truck will retain heat for a remarkably long period of time. The estimated temperature would be the core temperature of the material in the truck; the material closer to the surface would be much cooler.

The average cooling constant from Table H-2 was then used to investigate the cooling properties of a theoretical asphalt mixture being hauled in an ambient temperature of 25 C. This theoretical asphalt mixture might be either HMA or WMA and would have mixture properties similar to the Virginia field trial mixture described earlier.

A series of cooling curves for this theoretical asphalt mixture are presented in Figure H-2 for various production temperatures between 170 and 150 C. Ambient temperature of 25 C was chosen since it was close to the ambient temperature of the Virginia field trial data from which the cooling constant was derived.



a) Mixture Cooling in Truck during Transport to Paving Site



b) Mixture Cooling Extrapolated over 24 hour Period in Truck

Figure H-1. Asphalt Mixture Cooling from Virginia Data

The trend of cooling is the same for the series of curves since all utilize the same cooling constant and ambient temperature. Simply varying the production temperature will change the mixture temperature for a given haul time. The production temperatures span the range of typical HMA temperatures with neat asphalt binder. Mixture temperature values for several haul times are given in Table H-3 from the curves represented in Figure H-2. Haul times of 90 min, 120 min, 240 min, 360 min, 480 min, and 600 min are tabulated.

Table H-3. Temperatures at Various Haul Times for Theoretical Asphalt Mixture

Production	**Haul Time after Production**					
Temp (C)	**90 min (C)**	**120 min (C)**	**240 min (C)**	**360 min (C)**	**480 min (C)**	**600 min (C)**
170	156	152	136	122	110	100
165	152	148	132	119	107	97
160	147	143	128	116	104	947
155	143	139	125	112	101	92
150	138	134	121	109	98	89

It must be emphasized that the preceding discussion represents a significant extrapolation from a limited data set and is only included to illustrate the trends of asphalt mix temperature during transport from the plant to the paving location. Based on the research team's prior experience the mix temperatures for long haul times predicted in Table H-3 appeared to be higher than would occur in typical practice since they are only for the interior portion of a truck and will reduce once mixed with the outer material that is cooler. A more conservative set of temperatures was ultimately used after testing and analysis discussed in the experimental program.

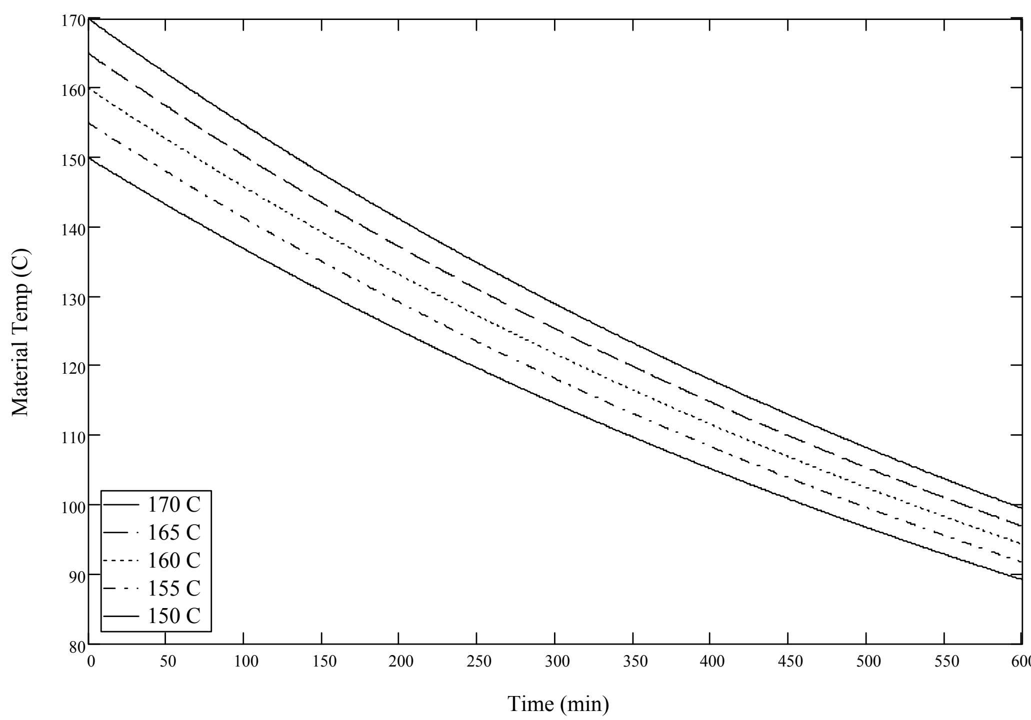


Figure H-2. Cooling Properties of Theoretical Asphalt Mixture

Experimental Program-Hot Mixed Warm Compacted Asphalt

The purpose of the hot mixed warm compacted asphalt is a quick deployment temporary paving material with an estimated 30 to 45 day service life. Power would likely be restored in the vicinity of the disaster in that length of time, drastically diminishing the value of these mixtures that are being hauled from remote areas with power. Research therefore focused on: 1) the ability of potential mixtures to be compacted at anticipated conditions; and 2) short term performance. During development of the experimental program short term aging protocol and target compaction temperature parameters were developed from available literature and experimental asphalt mixture cooling data.

To investigate the feasibility of hot mixed warm compacted asphalt a two component laboratory experimental program was developed: 1) compaction of mixture slabs to evaluate relative field compaction; and 2) compaction of *Superpave Gyratory Compactor (SGC)* samples to desired air voids for rut testing. A minimum of two replicates at each factor-level combination were used for all testing in the experimental program.

Component one of the experimental program consisted of twenty four factor-level combinations: two gradations/aggregate types; four compactability scenarios; and three short term aging and compaction temperature parameter sets. The experimental program did not consider lift thickness as a variable; a moderate thickness on the order of 76 mm was chosen for all testing. The two gradations and aggregate types will be discussed in the section on materials. Short term aging and compaction temperature parameter sets will be discussed in detail in the section on development of short term aging protocol. Slabs were compacted with a *Linear Asphalt Compactor (LAC)*; this allowed for evaluation of relative compactability of mixture factor-level combinations. A target on the order of 10% (+) air voids was selected by the research team for slab compacted control specimens. Compacted slabs were sawn into core samples for further testing. Three categories of short term performance were evaluated: 1) rutting resistance; 2) indirect tensile strength; and 3) moisture damage. Rutting potential was assessed with the *Asphalt Pavement Analyzer (APA)*. Indirect tensile strength was determined in accordance with *AASHTO T 283 Section 11*. Moisture damage was expressed as *Tensile Strength Ratio (TSR)*; the conditioning protocol is described in the appropriate section.

Four compactability scenarios were investigated: 1) control mixture; 2) sequential mixing to simulate the effects of foaming asphalt in absence of water; 3) Sasobit® warm mix additive; and 4) Evotherm 3G™ warm mix additive. Control mixture samples utilized standard binder without additives and were mixed according to laboratory standard practice. Sequentially mixed samples did not utilize additives but instead were mixed in two stages similar to (Ohlson 1975) and will be described in detail in the appropriate section. The concept of sequential mixing was to improve aggregate coating similar to foamed asphalt without the use of water. Sasobit® and Evotherm 3G™ warm mix additives were added to binder before use at appropriate dosage rates; binder was then mixed with aggregate in ordinary manner.

Component two of the experimental program included all of the factor-level combinations in component one as well as two target air void levels. Target air void levels were 7% and 10%; standard *APA* testing is conducted with 7% air void samples. 10% air voids (V_a) was selected at the beginning of the experimental program to be on the order of the minimum air void levels for slab compacted specimens in component one. Samples were compacted in the *SGC* to target air voids, cooled from compaction temperature to test temperature, and then immediately subjected to *APA* rut testing without ever being allowed to reach ambient temperature. The purpose was to assess rutting potential of mix opened to traffic very soon after compaction without being allowed to cool completely. Quick opening of hot mixed warm compacted pavement to traffic would be highly desirable in a disaster response environment.

<u>Materials</u>

Selection of asphalt mixtures suitable for the experimental program was given significant consideration. The *MDOT Materials Division* provided substantial assistance in selection of the mixtures. Dozens of *MDOT* approved mixtures were evaluated with the goal of selecting two mixtures with different properties from different geographic locations.

The primary criterion selected by the research team was that the mixtures were approved by *MDOT*. The majority of *MDOT* approved asphalt mixtures produced in the state of Mississippi are made of local crushed gravel, imported crushed limestone, or a blend of the two. Therefore one of the mixtures was to have in excess of 60% gravel and the other was to have in excess of 60% limestone. A maximum of 15% Reclaimed Asphalt Pavement (RAP) was also chosen since RAP materials fluctuate over time, stiffen the mixture, provide additional compaction difficulty, and often require elevated warm mix additive contents.

Geographic location was also carefully evaluated. First, a list of asphalt production facilities within Mississippi was obtained from the *Mississippi Asphalt Paving Association (MAPA)*. In general, only plants in the southern half of Mississippi producing one of the aforementioned *MDOT* approved mixtures were considered. One plant was selected that was near the northernmost area considered, and the other plant was selected near the southernmost area considered. The rational for selecting the extreme areas was that having one plant a considerable distance from the high risk power outage area provided a high level of confidence of delivery but would take a considerable amount of time, while having a plant relatively close to the gulf would provide a much shorter travel distance but would be at risk for power outage after the disaster. Note that other plants could also provide materials depending on the actual conditions of the disaster; the research team chose the parameters to represent a considerable range of properties over a wide geographic area. Plants along the coast are at a higher probability of damage (or power outage) during a hurricane, but it is unlikely that any event would damage all plants along the coast that are within responding distance.

With the aforementioned criterion in mind two mixes were selected: 1) a mixture containing 74% crushed limestone aggregate and 15% RAP produced in Meridian, MS by APAC-Mississippi Inc.; and 2) a mixture containing 63% crushed gravel aggregate and 15% RAP produced in Picayune, MS by Huey Stockstill Inc. Both mixtures were *MDOT* approved and material was available for laboratory investigation. The asphalt mixture predominately composed of crushed limestone will hereafter be referred to as *Mixture* 1 and the mixture composed of predominately crushed gravel will hereafter be referred to as *Mixture* 2. The locations of the asphalt plants producing the respective mixtures within Mississippi and relative to the coast are seen in Figure H-3.

For *Mixture* 1 the distance by major arterial road from the asphalt plant to the intersection of U.S. 49 and U.S. 90 in Gulfport, MS is 254 km. Assuming an average speed of 56 kph it would take approximately 270 min (4.5 hr) to travel that distance. For *Mixture* 2 the distance by major arterial road from the asphalt plant to the intersection of U.S. 49 and U.S. 90 in Gulfport, MS is 85 km. Assuming an average speed of 56 kph it would take approximately 90 min to travel that distance.

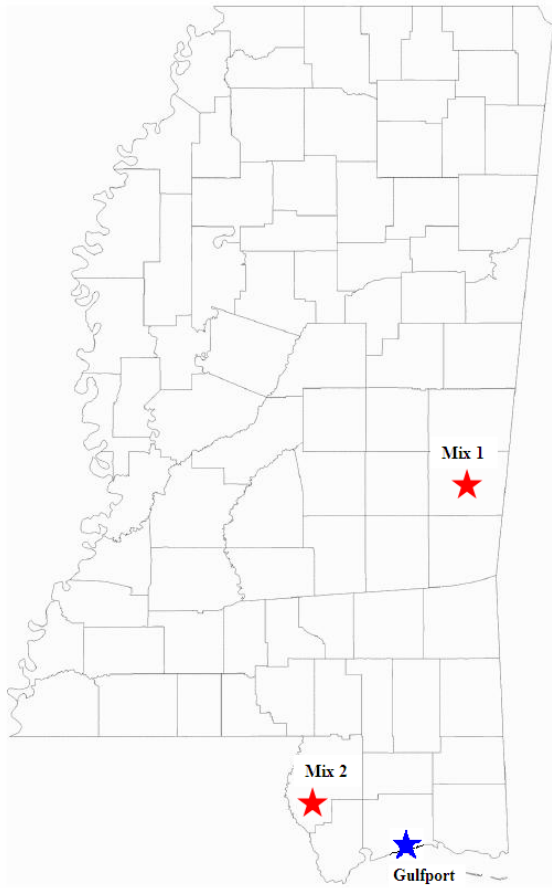


Figure H-3. Locations of Asphalt Plants Producing Selected *MDOT* Approved Mixtures

The properties of *Mixture* 1 virgin aggregates are given in Table H-4; 15% RAP and 1% hydrated lime complete the 19 mm Nominal Maximum Aggregate Size (NMAS) aggregate component. Hydrated lime is required as 1% of total aggregate in all *MDOT* mixtures as asphalt binder anti-strip (MDOT 2004). Once testing began a laboratory mixed and compacted material was randomly sampled, asphalt binder extracted, and aggregate recovered for quality control. The extracted aggregate gradation fell within *MDOT* Job Mix Formula (JMF) allowable tolerances compared to the mix design target combined gradation. The design asphalt content of 4.1% was utilized during laboratory testing for *Mixture* 1. Mix design G_{mm} was 2.545; six laboratory mixed samples of material were tested for G_{mm} and the value of 2.534 determined was used for all subsequent testing. *Mixture* 1 was classified as a Medium Traffic (MT) design traffic level and used PG 67-22 asphalt binder.

Table H-4. Properties of Asphalt *Mixture* 1 Aggregate

Sieve Size (mm)	Percent Passing #672 LST[1]	#89 LST	6.4 mm x 0 LST	#7 LST	Coarse Sand	Combined Gradation	Extracted Gradation[2]
% Used	33	19	7	15	10	100	100
25.0	100	100	100	100	100	100	100
19.0	98	100	100	100	100	99	99
12.5	58	100	100	94	100	85	87
9.5	42	100	100	66	100	75	77
4.75	15	50	90	10	88	43	47
2.36	5.0	12	71	2.1	75	26	29
1.18	4.0	4.0	45	1.7	59	19	19
0.60	3.0	2.0	29	1.4	46	15	14
0.30	2.3	1.5	20	1.3	32	10	10
0.15	2.1	1.4	15	1.2	5.0	5.8	6.5
0.075	1.8	1.3	12	1.0	0.5	4.2	5.3
G_{sa}	2.768	2.773	2.749	2.722	2.645	2.735	---
G_{sb}	2.738	2.738	2.719	2.700	2.606	2.691	---
% Abs	0.40	0.46	0.40	0.30	0.57	0.59	---

1) Limestone

2) Random sample was taken from a compacted slab; binder was completely extracted and aggregate gradation was determined for quality control.

Mixture 2 virgin aggregate properties are summarized in Table 5; 15% RAP and 1% hydrated lime complete the 12.5 mm NMAS aggregate component. During testing a laboratory mixed and compacted material was randomly sampled for quality control, the binder was extracted, and the aggregate component was recovered for gradation testing. The extracted aggregate gradation fell within *MDOT* JMF allowable tolerances compared to the mix design target combined gradation. *Mixture* 2 was classified as a High Traffic (HT) design traffic level.

A PG 76-22 binder was approved by *MDOT* for *Mixture* 2. This material would be modified using polymers. For purposes of this study, a non polymer modified (i.e. neat) PG 67-22 binder was substituted. This material is readily available in Mississippi, and it is believed that using polymer modified binders in conjunction with warm mix technology could shorten haul distances. The decision to substitute a PG 67-22 for the approved PG 76-22 was supported in concept by the *MDOT State Materials Engineer* in temporary mixtures used for disaster recovery. Rational for supporting the non polymer modified binder included: 1) essentially the same volumetric mix design properties from the *SGC*; 2) reduction in cost with no appreciable reduction in performance for temporary solution; and 3) alleviation of potential concerns regarding using warm mixed additives with polymer modified binders.

Due to the change in binder grade for *Mixture* 2 eight *SGC* samples were compacted with PG 67-22 binder to verify the mix design volumetric properties. The original mix design asphalt content was 5.6%; a 0.1% increase in binder content was required to produce desired 4% air voids. An asphalt content of 5.7% was used for all subsequent testing with *Mixture 2*; This was acceptable according to *MDOT JMF* specifications which allow a variation in asphalt content up to +0.5% from the original mix design during plant production (MDOT 2004). Mix design G_{mm} was 2.374; six laboratory mixed samples of material were tested for G_{mm} and the value of 2.350 determined was used for all subsequent testing.

Table H-5. Properties of Asphalt *Mixture* 2 Aggregate

Sieve Size (mm)	Percent Passing 19.0 mm CR GR[1]	7.9 mm CR GR	#11 LST[2]	Coarse Sand	Combined Gradation	Extracted Gradation[3]
% Used	15	48	15	6	100	100
25.0	100	100	100	100	100	100
19.0	98	100	100	100	100	100
12.5	54	100	100	100	93	92
9.5	18	98	100	100	86	83
4.75	7.0	56	93	96	60	57
2.36	6.0	32	64	89	40	39
1.18	5.5	18	39	82	27	28
0.60	5.0	12	25	65	20	20
0.30	4.0	7.0	18	20	11	12
0.15	3.0	5.0	14	1.0	7.5	8.3
0.075	2.0	4.5	11	0.1	5.8	7.1
G_{sa}	2.625	2.621	2.685	2.638	2.628	---
G_{sb}	2.490	2.458	2.641	2.613	2.510	---
% Abs	2.07	2.53	0.62	0.36	1.79	---

1) Crushed Gravel
2) Limestone
3) Random sample was taken from a compacted slab; binder was completely extracted and aggregate gradation was determined for quality control.

All aggregates for *Mixtures* 1 and 2 were processed before use. Aggregates were first air dried with the use of fans and a de-humidifier then sieved into separate retained particle sizes for each standard sieve size greater than 2.36 mm. The aggregate fraction consisting of all particles smaller than 2.36 mm was thoroughly remixed after sieving before use in mixture design gradations. Washed gradations were performed on aggregate stockpiles and combined virgin aggregate samples to adjust batching proportions to meet design aggregate gradations.

PG 67-22 binder was utilized for all testing with *Mixtures* 1 and 2; all binder was provided by *Ergon, Inc.* from its Vicksburg, MS facility. Adequate binder was obtained to complete all phases of the experimental program; warm mix additive technologies were added to the same base PG 67-22 binder as required.

Two warm mix additives were used as part of the hot mixed warm compacted experimental program: 1) Evotherm 3G™; and 2) Sasobit®. Additives were provided by their respective manufacturers. Sasobit® was pre-mixed with PG 67-22 binder at 127 C then either used immediately or cooled off to store for later use. Evotherm 3G™ was pre-mixed with PG 67-22 binder at 149 C and handled in the same manner. Sasobit® dosage was 1.0% by weight of total mixture binder content; dosage rate was chosen based on previous experience by the research team (*15*). Manufacturer recommended dosage of 0.5% by total mixture binder weight for Evotherm 3G™ was followed. Total binder mixture weight includes all of the binder contributed by the 15% RAP component of the aggregate gradations. Since the ratio of total asphalt content to new binder added was different for *Mixture* 1 and *Mixture* 2, the dosage rate of Sasobit® and Evotherm 3G™ added to virgin binder was slightly different for each mix to account for RAP binder.

Table H-6 provides *Dynamic Shear Rheometer (DSR)* properties of all original (un-aged) binder used in the experimental program. It can be seen that the values of G* /sin δ were lowest for binder containing Evotherm 3G™, highest for binder containing Sasobit® and in between the maximum and minimum values for all tested samples of the neat binder. High *G** and low *δ* are desirable for rutting as would occur in a stiff and elastic material.

Table H-6. Un-aged Binder *DSR* Properties

Mix	**Type**	**Sample**	**Rep**	***G**** **(kPa)**	***δ***	***G**** **/ sin *δ* (kPa)**
All	**Specification[1]**	**---**	**---**	**---**	**---**	**Min 1.00**
All	Neat PG 67-22	1	1	1.35	84.7	1.35
			2	1.30	85.1	1.31
		2	1	1.25	85.1	1.26
			2	1.24	84.6	1.25
			Avg.	**1.29**	**84.9**	**1.29**
Mix 1	Sasobit®	3	1	1.72	83.7	1.73
			2	1.74	83.2	1.76
			Avg.	**1.73**	**83.5**	**1.75**
	Evotherm 3G™	4	1	1.06	85.8	1.06
			2	1.06	85.5	1.06
			Avg.	**1.06**	**85.7**	**1.06**
Mix 2	Sasobit®	5	1	1.54	83.9	1.55
			2	1.58	83.8	1.59
			Avg.	**1.56**	**83.9**	**1.57**
	Evotherm 3G™	6	1	1.14	85.1	1.15
			2	1.14	85.3	1.15
			Avg.	**1.14**	**85.2**	**1.15**

Note: Test temperature was 67 C and angular frequency was 10 rad/s.
1) AASHTO M 320-09

As a reference, it is estimated that a PG 76-22 binder modified with SBS polymer having a *G** / sin *δ* of 1 kPa at 76 C could easily be in excess of 3 kPa if tested at 67 C. Un-aged binder viscosity for control and *Mixture* 1 materials was determined at the three compaction temperatures selected for the experimental program (Table H-7) according to *AASHTO T 316-06* using a Brookfield Viscometer. At the elevated temperatures, viscosity trends were not the same as with the *DSR* at 67 C.

Table H-7. Un-aged Binder Viscosity at Compaction Temperatures

Mix	Type	Temperature (C)	Rep	Viscosity (cP)
All	PG 67-22	105	1	4400
			2	4387
			3	4387
			Avg.	**4391**
		116	1	2362
			2	2375
			3	2362
			Avg.	**2366**
		146	1	388
			2	375
			3	375
			Avg.	**379**
Mix 1	Sasobit®	105	1	4287
			2	4262
			3	4238
			Avg.	**4262**
		116	1	2125
			2	2088
			3	2088
			Avg.	**2100**
		146	1	350
			2	363
			3	350
			Avg.	**354**
	Evotherm 3G™	105	1	4063
			2	4050
			3	4063
			4	4175
			5	4175
			6	4162
			Avg.[1]	**4115**
		116	1	2088
			2	2075
			3	2088
			Avg.	**2084**
		146	1	450
			2	450
			3	438
			Avg.	**446**

1) Two independent samples tested at three reps each.

Cooling Rate Testing

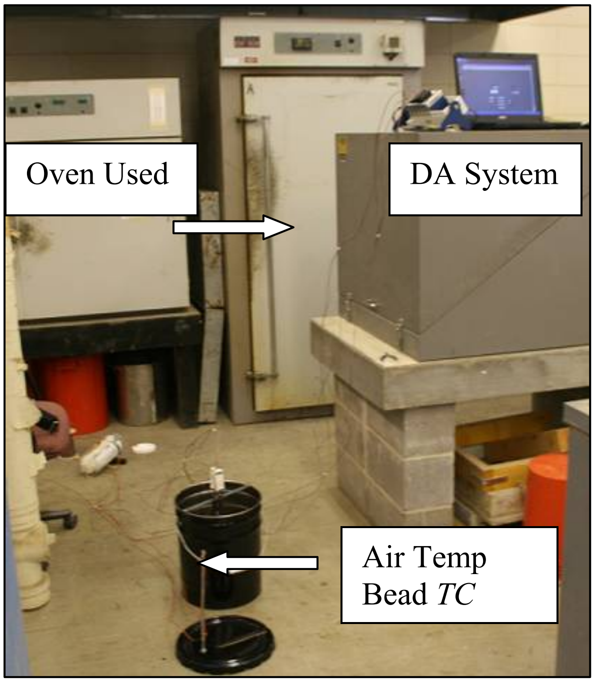
Review of literature did not provide adequate information to develop a laboratory test protocol for hot mixed warm compacted slab specimens. A series of laboratory experiments were conducted to develop the necessary information that could be coupled with literature to develop a suitable protocol. A private (i.e. not *MDOT* approved) 9.5 mm NMAS surface mixture produced by APAC Mississippi Inc. at their Columbus, MS plant was utilized for all cooling rate testing. Aggregate properties as well as individual stockpile and combined gradations are given in Table H-8. The total design asphalt content was 6.0% of PG 67-22.

Table H-8. Properties of Plant Mix Aggregate for Cooling Rate Testing

	Percent Passing				
Sieve Size (mm)	**9.5 mm Crush Gravel**	**Coarse Sand**	**12.7 mm x 0 Plant Screenings**	**6.4 mm x 0 Limestone**	**Combined Gradation**
% Used	35	20	25	20	100
25.0	100	100	100	100	100
19.0	100	100	100	100	100
12.5	100	100	100	100	100
9.5	88	100	92	100	94
4.75	40	96	67	91	68
2.36	22	82	50	59	48
1.18	12	70	39	37	35
0.60	8.4	55	29	25	26
0.30	6.2	19	15	18	13
0.15	4.7	2.5	8.6	14	7.1
0.075	3.6	1.8	6.3	11	5.4
G_{sa}	2.608	2.647	2.592	2.729	2.635
G_{sb}	2.403	2.578	2.472	2.608	2.493
% Abs	3.27	1.01	1.87	1.70	2.16

To prepare the cooling rate test specimen, the procedure summarized in Figure H-4 was utilized. All thermocouples to be used were placed in a water bath and checked against an externally calibrated mercury thermometer. Figure H-4a shows all major components of the experiment. A *National Instruments NI Compaq Daq 9172* chassis and *NI 9211* module were used in conjunction with a program written in *LabView*™ to acquire the temperature measurements. Samples were taken every ten seconds, and with exception of crust temperature measurements were made in duplicate.

A metal pail was adapted to allow two probe thermocouples on the order of the depth of the pail to be placed at what was eventually the middle of the asphalt mixture (Figure H-4c). The aforementioned mixture was heated in covered pans to 171 C and then loosely transferred into the pail (Figure H-4b) which had been heated alongside the lid and probes to the temperature of the first test. The mix was struck off level with the top of the pail (Figure H-4d), which required 33.1 kg of mix and resulted in 25.5% air voids in the loosely placed sample. The pail, lid, and fixtures weighed on the order of 2 kg. The mix was immediately placed into a *VWR Model 1685* oven with 0.1 C temperature control increments and the first cooling rate test conducted. Oven volume was 0.708 m^3 and the manufacturer specified temperature uniformity was ± 1.0° @ 100 C. The bead thermocouples (*TC*) measuring air temperature were secured to the lid with a metal rod and were 300 mm from the top of the mix. All tests were conducted on the same sample which was never removed from the pail.



(a) Overall View of Cooling Rate Testing

(b) Transfer of Mix Into Pail

(c) Probe Thermocouples and Fixtures

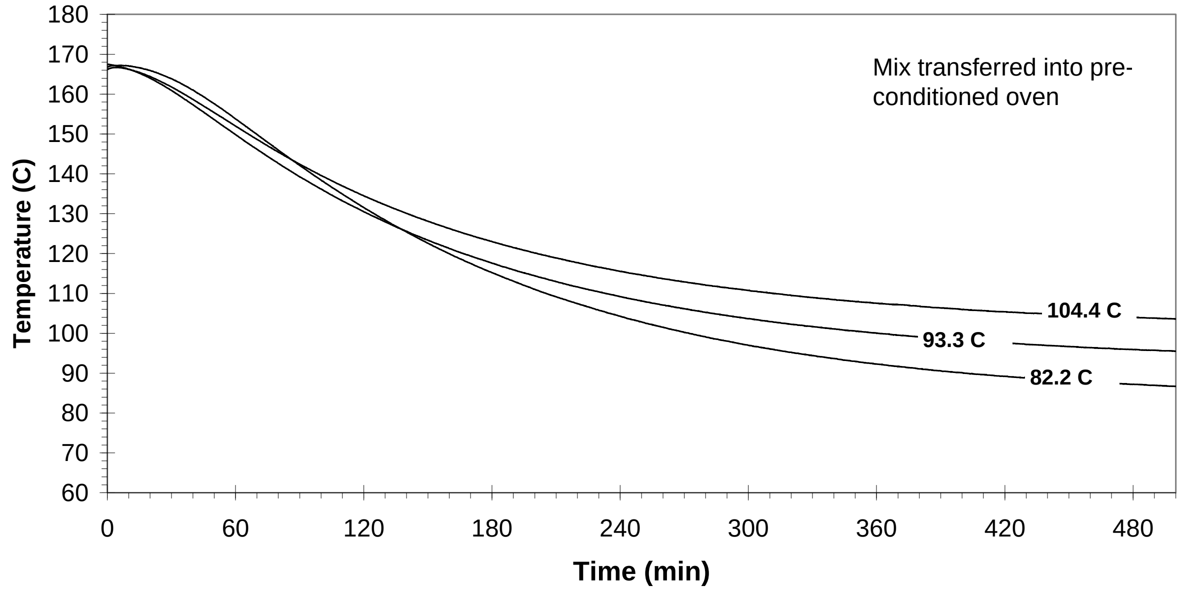
(d) Pail Filled With Mix Without Lid

Figure H-4. Cooling Rate Test Photos

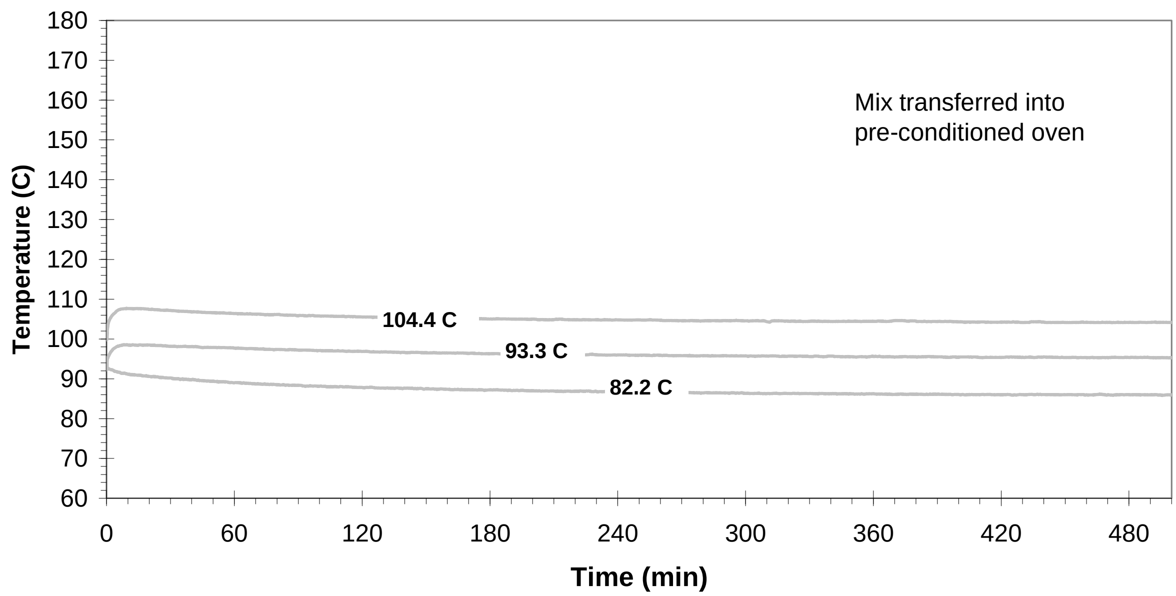
Four types of cooling rate testing were performed as part of this research: 1) mix heated in one oven and transferred into the oven shown in Figure H-4a that was pre-conditioned to the desired temperature (*pre-conditioned*); 2) mix heated in Figure H-4a oven to desired temperature and then the oven setting dropped from 171.1 C to a given temperature while the oven door remained closed (*setting dropped*); 3) mix heated in Figure H-4a oven to desired temperature then the temperature setting was dropped from 170 C to 80 C in pre-selected increments and then maintained at 80 C (*incremental cooling*); and 4) mix heated in Figure H-4a oven to desired temperature and then the oven shut off while the door remained closed (*expeditious cooling*). To provide consistency between all comparisons, the temperature of the mix at beginning of the cooling procedure rounded to the nearest whole number was maintained at 166 to 168 C.

A total of eleven experiments were performed, and the results of nine of the experiments are provided in Figures H-5 through H-8. Two of the experiments shown in Figures H-5 through H-8 were repeated to ensure accuracy of the data; they were essentially the same as the original test suites and were not shown in the figures as a result.

Cooling rate constants were determined from the *Pre-Conditioned* experimental data presented in Figure H-5. The temperature after 105 min of cooling was used for the cooling constant calculations to provide a direct comparison to the data provided in Table H-2 for field cooling rates. For the pre-conditioned oven temperatures of 104.4 C, 93.3 C, and 82.2 C, the associated cooling rate constants were $6481(10^{-6})$, $6116(10^{-6})$, and $4773(10^{-6})$, respectively. These constants are 4.3 to 5.8 times higher than the average cooling constant calculated in Table H-2 indicating a much faster rate of cooling than the estimated field cooling rate. The faster cooling rate for the laboratory experimental data is credible considering the much smaller mass of asphalt mixture being cooled. The difference in cooling rate could be viewed as a scale factor of sorts.

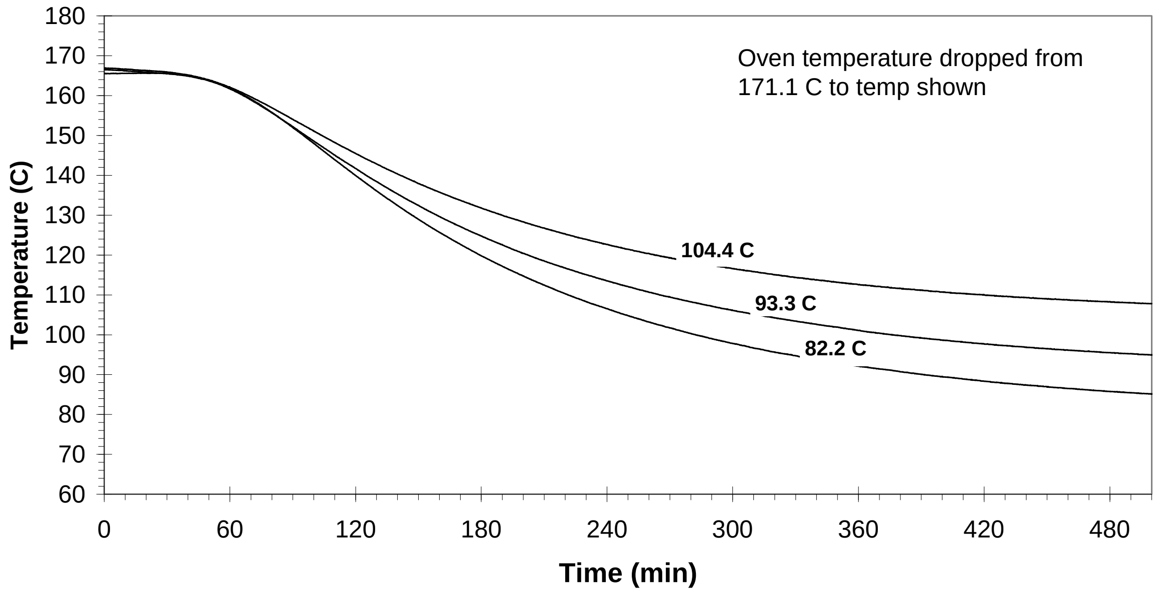


(a) Temperature of Center of Asphalt Concrete

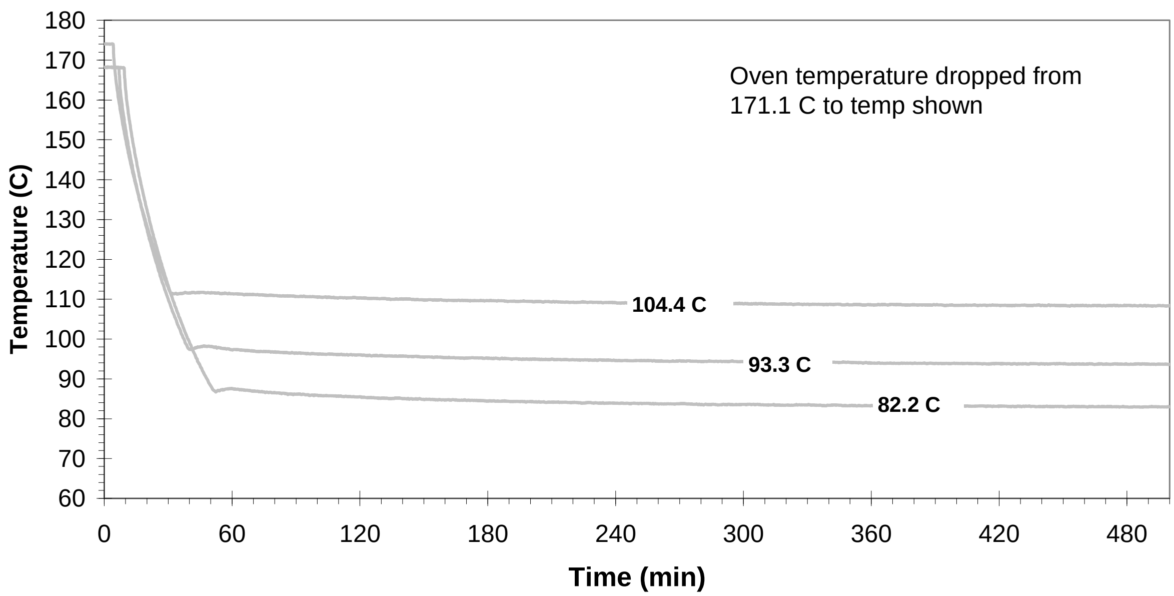


(b) Temperature of Air 300 mm Above Asphalt Concrete

Figure H-5. Cooling Rate Test Results: *Pre-Conditioned*

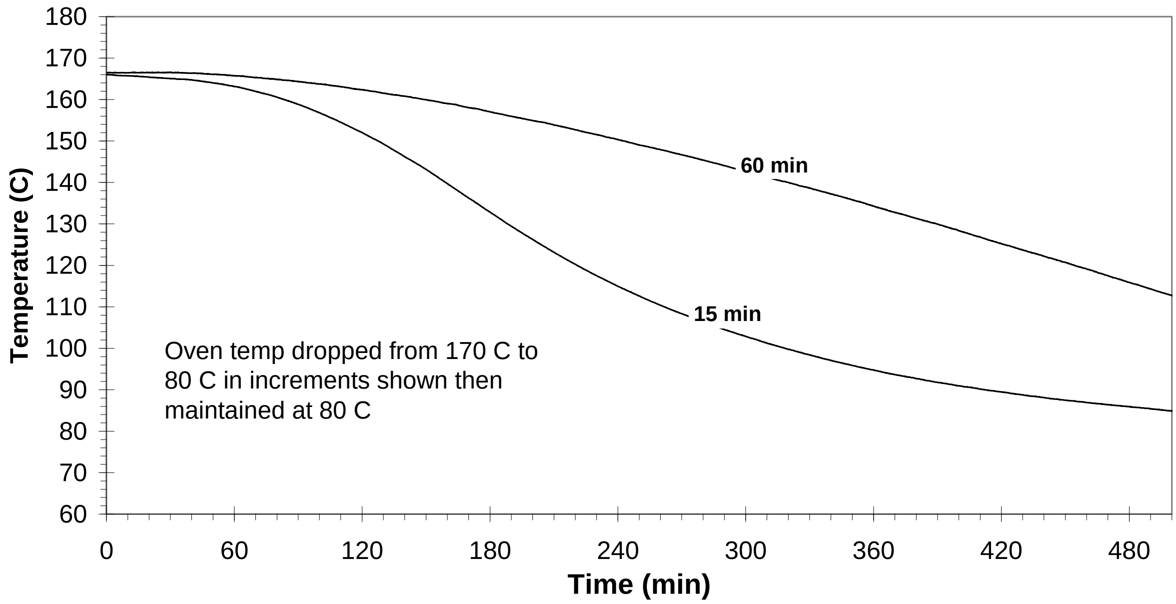


(a) Temperature of Center of Asphalt Concrete

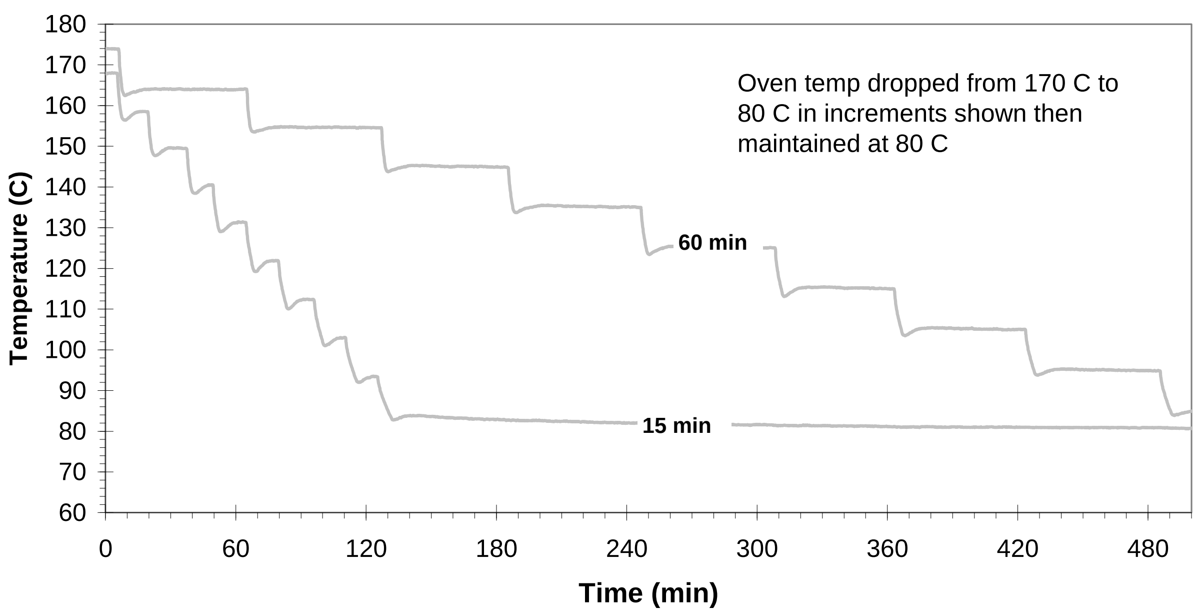


(b) Temperature of Air 300 mm Above Asphalt Concrete

Figure H-6. Cooling Rate Test Results: *Setting Dropped*

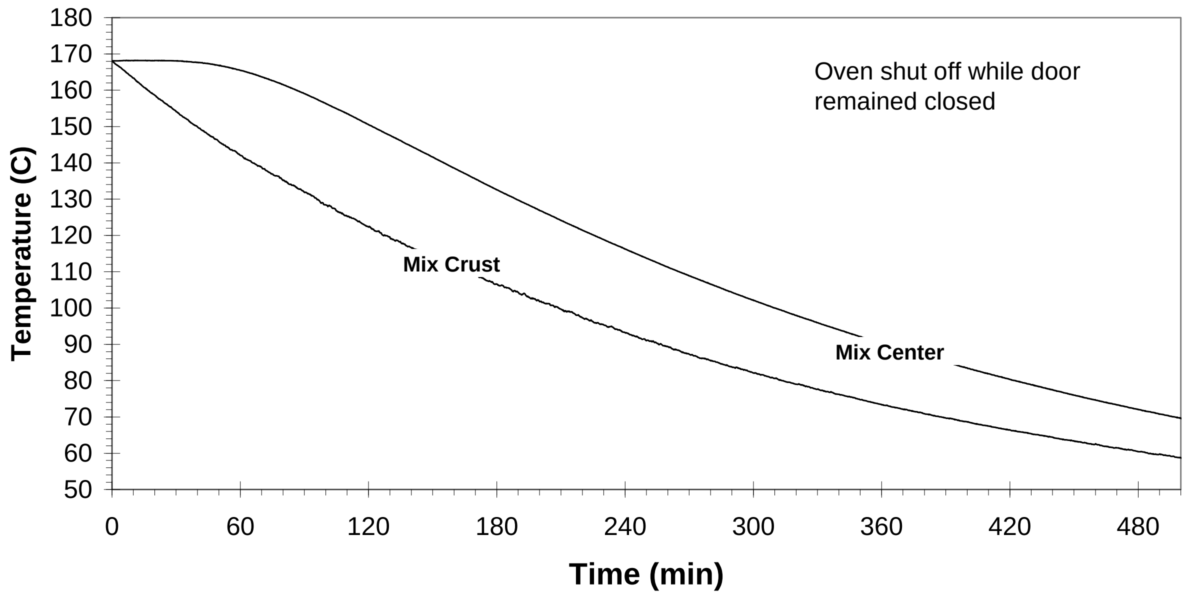


(a) Temperature of Center of Asphalt Concrete

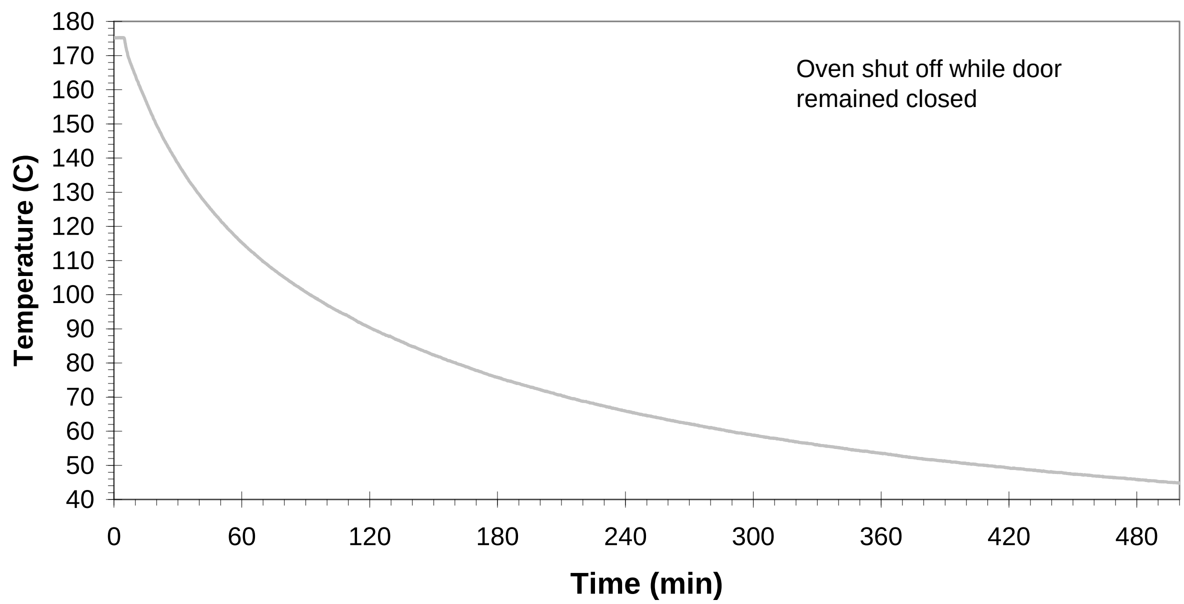


(b) Temperature of Air 300 mm Above Asphalt Concrete

Figure H-7. Cooling Rate Test Results: *Incremental Cooling*



(a) Temperature of Center and Crust of Asphalt Concrete



(b) Temperature of Air 300 mm Above Asphalt Concrete

Figure H-8. Cooling Rate Test Results: *Expeditious Cooling*

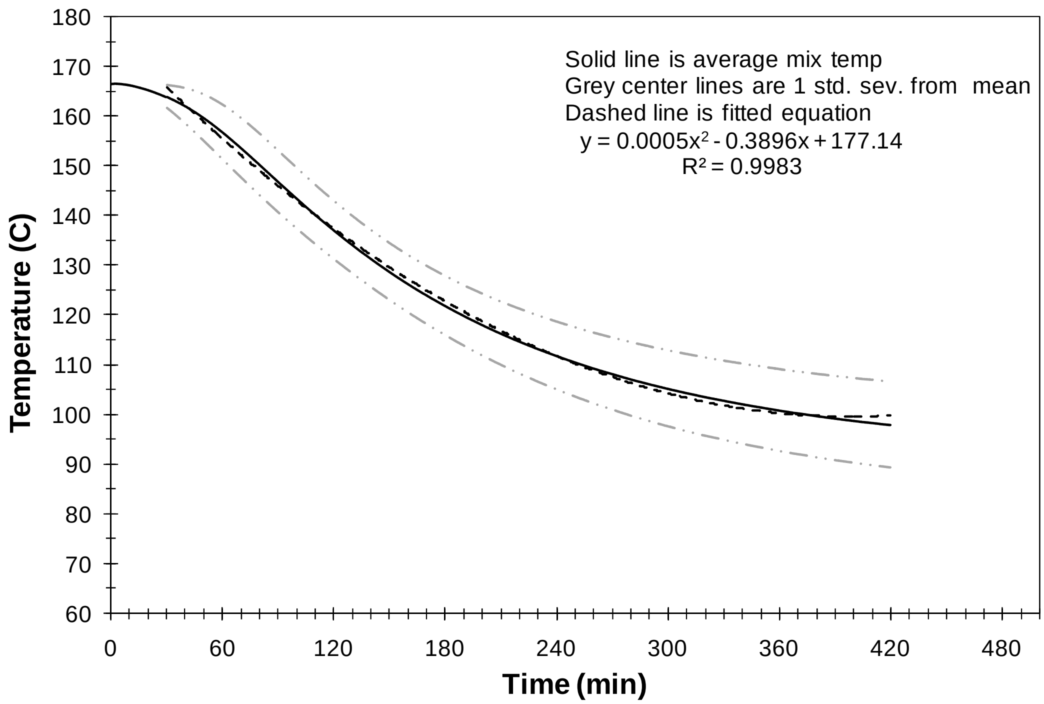
Development of Short Term Aging Protocols

Six short term aging protocols (*STAPs)* were developed for hot mixed warm compacted asphalt; each *STAP* consisted of a specific combination of target mixture temperature and oven aging time. The goal was reasonable simulation of probable field conditions for long haul times and that could be practically implemented in a laboratory. Three oven curing time periods were chosen by the research team to be simulated with laboratory *STAP*s; 1) 90 min, corresponding to *MDOT* standard short term aging practice; 2) 240 min; and 3) 360 min. The goal of 240 and 360 min aging periods was simulation of extended truck haul times between the asphalt plant and paving location; they were chosen based on the cooling rate testing data and the overall research goals. For the 90 min standard protocol a target compaction temperature of 146 C was chosen corresponding to recommended compaction temperature for PG 67-22 binder and standard practice; it is labeled *STAP 1* in Table H-9. Compaction temperatures corresponding to 240 and 360 min aging times were determined with cooling rate data as described in the following paragraphs.

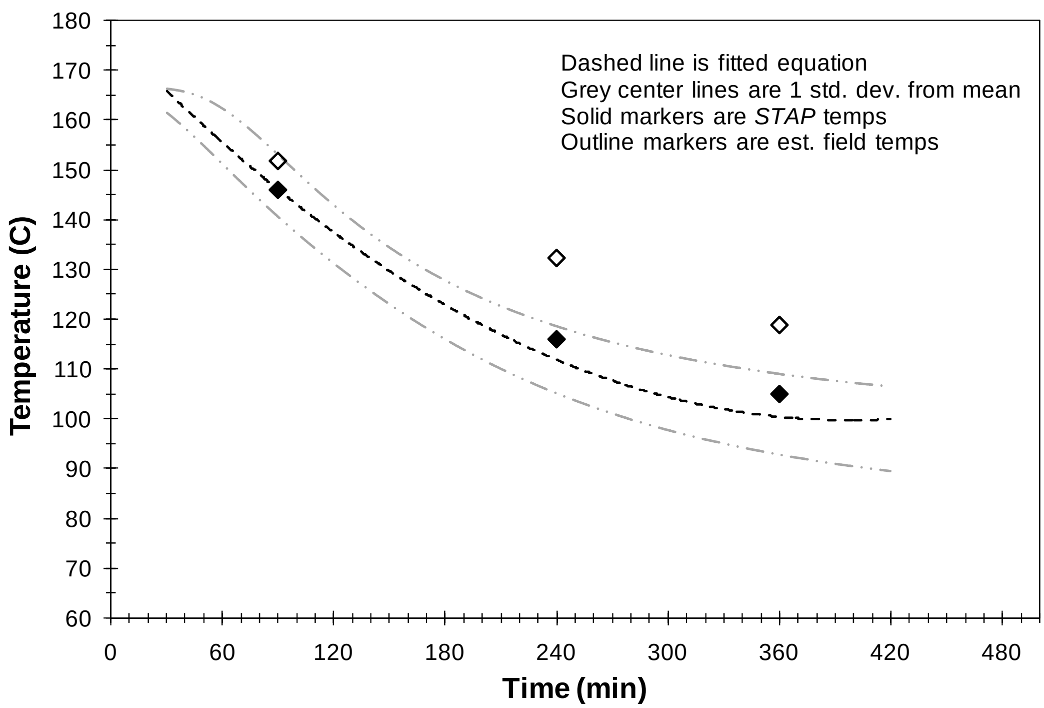
Mix temperatures predicted from *expeditious cooling* (Figure H-8) data were deemed below anticipated field conditions and were not utilized. Continuous changing of oven settings such as required for *incremental cooling* data (Figure H-7) would be cumbersome for a laboratory protocol and the efforts were deemed to outweigh any benefits; resultant data was not utilized. Data from the six *setting dropped* and *pre-conditioned* cooling rate tests (Figures H-5 and H-6) was averaged then plotted in Figure H-9a alongside overall standard deviations for the data; temperatures are those measured for the center of the test sample as seen in Figure H-4. A general flatness of the curve in the first 60 min was observed in Figure H-9a but was not incorporated into the curve fit. Likewise data at times above 420 min was not utilized since it is well beyond the time period of interest.

The measured laboratory mix temperatures at 240 and 360 min in Figure H-9a are significantly lower than estimated temperatures in Table H-3 calculated using information found during literature review of extended haul times for field cooled mix at corresponding times. Temperatures in Table H-3 were previously judged higher than probable field conditions in many applications; however the tendency of a large mixture mass (> 20,000 kg) in the field to retain more heat than the comparatively small mixture mass (~30 kg) utilized during laboratory testing is important. The insulating effect of an oven at temperatures above ambient in the laboratory accounts for some of the divergence but the actual difference between laboratory and true field mix temperatures is impossible to quantify with available data. From a practical laboratory standpoint increased complexity would be entailed to stray significantly from the measured laboratory mix temperatures. Target compaction temperatures for 240 and 360 min of aging time were chosen above the fitted equation temperatures but within one standard deviation at the time periods of interest. Selected *STAP* compaction temperatures, corresponding estimated field temperatures, and cooling rate testing data are shown in Figure H-9b.

During slab compaction for experimental program component one the elapsed time between mixture being brought out of the oven and beginning of the compaction process was approximately 10 minutes. To compensate for loss of mix temperature during this time target temperatures of mix at the conclusion of short term aging were increased 6 C above the target compaction temperature. Target temperatures at the conclusion of short term aging are included in Table H-9 for *STAP*s 1 through 3.



a) Combined Cooling Rate Test Data with Fitted Equation



b) Fitted Equation compared to STAP and Estimated Field Temperatures

Figure H-9. Development of Short Term Aging Protocols (*STAPs*)

Table H-9. Short Term Aging Protocols *(STAPs)*

STAP (---)	**Aging Time**[1] (min)	**Target Temperatures** Mixing (C)	End of *STAP*[2,3] (C)	Compaction[4] (C)
Slab protocols				
1	90	165	152	146
2	240	165	122	116
3	360	165	111	105
SGC protocols				
4	90	165	146	146
5	240	165	116	116
6	240	165	105	105

1) Time elapsed from conclusion of mixing and placement of mix in oven until removing mix from oven just prior to compaction. Time period targets were ± 5 min.
2) Temperature targets were ± 3 C.
3) Oven settings were as necessary to produce desired mixture temperatures at conclusion of STAP.
4) Slab compaction temperatures were estimated from STAP data.

There is some minimum temperature below which compaction cannot be completed successfully; the goal is to approach but not exceed this (unknown) temperature with hot mixed warm compacted asphalt and to lengthen the time period between mixing and final compaction of product. The realistic lower limit of compaction temperature for WMA will vary based on the specific mixture properties and the warm mix technology employed. The time required for mixture to reach minimum compaction temperature, or in this case target compaction temperature, will increase as the initial temperature is increased. Therefore maximizing the target mixing temperature within the recommended range for PG 67-22 binder was desirable and 165 C was chosen as target mixing temperature (Table H-9).

For *SGC* samples identical target mixing and compaction temperatures were utilized. Due to the much smaller quantity of mix required for *SGC* samples compared to slab samples, the difference between 240 min and 360 min of aging time was deemed insignificant by the research team. The *SGC* mix samples were expected to reach thermal equilibrium well before 360 min; as a result the aging time was truncated to 240 min for lowest target compaction temperature (*STAP* 6 in Table H-9). The need for an increase in target temperature at conclusion of the *STAP* was not necessary; mix samples were compacted immediately after short term aging according to standard practice.

Fabrication of Slab Samples

Component 1 of the experimental program required large samples of mixture to be made in the lab then compacted into slabs to simulate field compaction as best as possible. A total of 79 slabs were produced during the research. Dry aggregate was weighed out according to the mix design gradation proportions and mixed with approximately 2% water to provide adequate aggregate particle coating by the hydrated lime. Aggregate batches were then heated overnight in an oven at 171 C. Asphalt binder was heated to its Superpave mixing temperature of 154.4 C before being combined with aggregate. Binder was not held at mixing temperature in small containers for more than 6 hours to prevent premature oxidation and stiffening.

The mixing process is shown in Figure H-10; all mixing buckets, tools, and equipment in contact with asphalt were kept hot during the process. First the pre-batched and heated aggregate was weighed into a large steel mixing bucket (Figure H-10a). The scale was then tared before the correct amount of binder was weighed into the mixing bucket (Figure H-10b). Material was then mixed for approximately 60 to 70 seconds while an operator used a trowel to check for thorough mixing and to prevent material from sticking in corners of the mixing bucket (Figure H-10c). The mixed material was placed in a steel pail for short term oven aging in accordance with *STAP* 1, 2, or 3; an asphalt thermometer was inserted to monitor mix temperature (Figure H-10d). Due to mixer volume limitations the total mass of mix needed to produce one compacted slab was mixed in two separate back to back batches and combined in a single 19 L pail for short term aging.

(a) Aggregate Weighing

(b) Binder Weighing

(c) Sample Mixing

(d) Sample Ready for Short Term Aging

Figure H-10. Asphalt Slab Mixing Process

The protocol for sequential mixing was the same as described in the preceding paragraph with the following exceptions. Aggregate was pre-batched into two fractions; 1) coarse aggregate (+ 2.36 mm) and a proportional amount of the hydrated lime; and 2) fine aggregate (– 2.36 mm) and the remainder of the hydrated lime. The two fractions were kept separate during initial mixing with water/lime and also during heating. During the mixing process the coarse aggregate fraction and all required binder were first weighed out and then mixed for 40 seconds. The mixer was stopped and the remaining fine aggregate fraction was introduced. To produce the second half of the needed material, the aforementioned process was repeated. Total mixture was mixed for an additional 40 seconds and mixed material was then treated in the same manner as all other material.

To attempt to simulate field compaction of hot mixed warm compacted material a *Linear Asphalt Compactor (LAC)* was utilized to fabricate large slabs of compacted material. The *LAC* is a device that simulates the compactive action of a static steel wheel roller; its use is seen in Figure H-11. The *LAC* features a two-part compaction mold that will produce rectangular slabs 29.2 cm by 62.2 cm and 3.8 cm to 10.2 cm thick. One half of the compaction mold is fixed and the other half is detachable to allow for removal of the compacted slabs. During compaction asphalt mix in the compaction chamber is moved back and forth under a roller that exerts the compactive effort. The upper frame of the *LAC* to which the roller is attached is hinged at one end and pinned to a hydraulic cylinder at the other; the hydraulic cylinder provides the desired compactive force reaction at the roller. Vertically arranged plates transmit the compactive force from the roller into the loose asphalt mix; as each plate passes underneath the roller it can slide past neighboring plates which applies a kneading action to the mix. The total compactive energy applied to the sample is a combination of hydraulic system pressure and number of passes of the compaction chamber underneath the roller. Preliminary slabs were compacted to determine the compaction parameters for the experimental program with a target of 10% (+) air voids for the control standard mixture subjected to *STAP* 1. Within the experimental program hydraulic system pressure of 1379 kPa and 2413 kPa was used for *Mixtures* 1 and 2 respectively in combination with 18 passes of the compaction chamber for both mixes. Prior to compaction an infrared heater was used to heat the steel compaction mold to the desired temperature.

Just before compaction the infrared heater was removed; the compaction mold temperature was recorded and a piece of release paper was placed in the bottom of the compaction mold. A quantity of short term aged asphalt mixture was removed from the oven and its temperature recorded; it was then introduced into the compaction chamber (Figure H-11a). The mass of asphalt mix needed was estimated based on the volume of the compaction mold and the target slab thickness; a consistent target mass was used throughout the experimental program for each mixture. Figure H-11b shows how the asphalt was leveled to produce a slab of uniform thickness; the temperature of the mix was recorded at this point. A second piece of release paper was placed on top of the mix followed by a thin piece of sheet metal; the sheet metal prevented the plates from settling too deeply into the loose mix before compaction. A number of steel plates were then lowered on top of the mix in the compaction chamber (Figure H-11c). The upper frame of the *LAC* was brought down and pinned to the hydraulic cylinder (Figure H-11d).

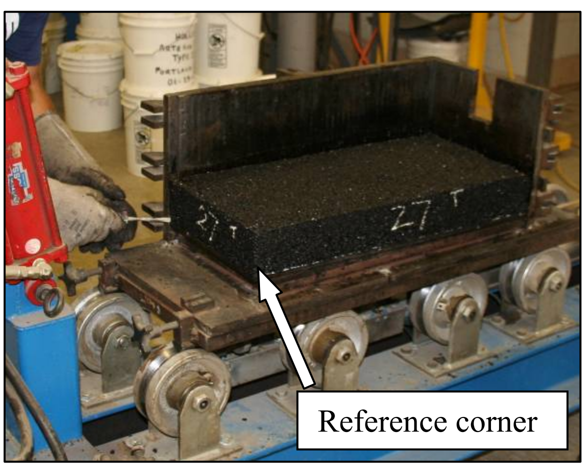
After completion of the aforementioned steps compaction of the slab sample began. The hydraulic pump was operated continuously while a relief valve held the pressure in the

(a) Loading Mix into LAC Compaction Mold

(b) Leveling of Mix in LAC

(c) Lowering Weights onto Mix

(d) LAC Ready for Compaction

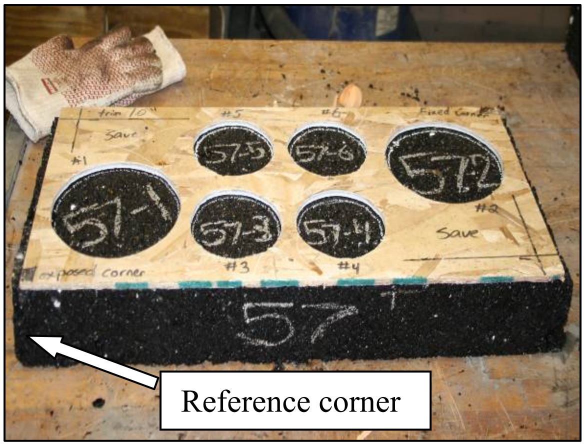


(e) Compacted Slab

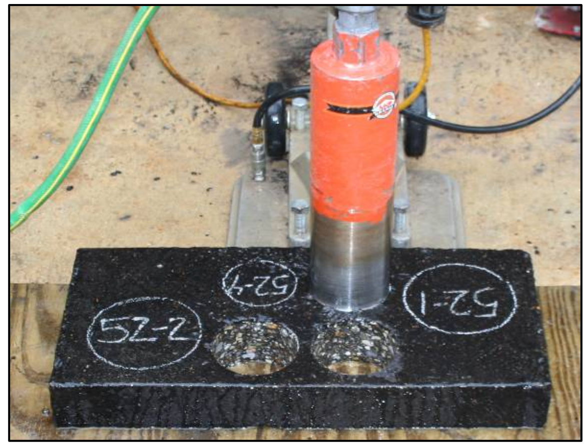
(f) Disassembled LAC Detail

Figure H-11. Slab Compaction Process

system steady such that a constant force was exerted through the roller and into the asphalt mix. Once the hydraulic system pressure stabilized a separate compressed air system was actuated to move the compaction chamber back and forth on roller guides for 18 passes. After compaction was complete the upper frame was unpinned, the plates were removed, and half of the compaction chamber was detached. Figure H-11e shows a compacted slab with the detachable portion of the chamber removed; two exposed edges of each slab were marked to maintain a reference corner when cores were sawn for testing.



(a) Slab Layout



(b) 101.6 mm Coring Process

(c) 152.4 mm Coring Process

(d) Cores in Drying Area

Figure H-12. Slab Coring Process

Compacted slabs were placed such that they remained flat and fully supported until completely cooled to ambient temperature. Six core samples were sawn from each slab, two 101.6 mm diameter and two 152.4 mm diameter. A wooden template was used to mark the locations to be cored as seen in Figure H-12a; the aforementioned reference corner was used to orient the template. All cores were sawn from an interior region of the slab formed by offsetting the exterior edges of the slab 25.4 mm towards the interior, represented by the dashed line in Figure H-13. This was performed to prevent any potential areas of low compaction near the edges or handling damage from affecting subsequent testing. Samples were sawn using a carbide-tipped masonry drill as seen in Figure H-12b and Figure H-12c for 101.6 mm and 152.4 mm cores respectively; water is used during the cutting process to force cutting debris away and to cool the drill bits. The use of water during sawing introduces significant moisture into the samples; this moisture must be removed before further testing is conducted. An environmentally controlled room was maintained at approximately 35 C and 25 to 30% relative humidity in which sawn samples were kept until dry to constant mass (Figure H-12d). Constant dry mass was defined as less than 0.05% reduction in sample mass over a 24 hour period in the environmental room; this was based on the requirement of *AASHTO T 166-07 Section 3.1.2* which requires less than 0.05% change in mass at two hour weighing intervals when dried in an oven at 52 C.

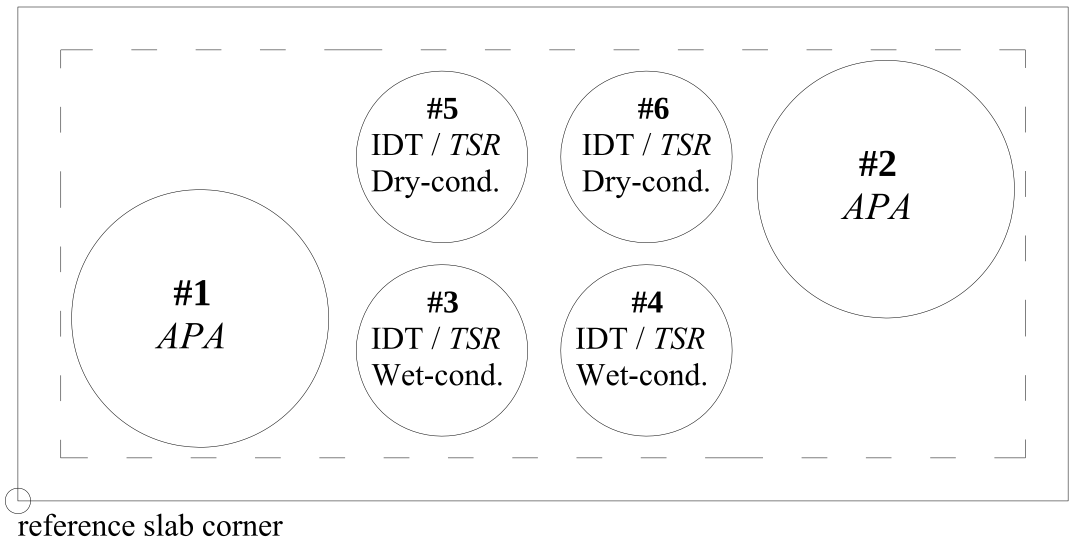
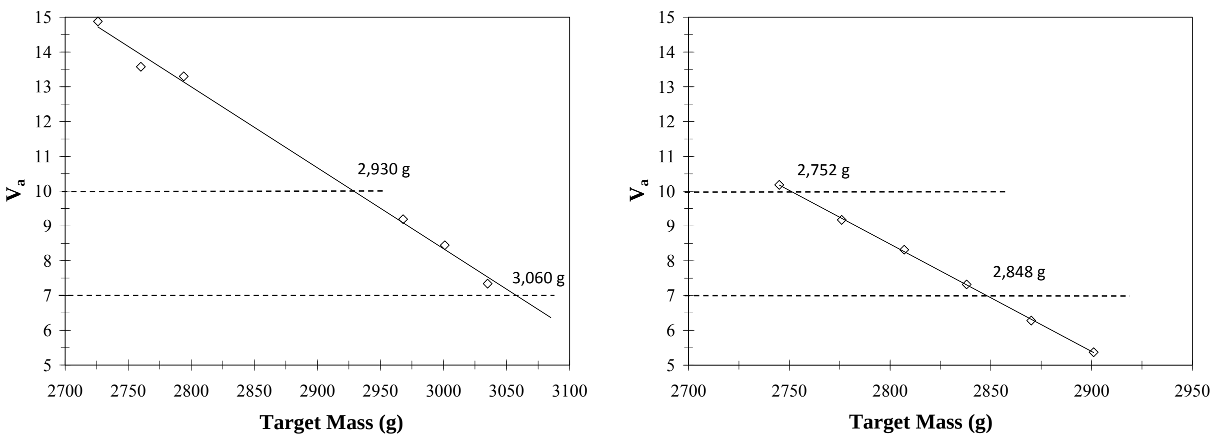


Figure H-13. Layout of Samples Sawn from Slabs and Test Method Used

Layout for sawn samples is seen in Figure H-13, the two 152.4 mm cores (identified as #1 and #2) were designated for *APA* testing. Two of the 101.6 mm cores (#3 and #4) were subjected to wet conditioning followed by indirect tensile strength testing. The remaining two 101.6 mm cores (#5 and #6) were subjected to dry conditioning followed by indirect tensile strength testing.

<u>*Fabrication of SGC Samples*</u>

For component two of the experimental program samples were compacted in the *SGC* to a 75 mm height and either 7 or 10% air void level for *APA* testing. Separate pre-batched samples of aggregate for each final compacted sample were heated, mixed with an appropriate quantity of binder and then subjected to short-term aging. The development of suitable short term aging protocols has been previously discussed; *STAP*s 4, 5, and 6 were used in producing *SGC* samples. After short term aging an appropriate mass of mixture to achieve the target air void level the mix was batched into a compaction mold which was then placed in the *SGC* and compacted to height. To determine the mass of mix needed to obtain target air void levels of 7% and 10%, preliminary samples were compacted at trial mix masses and cooled to room temperature; bulk density based on core mass and volume (D_{b-c}) and air void level was then determined. Data for *Mixture 1* is seen in Figure H-14a; data for *Mixture 2* is in Figure H-14b. Once compacted, the samples to be tested were extruded, allowed to cool just enough to allow handling and the final mass was measured. While still at a temperature above the desired testing temperature samples were placed in *APA* test molds then placed in an oven to cool and equilibrate to *APA* test temperature but never below APA test temperature.



a) Mixture 1 data *b) Mixture 2 data*

Figure H-14. Preliminary Data for Target Air Void Levels for Component Two

<u>Test Methods</u>

Bulk specific gravity (G_{mb}) of sawn dry samples was determined by vacuum sealing (*AASHTO* T 331-08) with the CoreLok® device; this method was selected due to initial samples tested according to *AASHTO T 166-07* exhibiting high water absorption. Bulk density (D_{b-c}) of sawn samples was also estimated through dimensional analysis; four measurements of diameter and four measurements of height were taken for each sample to compute the approximate volume. Work performed by (Buchanan 2000) indicated that the vacuum sealing method yielded the most consistent and accurate results of bulk gravity for compacted asphalt mixtures with high air void contents.

For the anticipated use of hot mixed warm compacted asphalt as a temporary road material in disaster recovery very quick opening of the road to traffic after placement is highly desirable. If the roadway is opened to traffic while the material is still at elevated temperatures after compaction, rutting of the compacted material by trucks and equipment is a potential concern in that little to no data exists for this scenario. Three evaluations of rutting potential were conducted: 1) on *SGC* samples compacted to target 7% air voids in accordance with standard *APA* testing; 2) on *SGC* samples compacted to target 10% air voids; and 3) on sawn samples from compacted slab samples where air void levels were generally in excess of 10%. Rut testing was performed with an *APA* and expressed as depth of rutting in millimeters after 8,000 cycles unless it was specifically stated otherwise. All *APA* testing was performed at 64 C, the 50% reliability high temperature for PG 64-22 or PG

67-22 binder and typical practice by the *MDOT Materials Division*. Wheel load was 445 N and hose pressure was 690 kPa.

Sawn samples from compacted slabs that were more than 80 mm thick were trimmed to the specified 75 ± 5 mm thickness for *APA* testing. Samples were placed in *APA* molds and brought to test temperature for a minimum equilibration period of 4 hours before testing. *SGC* samples were allowed to equilibrate to test temperature in an oven after compaction for approximately 90 min before testing (specimens were at higher temperature than oven).

Indirect tensile strength (S_t) was determined in accordance with *AASHTO T 283 Section 11* with a 50 mm-per-minute loading rate. Dry conditioned samples were placed in a water bath maintained at 25 C for two hours before being tested and S_t reported. Wet conditioned samples were placed in a vacuum pot 2/3 full with water sufficient to cover the sample and vacuum saturated for three minutes with full vacuum; samples were allowed to rest for five minutes before being patted dry and percent saturation determined. They were then placed in a 60 C water bath to soak for 24 hours followed by a two hour soak in a 25 C water bath before S_t was measured.

Test Results

Preliminary Slab Data

As a portion of component 1 of experimental program for hot mixed warm compacted slabs appropriate settings for the *LAC* were determined to produce desired air void ranges for *Mixtures 1* and *2*. Fifteen preliminary slabs were produced with varying numbers of passes and hydraulic system pressure in the *LAC*; air void levels were determined and used to select the appropriate settings for the remainder of the experimental program.

Table H-11. Preliminary Slab Data for *Mixture* 1, Subjected to *STAP* 1, Control Mixture

		Height[1]	Dimensional		Vacuum Seal		Rut	Dry S_t	Wet S_t	Sat[2]
Pass	**Core**	**(mm)**	$D_{b\text{-}c}$	$V_{a\text{-}b}$	G_{mb}	V_a	**(mm)**	**(kPa)**	**(kPa)**	**(%)**
6	1	85.75	2.167	14.5	2.209	12.8	8.09	---	---	---
	2	81.75	2.149	15.2	2.196	13.3	8.06	---	---	---
	3	85.65	2.153	15.0	2.201	13.1	---	---	793	78
	4	84.43	2.128	16.0	2.183	13.9	---	---	738	77
	5	85.39	2.206	12.9	2.237	11.7	---	867	---	---
	6	84.10	2.156	14.9	2.202	13.1	---	761	---	---
	Avg	**84.51**	**2.160**	**14.8**	**2.205**	**13.0**	**8.07**	**814**	**765**	**78**
	Stdev	**1.51**	**0.026**	**1.0**	**0.018**	**0.7**	**---**	**---**	**---**	**---**
12	1	84.39	2.197	13.3	2.244	11.5	10.98	---	---	---
	2	79.92	2.183	13.9	2.230	12.0	10.92	---	---	---
	3	83.55	2.188	13.6	2.240	11.6	---	---	847	78
	4	82.27	2.193	13.4	2.239	11.6	---	---	811	70
	5	83.56	2.217	12.5	2.259	10.8	---	851	---	---
	6	82.17	2.205	13.0	2.247	11.3	---	849	---	---
	Avg	**82.64**	**2.197**	**13.3**	**2.243**	**11.5**	**10.95**	**850**	**829**	**74**
	Stdev	**1.58**	**0.012**	**0.5**	**0.010**	**0.4**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534
1) Average of 4 measurements.
2) Degree of saturation.

Table H-12. Preliminary Slab Data for *Mixture* 2, Subjected to *STAP* 1, Control Mixture

Pass	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
12	1	82.15	1.972	16.1	2.014	14.3	14.00	---	---	---
	2	83.78	2.006	14.6	2.045	13.0	14.00	---	---	---
	3	82.62	1.952	16.9	1.995	15.1	---	---	619	86
	4	83.51	1.947	17.1	1.994	15.1	---	---	579	81
	5	82.61	2.005	14.7	2.031	13.6	---	776	---	---
	6	83.40	2.001	14.9	2.035	13.4	---	851	---	---
	Avg	**83.01**	**1.980**	**15.7**	**2.019**	**14.1**	**14.00**	**813**	**599**	**83**
	Stdev	**0.64**	**0.027**	**1.2**	**0.021**	**0.9**	**---**	**---**	**---**	**---**
18	1	84.64	1.931	17.8	1.980	15.7	12.70	---	---	---
	2	84.21	1.954	16.9	2.002	14.8	12.09	---	---	---
	3	84.28	1.947	17.1	1.981	15.7	---	---	557	83
	4	84.99	1.953	16.9	2.000	14.9	---	---	535	87
	5	84.42	2.001	14.8	2.032	13.5	---	758	---	---
	6	85.16	1.968	16.2	2.010	14.5	---	701	---	---
	Avg	**84.62**	**1.959**	**16.6**	**2.001**	**14.9**	**12.39**	**729**	**546**	**85**
	Stdev	**0.39**	**0.024**	**1.0**	**0.019**	**0.8**	**---**	**---**	**---**	**---**
18	1	85.20	1.936	17.6	1.985	15.6	11.37	---	---	---
	2	84.71	1.991	15.3	2.037	13.3	11.15	---	---	---
	3	85.50	1.970	16.2	2.000	14.9	---	---	703	88
	4	86.53	1.990	15.3	2.014	14.3	---	---	730	83
	5	85.02	2.005	14.7	2.032	13.5	---	786	---	---
	6	86.26	2.002	14.8	2.031	13.6	---	792	---	---
	Avg	**85.54**	**1.983**	**15.6**	**2.016**	**14.2**	**11.26**	**789**	**716**	**85**
	Stdev	**0.71**	**0.026**	**1.1**	**0.021**	**0.9**	**---**	**---**	**---**	**---**
24	1	83.70	1.868	20.5	1.930	17.9	14.50	---	---	---
	2	88.37	1.889	19.6	1.948	17.1	14.50	---	---	---
	3	85.26	1.912	18.6	1.964	16.4	---	---	481	82
	4	87.82	1.917	18.4	1.962	16.5	---	---	494	78
	5	85.48	1.924	18.1	1.974	16.0	---	615	---	---
	6	87.99	1.910	18.7	1.973	16.0	---	615	---	---
	Avg	**86.43**	**1.903**	**19.0**	**1.959**	**16.7**	**14.50**	**615**	**488**	**80**
	Stdev	**1.89**	**0.021**	**0.9**	**0.017**	**0.7**	**---**	**---**	**---**	**---**
24	1	81.41	1.941	17.4	2.003	14.8	9.60	---	---	---
	2	88.22	1.927	18.0	1.977	15.9	9.56	---	---	---
	3	83.04	1.972	16.1	2.028	13.7	---	---	599	87
	4	85.30	1.942	17.4	1.992	15.2	---	---	501	82
	5	83.04	1.962	16.5	2.007	14.6	---	735	---	---
	6	85.91	1.948	17.1	2.020	14.0	---	708	---	---
	Avg	**84.48**	**1.949**	**17.1**	**2.005**	**14.7**	**9.58**	**722**	**550**	**85**
	Stdev	**2.46**	**0.016**	**0.7**	**0.019**	**0.8**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350
1) Average of 4 measurements.
2) Degree of saturation.

Table H-11 provides data from preliminary slabs of *Mixture* 1 control mixture subjected to *STAP* 1. Both slabs were produced using 1379 kPa hydraulic system pressure in the *LAC* and only the number of passes (Pass) was varied. Tables H-12 through H-15 provide data from preliminary slabs of *Mixture* 2 control mixture. Preliminary slab data in Tables H-12 and H-13 was produced with 1379 kPa hydraulic system pressure and varying passes. Preliminary slab data in Table H-14 was produced with 18 passes and varying hydraulic system pressures. Preliminary slab data in Table H-15 was produced with 18 passes and 1379 kPa hydraulic system pressure and subjected to *STAP* 3. All rut data in excess of approximately 13.5 mm was extrapolated to 8,000 cycles as the test was terminated at this level of rutting.

Table H-13. Preliminary Slab Data for *Mixture* 2, Subjected to *STAP* 1, Control Mixture

Pass	Core	Height[1] (mm)	Dimensional $D_{b\text{-}c}$	Dimensional $V_{a\text{-}b}$	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
30	1	86.66	1.856	21.0	1.918	18.4	14.00	---	---	---
	2	86.94	1.959	16.6	2.006	14.6	14.00	---	---	---
	3	86.35	1.893	19.4	1.952	16.9	---	---	437	81
	4	87.51	1.908	18.8	1.961	16.6	---	---	431	82
	5	86.01	1.926	18.0	1.966	16.3	---	627	---	---
	6	87.23	1.914	18.6	1.962	16.5	---	554	---	---
	Avg	**86.78**	**1.909**	**18.7**	**1.961**	**16.6**	**14.00**	**590**	**434**	**82**
	Stdev	**0.56**	**0.034**	**1.5**	**0.028**	**1.2**	**---**	**---**	**---**	**---**
36	1	86.28	1.858	20.9	1.924	18.1	13.19	---	---	---
	2	86.21	1.932	17.8	1.979	15.8	12.95	---	---	---
	3	86.79	1.926	18.0	1.963	16.5	---	---	533	84
	4	87.60	1.929	17.9	1.971	16.1	---	---	569	85
	5	86.93	1.918	18.4	1.963	16.5	---	587	---	---
	6	87.54	1.938	17.5	1.986	15.5	---	568	---	---
	Avg	**86.89**	**1.917**	**18.4**	**1.964**	**16.4**	**13.07**	**578**	**551**	**85**
	Stdev	**0.59**	**0.029**	**1.3**	**0.022**	**0.9**	**---**	**---**	**---**	**---**
60	1	83.54	1.902	19.1	1.964	16.4	12.96	---	---	---
	2	89.02	1.889	19.6	1.934	17.7	12.70	---	---	---
	3	86.07	1.922	18.2	1.963	16.5	---	---	677	90
	4	86.77	1.895	19.3	1.950	17.0	---	---	571	77
	5	85.70	1.906	18.9	1.964	16.4	---	612	---	---
	6	86.71	1.915	18.5	1.959	16.7	---	623	---	---
	Avg	**86.30**	**1.905**	**18.9**	**1.955**	**16.8**	**12.83**	**618**	**624**	**83**
	Stdev	**1.78**	**0.012**	**0.5**	**0.012**	**0.5**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-14. Preliminary Slab Data for *Mixture* 2, Subjected to *STAP* 1, Control Mixture

SP[1] (kPa)	Core	Height[2] (mm)	Dimensional $D_{b\text{-}c}$	Dimensional $V_{a\text{-}b}$	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[3] (%)
2069	1	80.22	2.014	14.3	2.047	12.9	9.21	---	---	---
	2	82.70	2.056	12.5	2.099	10.7	9.14	---	---	---
	3	81.52	2.047	12.9	2.075	11.7	---	---	801	91
	4	82.85	2.028	13.7	2.069	11.9	---	---	750	90
	5	81.20	2.053	12.7	2.091	11.0	---	943	---	---
	6	82.30	2.053	12.6	2.095	10.8	---	879	---	---
	Avg	**81.80**	**2.042**	**13.1**	**2.079**	**11.5**	**9.18**	**911**	**775**	**90**
	Stdev	**1.01**	**0.017**	**0.7**	**0.020**	**0.8**	**---**	**---**	**---**	**---**
2758	1	76.09	2.097	10.8	2.142	8.8	7.61	---	---	---
	2	79.11	2.124	9.6	2.173	7.5	7.22	---	---	---
	3	77.42	2.138	9.0	2.159	8.1	---	---	1096	90
	4	78.54	2.132	9.3	2.154	8.3	---	---	1054	91
	5	77.10	2.145	8.7	2.186	7.0	---	1068	---	---
	6	78.07	2.141	8.9	2.175	7.4	---	1126	---	---
	Avg	**77.72**	**2.129**	**9.4**	**2.165**	**7.9**	**7.41**	**1097**	**1075**	**90**
	Stdev	**1.08**	**0.017**	**0.7**	**0.016**	**0.7**	**---**	**---**	**---**	**---**
3448	1	75.62	2.115	10.0	2.166	7.8	5.93	---	---	---
	2	77.50	2.153	8.4	2.191	6.7	5.53	---	---	---
	3	76.50	2.167	7.8	2.195	6.6	---	---	1313	89
	4	77.16	2.163	8.0	2.193	6.7	---	---	1288	96
	5	75.77	2.182	7.2	2.212	5.9	---	1350	---	---
	6	76.46	2.172	7.6	2.191	6.7	---	1209	---	---
	Avg	**76.50**	**2.159**	**8.1**	**2.191**	**6.8**	**5.73**	**1280**	**1300**	**92**
	Stdev	**0.74**	**0.023**	**1.0**	**0.015**	**0.6**	**---**	**---**	**---**	**---**
3448	1	81.58	2.051	12.7	2.083	11.4	7.64	---	---	---
	2	76.99	2.104	10.5	2.138	9.0	7.52	---	---	---
	3	79.80	2.089	11.1	2.126	9.5	---	---	976	93
	4	79.70	2.092	11.0	2.134	9.2	---	---	1021	90
	5	79.77	2.105	10.4	2.147	8.6	---	1104	---	---
	6	79.30	2.103	10.5	2.142	8.9	---	1075	---	---
	Avg	**79.52**	**2.091**	**11.0**	**2.128**	**9.4**	**7.58**	**1089**	**998**	**92**
	Stdev	**1.47**	**0.020**	**0.9**	**0.023**	**1.0**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350 1) Hydraulic System Pressure. 2) Average of 4 measurements. 3) Degree of saturation.

Table H-15. Preliminary Slab Data for *Mixture* 2, Subjected to *STAP* 3, Control Mixture

Core	Height[1] (mm)	Dimensional $D_{b\text{-}c}$	Dimensional $V_{a\text{-}b}$	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	84.82	1.825	22.3	1.877	20.1	14.50	---	---	---
2	89.76	1.915	18.5	1.959	16.6	14.50	---	---	---
3	86.06	1.873	20.3	1.930	17.9	---	---	395	81
4	88.76	1.864	20.7	1.919	18.3	---	---	401	73
5	86.13	1.900	19.2	1.945	17.2	---	544	---	---
6	88.20	1.896	19.3	1.933	17.8	---	531	---	---
Avg	**87.29**	**1.879**	**20.0**	**1.927**	**18.0**	**14.50**	**538**	**398**	**77**
Stdev	**1.90**	**0.032**	**1.4**	**0.028**	**1.2**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350 1) Average of 4 measurements. 2) Degree of saturation.

Slab Data Used for Analysis

Results of the remaining 64 slab samples compacted in the *LAC* are given in Tables H-16 through H-39; preliminary slab data provided previously is excluded from these tables. *Mixture* 1 raw data is found in Tables H-16 through H-27 and *Mixture* 2 raw data is found in Tables H-28 through H-39. Tables H-40 and H-41 provide summary air voids and sample height data for *Mixtures* 1 and 2 respectively. All rut data in excess of approximately 13.5 mm was extrapolated to 8,000 cycles as the test was terminated at this level of rutting.

Table H-16. Slab Data for *Mixture* 1, Subjected to *STAP* 1, Control Mixture

		Height[1]	Dimensional		Vacuum Seal		Rut	Dry S_t	Wet S_t	Sat[2]
Rep	**Core**	**(mm)**	D_{b-c}	V_{a-b}	G_{mb}	V_a	**(mm)**	**(kPa)**	**(kPa)**	**(%)**
1	1	81.25	2.183	13.9	2.232	11.9	9.69	---	---	---
	2	82.61	2.206	12.9	2.254	11.0	9.62	---	---	---
	3	82.35	2.214	12.6	2.250	11.2	---	---	759	75
	4	83.18	2.202	13.1	2.248	11.3	---	---	719	71
	5	82.39	2.210	12.8	2.249	11.2	---	786	---	---
	6	83.10	2.212	12.7	2.246	11.4	---	771	---	---
	Avg	**82.48**	**2.204**	**13.0**	**2.247**	**11.3**	**9.66**	**778**	**739**	**73**
	Stdev	**0.70**	**0.012**	**0.5**	**0.008**	**0.3**	**---**	**---**	**---**	**---**
2	1	75.81	2.152	15.1	2.205	13.0	9.66	---	---	---
	2	80.58	2.165	14.5	2.209	12.8	9.71	---	---	---
	3	78.87	2.157	14.9	2.274	10.2	---	---	777	72
	4	79.91	2.157	14.9	2.218	12.5	---	---	729	66
	5	78.64	2.154	15.0	2.221	12.4	---	757	---	---
	6	79.92	2.154	15.0	2.219	12.4	---	746	---	---
	Avg	**78.95**	**2.157**	**14.9**	**2.224**	**12.2**	**9.69**	**752**	**753**	**69**
	Stdev	**1.70**	**0.005**	**0.2**	**0.025**	**1.0**	**---**	**---**	**---**	**---**
3	1	84.94	2.057	18.8	2.134	15.8	11.48	---	---	---
	2	82.71	2.216	12.6	2.204	13.0	11.63	---	---	---
	3	84.86	2.114	16.6	2.170	14.4	---	---	749	70
	4	84.57	2.143	15.4	2.179	14.0	---	---	762	68
	5	84.26	2.137	15.7	2.197	13.3	---	826	---	---
	6	84.13	2.188	13.7	2.206	12.9	---	793	---	---
	Avg	**84.25**	**2.142**	**15.5**	**2.182**	**13.9**	**11.55**	**810**	**755**	**69**
	Stdev	**0.82**	**0.056**	**2.2**	**0.027**	**1.1**	**---**	**---**	**---**	**---**
4	1	81.89	2.215	12.6	2.256	11.0	6.73	---	---	---
	2	80.42	2.182	13.9	2.262	10.7	6.76	---	---	---
	3	81.69	2.243	11.5	2.285	9.8	---	---	790	86
	4	81.51	2.216	12.5	2.286	9.8	---	---	750	78
	5	81.33	2.225	12.2	2.284	9.9	---	1169	---	---
	6	80.79	2.235	11.8	2.270	10.4	---	1195	---	---
	Avg	**81.27**	**2.220**	**12.4**	**2.274**	**10.3**	**6.74**	**1182**	**770**	**82**
	Stdev	**0.56**	**0.021**	**0.8**	**0.013**	**0.5**	**---**	**---**	**---**	**---**
All	**Avg**	**81.74**	**2.181**	**13.9**	**2.232**	**11.9**	**9.41**	**880**	**754**	**73**
	Stdev	**2.19**	**0.043**	**1.7**	**0.039**	**1.5**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-17. Slab Data for *Mixture* 1, Subjected to *STAP* 2, Control Mixture

		Height[1]	Dimensional		Vacuum Seal		Rut	Dry S_t	Wet S_t	Sat[2]
Rep	**Core**	**(mm)**	$D_{b\text{-}c}$	$V_{a\text{-}b}$	G_{mb}	V_a	**(mm)**	**(kPa)**	**(kPa)**	**(%)**
1	1	85.55	2.081	17.9	2.137	15.7	10.55	---	---	---
	2	82.17	2.134	15.8	2.186	13.7	10.45	---	---	---
	3	85.30	2.129	16.0	2.171	14.3	---	---	651	59
	4	84.52	2.137	15.7	2.181	13.9	---	---	654	59
	5	85.13	2.147	15.3	2.148	15.2	---	727	---	---
	6	84.33	2.138	15.6	2.231	11.9	---	660	---	---
	Avg	**84.50**	**2.128**	**16.0**	**2.176**	**14.1**	**10.50**	**693**	**652**	**59**
	Stdev	**1.23**	**0.024**	**0.9**	**0.033**	**1.3**	**---**	**---**	**---**	**---**
2	1	85.18	2.120	16.3	2.178	14.1	15.00	---	---	---
	2	80.41	2.163	14.6	2.206	12.9	15.00	---	---	---
	3	83.69	2.127	16.1	2.187	13.7	---	---	641	65
	4	83.16	2.130	15.9	2.199	13.2	---	---	616	64
	5	83.68	2.143	15.4	2.211	12.7	---	611	---	---
	6	83.25	2.149	15.2	2.220	12.4	---	664	---	---
	Avg	**83.23**	**2.139**	**15.6**	**2.200**	**13.2**	**15.00**	**637**	**629**	**64**
	Stdev	**1.56**	**0.016**	**0.6**	**0.016**	**0.6**	**---**	**---**	**---**	**---**
3	1	85.28	2.157	14.9	2.202	13.1	8.82	---	---	---
	2	81.93	2.162	14.7	2.190	13.6	8.82	---	---	---
	3	84.38	2.148	15.2	2.191	13.5	---	---	532	81
	4	84.05	2.171	14.3	2.204	13.0	---	---	600	80
	5	84.06	2.155	15.0	2.198	13.3	---	818	---	---
	6	83.46	2.159	14.8	2.207	12.9	---	896	---	---
	Avg	**83.86**	**2.158**	**14.8**	**2.199**	**13.2**	**8.82**	**857**	**566**	**80**
	Stdev	**1.12**	**0.008**	**0.3**	**0.007**	**0.3**	**---**	**---**	**---**	**---**
All	**Avg**	**83.86**	**2.142**	**15.5**	**2.191**	**13.5**	**11.44**	**729**	**616**	**68**
	Stdev	**1.35**	**0.021**	**0.8**	**0.023**	**0.9**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-18. Slab Data for *Mixture* 1, Subjected to *STAP* 3, Control Mixture

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	83.73	2.063	18.6	2.163	14.7	10.06	---	---	---
	2	86.24	2.245	11.4	2.159	14.8	9.95	---	---	---
	3	86.05	2.164	14.6	2.198	13.3	---	---	695	62
	4	86.74	2.194	13.4	2.173	14.3	---	---	622	57
	5	85.87	2.171	14.3	2.187	13.7	---	713	---	---
	6	87.07	2.205	13.0	2.176	14.1	---	653	---	---
	Avg	**85.95**	**2.174**	**14.2**	**2.176**	**14.1**	**10.01**	**683**	**658**	**59**
	Stdev	**1.18**	**0.062**	**2.4**	**0.015**	**0.6**	**---**	**---**	**---**	**---**
2	1	82.92	2.119	16.4	2.173	14.2	11.65	---	---	---
	2	80.90	2.109	16.8	2.161	14.7	11.64	---	---	---
	3	84.10	2.145	15.3	2.191	13.5	---	---	623	56
	4	83.52	2.154	15.0	2.207	12.9	---	---	730	68
	5	84.02	2.154	15.0	2.200	13.2	---	696	---	---
	6	83.11	2.139	15.6	2.199	13.2	---	700	---	---
	Avg	**83.09**	**2.137**	**15.7**	**2.188**	**13.6**	**11.64**	**698**	**677**	**62**
	Stdev	**1.17**	**0.019**	**0.7**	**0.018**	**0.7**	**---**	**---**	**---**	**---**
3	1	88.27	2.093	17.4	2.134	15.8	10.31	---	---	---
	2	83.39	2.084	17.8	2.118	16.4	10.46	---	---	---
	3	87.42	2.099	17.2	2.141	15.5	---	---	464	75
	4	86.30	2.115	16.5	2.155	14.9	---	---	471	73
	5	87.04	2.096	17.3	2.150	15.2	---	636	---	---
	6	85.73	2.111	16.7	2.151	15.1	---	688	---	---
	Avg	**86.36**	**2.100**	**17.1**	**2.141**	**15.5**	**10.38**	**662**	**468**	**74**
	Stdev	**1.70**	**0.011**	**0.5**	**0.014**	**0.6**	**---**	**---**	**---**	**---**
All	**Avg**	**85.13**	**2.137**	**15.7**	**2.169**	**14.4**	**10.68**	**681**	**601**	**65**
	Stdev	**1.97**	**0.047**	**1.9**	**0.025**	**1.0**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-19. Slab Data for *Mixture* 1, Subjected to *STAP* 1, Sequential Mixing

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	87.20	2.077	18.0	2.132	15.9	12.52	---	---	---
	2	88.85	2.057	18.8	2.113	16.6	12.22	---	---	---
	3	87.73	2.064	18.6	2.130	15.9	---	---	504	50
	4	88.41	2.053	19.0	2.117	16.5	---	---	482	61
	5	87.95	2.051	19.0	2.137	15.7	---	579	---	---
	6	88.38	2.063	18.6	2.130	16.0	---	559	---	---
	Avg	**88.09**	**2.061**	**18.7**	**2.126**	**16.1**	**12.37**	**569**	**493**	**56**
	Stdev	**0.58**	**0.010**	**0.4**	**0.009**	**0.4**	**---**	**---**	**---**	**---**
2	1	83.12	2.114	16.6	2.165	14.6	9.38	---	---	---
	2	86.30	2.078	18.0	2.134	15.8	9.53	---	---	---
	3	84.36	2.133	15.8	2.187	13.7	---	---	580	67
	4	85.54	2.119	16.4	2.178	14.1	---	---	567	60
	5	84.76	2.109	16.8	2.187	13.7	---	653	---	---
	6	85.74	2.111	16.7	2.170	14.4	---	650	---	---
	Avg	**84.97**	**2.111**	**16.7**	**2.170**	**14.4**	**9.45**	**652**	**574**	**63**
	Stdev	**1.14**	**0.018**	**0.7**	**0.020**	**0.8**	**---**	**---**	**---**	**---**
All	**Avg**	**86.53**	**2.086**	**17.7**	**2.148**	**15.2**	**10.91**	**610**	**533**	**59**
	Stdev	**1.84**	**0.029**	**1.2**	**0.027**	**1.1**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534
1) Average of 4 measurements.
2) Degree of saturation.

Table H-20. Slab Data for *Mixture* 1, Subjected to *STAP* 2, Sequential Mixing

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	84.53	2.112	16.6	2.172	14.3	9.41	---	---	---
	2	84.93	2.147	15.3	2.208	12.9	9.16	---	---	---
	3	85.10	2.136	15.7	2.194	13.4	---	---	602	63
	4	85.92	2.121	16.3	2.183	13.9	---	---	597	69
	5	84.99	2.145	15.3	2.203	13.1	---	649	---	---
	6	85.60	2.143	15.4	2.204	13.0	---	701	---	---
	Avg	**85.18**	**2.134**	**15.8**	**2.194**	**13.4**	**9.29**	**675**	**599**	**66**
	Stdev	**0.50**	**0.014**	**0.6**	**0.014**	**0.6**	**---**	**---**	**---**	**---**
2	1	88.37	2.076	18.1	2.125	16.1	9.03	---	---	---
	2	88.03	2.128	16.0	2.172	14.3	9.06	---	---	---
	3	88.92	2.090	17.5	2.163	14.7	---	---	570	68
	4	89.12	2.070	18.3	2.153	15.0	---	---	592	64
	5	88.61	2.104	17.0	2.155	14.9	---	595	---	---
	6	88.73	2.103	17.0	2.151	15.1	---	702	---	---
	Avg	**88.63**	**2.095**	**17.3**	**2.153**	**15.0**	**9.04**	**648**	**581**	**66**
	Stdev	**0.39**	**0.021**	**0.8**	**0.016**	**0.6**	**---**	**---**	**---**	**---**
All	**Avg**	**86.90**	**2.115**	**16.5**	**2.173**	**14.2**	**9.16**	**662**	**590**	**66**
	Stdev	**1.85**	**0.027**	**1.1**	**0.026**	**1.0**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534
1) Average of 4 measurements.
2) Degree of saturation.

Table H-21. Slab Data for *Mixture* 1, Subjected to *STAP* 3, Sequential Mixing

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	90.27	2.009	20.7	2.074	18.2	11.09	---	---	---
	2	84.32	2.072	18.2	2.125	16.1	10.89	---	---	---
	3	88.82	2.043	19.4	2.111	16.7	---	---	467	66
	4	87.42	2.038	19.6	2.100	17.1	---	---	375	56
	5	88.77	2.070	18.3	2.124	16.2	---	575	---	---
	6	87.67	2.060	18.7	2.117	16.4	---	489	---	---
	Avg	**87.88**	**2.049**	**19.1**	**2.109**	**16.8**	**10.99**	**532**	**421**	**61**
	Stdev	**2.02**	**0.024**	**0.9**	**0.019**	**0.8**	**---**	**---**	**---**	**---**
2	1	83.88	2.148	15.2	2.201	13.2	10.59	---	---	---
	2	80.57	2.164	14.6	2.214	12.6	10.69	---	---	---
	3	84.06	2.156	14.9	2.210	12.8	---	---	679	73
	4	83.33	2.171	14.3	2.231	12.0	---	---	700	73
	5	83.89	2.170	14.3	2.221	12.4	---	744	---	---
	6	83.09	2.192	13.5	2.246	11.4	---	731	---	---
	Avg	**83.13**	**2.167**	**14.5**	**2.220**	**12.4**	**10.64**	**738**	**690**	**73**
	Stdev	**1.31**	**0.015**	**0.6**	**0.016**	**0.6**	**---**	**---**	**---**	**---**
3	1	84.29	2.113	16.6	2.149	15.2	9.33	---	---	---
	2	82.86	2.166	14.5	2.183	13.8	9.52	---	---	---
	3	85.05	2.140	15.6	2.170	14.3	---	---	682	72
	4	84.07	2.180	14.0	2.175	14.2	---	---	649	71
	5	84.54	2.139	15.6	2.180	14.0	---	623	---	---
	6	84.82	2.201	13.1	2.227	12.1	---	772	---	---
	Avg	**84.27**	**2.157**	**14.9**	**2.181**	**13.9**	**9.42**	**698**	**665**	**72**
	Stdev	**0.78**	**0.032**	**1.3**	**0.026**	**1.0**	**---**	**---**	**---**	**---**
All	**Avg**	**85.09**	**2.124**	**16.2**	**2.170**	**14.4**	**10.35**	**656**	**592**	**69**
	Stdev	**2.49**	**0.060**	**2.4**	**0.052**	**2.0**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-22. Slab Data for *Mixture* 1, Subjected to *STAP* 1, Sasobit®

		Height[1]	Dimensional		Vacuum Seal		Rut	Dry S_t	Wet S_t	Sat[2]
Rep	**Core**	**(mm)**	D_{b-c}	V_{a-b}	G_{mb}	V_a	**(mm)**	**(kPa)**	**(kPa)**	**(%)**
1	1	81.38	2.080	17.9	2.150	15.1	16.00	---	---	---
	2	80.14	2.081	17.9	2.146	15.3	16.00	---	---	---
	3	82.16	2.113	16.6	2.171	14.3	---	---	608	55
	4	81.22	2.127	16.0	2.187	13.7	---	---	615	57
	5	82.00	2.075	18.1	2.156	14.9	---	606	---	---
	6	81.11	2.129	16.0	2.164	14.6	---	565	---	---
	Avg	**81.33**	**2.101**	**17.1**	**2.163**	**14.7**	**16.00**	**585**	**612**	**56**
	Stdev	**0.73**	**0.025**	**1.0**	**0.015**	**0.6**	**---**	**---**	**---**	**---**
2	1	82.62	2.073	18.2	2.129	16.0	12.30	---	---	---
	2	79.97	2.089	17.6	2.152	15.1	12.18	---	---	---
	3	83.94	2.089	17.6	2.158	14.8	---	---	546	53
	4	82.42	2.079	18.0	2.147	15.3	---	---	538	53
	5	83.52	2.115	16.5	2.176	14.1	---	597	---	---
	6	82.24	2.093	17.4	2.164	14.6	---	578	---	---
	Avg	**82.45**	**2.090**	**17.5**	**2.154**	**15.0**	**12.24**	**587**	**542**	**53**
	Stdev	**1.39**	**0.014**	**0.6**	**0.016**	**0.6**	**---**	**---**	**---**	**---**
3	1	83.70	2.170	14.4	2.198	13.3	12.33	---	---	---
	2	82.25	2.196	13.3	2.223	12.3	12.43	---	---	---
	3	83.50	2.174	14.2	2.201	13.1	---	---	763	72
	4	83.49	2.154	15.0	2.198	13.3	---	---	765	70
	5	82.99	2.205	13.0	2.233	11.9	---	858	---	---
	6	82.74	2.218	12.5	2.240	11.6	---	859	---	---
	Avg	**83.11**	**2.186**	**13.7**	**2.216**	**12.6**	**12.38**	**859**	**764**	**71**
	Stdev	**0.55**	**0.024**	**1.0**	**0.019**	**0.7**	**---**	**---**	**---**	**---**
4	1	80.16	2.264	10.6	2.298	9.3	6.80	---	---	---
	2	78.13	2.245	11.4	2.298	9.3	6.77	---	---	---
	3	80.68	2.270	10.4	2.322	8.4	---	---	833	82
	4	79.92	2.269	10.5	2.321	8.4	---	---	886	83
	5	80.35	2.250	11.2	2.315	8.6	---	1182	---	---
	6	79.34	2.277	10.1	2.330	8.1	---	1173	---	---
	Avg	**79.76**	**2.263**	**10.7**	**2.314**	**8.7**	**6.78**	**1178**	**860**	**82**
	Stdev	**0.92**	**0.013**	**0.5**	**0.013**	**0.5**	**---**	**---**	**---**	**---**
All	**Avg**	**81.66**	**2.160**	**14.8**	**2.212**	**12.7**	**11.85**	**802**	**694**	**65**
	Stdev	**1.57**	**0.074**	**2.9**	**0.067**	**2.6**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-23. Slab Data for *Mixture* 1, Subjected to *STAP* 2, Sasobit®

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	87.71	2.091	17.5	2.135	15.7	14.00	---	---	---
	2	84.45	2.104	17.0	2.163	14.7	14.00	---	---	---
	3	87.68	2.104	17.0	2.158	14.8	---	---	582	74
	4	86.82	2.106	16.9	2.157	14.9	---	---	587	64
	5	87.41	2.080	17.9	2.150	15.1	---	593	---	---
	6	86.61	2.110	16.7	2.174	14.2	---	546	---	---
	Avg	**86.78**	**2.099**	**17.2**	**2.156**	**14.9**	**14.00**	**569**	**585**	**69**
	Stdev	**1.23**	**0.011**	**0.5**	**0.013**	**0.5**	**---**	**---**	**---**	**---**
2	1	84.36	2.097	17.2	2.146	15.3	12.07	---	---	---
	2	83.39	2.108	16.8	2.169	14.4	11.93	---	---	---
	3	85.57	2.130	16.0	2.184	13.8	---	---	574	67
	4	84.63	2.109	16.8	2.168	14.5	---	---	539	58
	5	85.85	2.145	15.4	2.197	13.3	---	693	---	---
	6	85.43	2.137	15.7	2.201	13.1	---	659	---	---
	Avg	**84.87**	**2.121**	**16.3**	**2.177**	**14.1**	**12.00**	**676**	**556**	**62**
	Stdev	**0.93**	**0.019**	**0.7**	**0.021**	**0.8**	**---**	**---**	**---**	**---**
3	1	83.21	2.131	15.9	2.157	14.9	5.53	---	---	---
	2	84.47	2.178	14.1	2.210	12.8	5.62	---	---	---
	3	83.83	2.143	15.4	2.169	14.4	---	---	743	64
	4	85.05	2.128	16.0	2.163	14.6	---	---	762	63
	5	83.32	2.157	14.9	2.181	13.9	---	801	---	---
	6	84.59	2.177	14.1	2.214	12.6	---	789	---	---
	Avg	**84.08**	**2.152**	**15.1**	**2.182**	**13.9**	**5.57**	**795**	**752**	**64**
	Stdev	**0.74**	**0.022**	**0.9**	**0.024**	**1.0**	**---**	**---**	**---**	**---**
4	1	80.93	2.273	10.3	2.316	8.6	6.39	---	---	---
	2	75.79	2.269	10.5	2.318	8.5	6.32	---	---	---
	3	79.90	2.286	9.8	2.340	7.7	---	---	946	81
	4	78.86	2.295	9.4	2.342	7.6	---	---	868	81
	5	78.86	2.303	9.1	2.337	7.8	---	1224	---	---
	6	78.48	2.285	9.8	2.344	7.5	---	1266	---	---
	Avg	**78.80**	**2.285**	**9.8**	**2.333**	**7.9**	**6.35**	**1245**	**907**	**81**
	Stdev	**1.73**	**0.013**	**0.5**	**0.013**	**0.5**	**---**	**---**	**---**	**---**
All	**Avg**	**83.63**	**2.164**	**14.6**	**2.212**	**12.7**	**9.48**	**821**	**700**	**69**
	Stdev	**3.23**	**0.075**	**3.0**	**0.074**	**2.9**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-24. Slab Data for *Mixture* 1, Subjected to *STAP* 3, Sasobit®

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	86.79	2.079	18.0	2.121	16.3	9.80	---	---	---
	2	82.68	2.096	17.3	2.147	15.3	9.74	---	---	---
	3	86.23	2.072	18.2	2.133	15.8	---	---	594	65
	4	85.44	2.075	18.1	2.132	15.8	---	---	578	65
	5	86.55	2.216	12.5	2.172	14.3	---	730	---	---
	6	85.91	2.104	17.0	2.164	14.6	---	630	---	---
	Avg	**85.60**	**2.107**	**16.8**	**2.145**	**15.4**	**9.77**	**680**	**586**	**65**
	Stdev	**1.51**	**0.055**	**2.2**	**0.020**	**0.8**	**---**	**---**	**---**	**---**
2	1	82.76	2.034	19.7	2.093	17.4	19.00	---	---	---
	2	86.39	2.033	19.8	2.100	17.1	19.00	---	---	---
	3	85.23	2.084	17.8	2.144	15.4	---	---	489	60
	4	86.65	2.051	19.1	2.115	16.5	---	---	478	54
	5	85.61	2.114	16.6	2.165	14.6	---	622	---	---
	6	86.96	2.088	17.6	2.139	15.6	---	559	---	---
	Avg	**85.60**	**2.067**	**18.4**	**2.126**	**16.1**	**19.00**	**591**	**483**	**57**
	Stdev	**1.53**	**0.033**	**1.3**	**0.028**	**1.1**	**---**	**---**	**---**	**---**
3	1	83.20	2.116	16.5	2.163	14.7	6.37	---	---	---
	2	82.15	2.184	13.8	2.227	12.1	5.79	---	---	---
	3	83.46	2.166	14.5	2.197	13.3	---	---	694	77
	4	83.23	2.193	13.4	2.215	12.6	---	---	693	79
	5	83.18	2.219	12.4	2.229	12.0	---	840	---	---
	6	82.71	2.194	13.4	2.218	12.5	---	704	---	---
	Avg	**82.99**	**2.179**	**14.0**	**2.208**	**12.9**	**6.08**	**772**	**693**	**78**
	Stdev	**0.48**	**0.035**	**1.4**	**0.025**	**1.0**	**---**	**---**	**---**	**---**
4	1	82.66	2.188	13.7	2.240	11.6	5.67	---	---	---
	2	79.16	2.230	12.0	2.279	10.1	5.62	---	---	---
	3	82.23	2.219	12.4	2.276	10.2	---	---	683	88
	4	82.15	2.198	13.3	2.267	10.5	---	---	617	84
	5	81.88	2.200	13.2	2.259	10.9	---	991	---	---
	6	81.43	2.218	12.5	2.282	10.0	---	1048	---	---
	Avg	**81.58**	**2.209**	**12.8**	**2.267**	**10.5**	**5.64**	**1019**	**650**	**86**
	Stdev	**1.25**	**0.016**	**0.6**	**0.016**	**0.6**	**---**	**---**	**---**	**---**
All	**Avg**	**83.94**	**2.140**	**15.5**	**2.186**	**13.7**	**10.12**	**765**	**603**	**71**
	Stdev	**2.13**	**0.067**	**2.6**	**0.061**	**2.4**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-25. Slab Data for *Mixture* 1, Subjected to *STAP* 1, Evotherm 3G™

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	V_{a-b}	Vacuum Seal G_{mb}	V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	80.11	2.187	13.7	2.230	12.0	14.00	---	---	---
	2	80.44	2.182	13.9	2.233	11.9	14.00	---	---	---
	3	80.53	2.197	13.3	2.244	11.5	---	---	688	62
	4	80.64	2.165	14.6	2.215	12.6	---	---	654	65
	5	80.69	2.191	13.5	2.246	11.4	---	773	---	---
	6	80.62	2.179	14.0	2.244	11.5	---	719	---	---
	Avg	**80.50**	**2.183**	**13.8**	**2.235**	**11.8**	**14.00**	**746**	**671**	**63**
	Stdev	**0.21**	**0.011**	**0.4**	**0.012**	**0.5**	**---**	**---**	**---**	**---**
2	1	81.36	2.156	14.9	2.206	12.9	11.77	---	---	---
	2	74.95	2.174	14.2	2.223	12.3	11.65	---	---	---
	3	79.60	2.183	13.8	2.231	11.9	---	---	641	68
	4	77.91	2.175	14.2	2.224	12.2	---	---	691	64
	5	79.89	2.174	14.2	2.235	11.8	---	729	---	---
	6	77.78	2.196	13.4	2.236	11.8	---	732	---	---
	Avg	**78.58**	**2.176**	**14.1**	**2.226**	**12.2**	**11.71**	**731**	**666**	**66**
	Stdev	**2.23**	**0.013**	**0.5**	**0.011**	**0.4**	**---**	**---**	**---**	**---**
All	**Avg**	**79.54**	**2.180**	**14.0**	**2.231**	**12.0**	**12.86**	**739**	**668**	**65**
	Stdev	**1.81**	**0.012**	**0.5**	**0.012**	**0.5**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-26. Slab Data for *Mixture* 1, Subjected to *STAP* 2, Evotherm 3G™

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	81.91	2.112	16.7	2.159	14.8	14.00	---	---	---
	2	82.79	2.166	14.5	2.211	12.7	14.00	---	---	---
	3	83.51	2.135	15.7	2.207	12.9	---	---	626	71
	4	84.11	2.130	16.0	2.200	13.2	---	---	607	67
	5	83.54	2.171	14.3	2.229	12.1	---	666	---	---
	6	84.23	2.174	14.2	2.233	11.9	---	657	---	---
	Avg	**83.35**	**2.148**	**15.2**	**2.207**	**12.9**	**14.00**	**662**	**617**	**69**
	Stdev	**0.87**	**0.026**	**1.0**	**0.026**	**1.0**	**---**	**---**	**---**	**---**
2	1	84.73	2.134	15.8	2.177	14.1	5.49	---	---	---
	2	81.45	2.152	15.1	2.207	12.9	5.45	---	---	---
	3	84.34	2.146	15.3	2.205	13.0	---	---	742	75
	4	83.34	2.138	15.6	2.194	13.4	---	---	753	71
	5	84.05	2.182	13.9	2.225	12.2	---	835	---	---
	6	83.26	2.161	14.7	2.208	12.9	---	751	---	---
	Avg	**83.53**	**2.152**	**15.1**	**2.203**	**13.1**	**5.47**	**793**	**747**	**73**
	Stdev	**1.16**	**0.018**	**0.7**	**0.016**	**0.6**	**---**	**---**	**---**	**---**
3	1	86.43	2.121	16.3	2.152	15.1	9.69	---	---	---
	2	81.76	2.166	14.5	2.194	13.4	9.57	---	---	---
	3	84.27	2.157	14.9	2.162	14.7	---	---	730	71
	4	84.22	2.145	15.4	2.175	14.2	---	---	771	70
	5	84.73	2.152	15.1	2.194	13.4	---	787	---	---
	6	83.52	2.176	14.1	2.210	12.8	---	766	---	---
	Avg	**84.15**	**2.153**	**15.0**	**2.181**	**13.9**	**9.63**	**776**	**750**	**70**
	Stdev	**1.53**	**0.019**	**0.8**	**0.022**	**0.9**	**---**	**---**	**---**	**---**
All	**Avg**	**83.68**	**2.151**	**15.1**	**2.197**	**13.3**	**9.70**	**744**	**705**	**71**
	Stdev	**1.20**	**0.020**	**0.8**	**0.024**	**0.9**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-27. Slab Data for *Mixture* 1, Subjected to *STAP* 3, Evotherm 3G™

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	80.59	2.152	15.1	2.186	13.7	9.35	---	---	---
	2	83.44	2.182	13.9	2.207	12.9	9.37	---	---	---
	3	83.22	2.261	10.8	2.219	12.4	---	---	666	67
	4	85.03	2.126	16.1	2.204	13.0	---	---	653	63
	5	82.91	2.150	15.2	2.220	12.4	---	683	---	---
	6	84.96	2.178	14.1	2.242	11.5	---	736	---	---
	Avg	**83.36**	**2.175**	**14.2**	**2.213**	**12.7**	**9.36**	**710**	**659**	**65**
	Stdev	**1.63**	**0.047**	**1.8**	**0.019**	**0.7**	**---**	**---**	**---**	**---**
2	1	80.78	2.138	15.6	2.178	14.1	12.96	---	---	---
	2	82.24	2.184	13.8	2.235	11.8	12.96	---	---	---
	3	83.14	2.160	14.8	2.220	12.4	---	---	614	69
	4	83.64	2.181	13.9	2.227	12.1	---	---	646	69
	5	83.20	2.212	12.7	2.253	11.1	---	730	---	---
	6	83.45	2.205	13.0	2.264	10.7	---	731	---	---
	Avg	**82.74**	**2.180**	**14.0**	**2.229**	**12.0**	**12.96**	**731**	**630**	**69**
	Stdev	**1.08**	**0.028**	**1.1**	**0.030**	**1.2**	**---**	**---**	**---**	**---**
All	**Avg**	**83.05**	**2.177**	**14.1**	**2.221**	**12.3**	**11.16**	**720**	**645**	**67**
	Stdev	**1.36**	**0.037**	**1.5**	**0.026**	**1.0**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.534

1) Average of 4 measurements.

2) Degree of saturation.

Table H-28. Slab Data for *Mixture* 2, Subjected to *STAP* 1, Control Mixture

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	79.50	2.063	12.2	2.095	10.8	10.42	---	---	---
	2	81.76	2.063	12.2	2.097	10.8	10.28	---	---	---
	3	80.51	2.066	12.1	2.106	10.4	---	---	690	91
	4	81.10	2.079	11.6	2.106	10.4	---	---	681	88
	5	79.65	2.059	12.4	2.112	10.1	---	854	---	---
	6	80.05	2.061	12.3	2.104	10.5	---	849	---	---
	Avg	**80.43**	**2.065**	**12.1**	**2.103**	**10.5**	**10.35**	**852**	**685**	**90**
	Stdev	**0.88**	**0.007**	**0.3**	**0.006**	**0.3**	**---**	**---**	**---**	**---**
2	1	80.64	2.015	14.2	2.034	13.4	8.75	---	---	---
	2	84.41	2.015	14.3	2.050	12.7	8.71	---	---	---
	3	82.53	1.994	15.2	2.035	13.4	---	---	654	84
	4	83.47	2.002	14.8	2.033	13.5	---	---	639	83
	5	82.06	2.046	12.9	2.088	11.1	---	814	---	---
	6	83.87	2.022	13.9	2.082	11.4	---	712	---	---
	Avg	**82.83**	**2.016**	**14.2**	**2.054**	**12.6**	**8.73**	**763**	**646**	**84**
	Stdev	**1.38**	**0.018**	**0.8**	**0.025**	**1.1**	**---**	**---**	**---**	**---**
3	1	82.02	2.081	11.5	2.105	10.4	9.01	---	---	---
	2	77.90	2.076	11.7	2.107	10.3	8.99	---	---	---
	3	79.32	2.117	9.9	2.111	10.2	---	---	594	89
	4	80.22	2.056	12.5	2.113	10.1	---	---	695	86
	5	81.10	2.096	10.8	2.125	9.6	---	1021	---	---
	6	79.90	2.111	10.2	2.139	9.0	---	1019	---	---
	Avg	**80.07**	**2.089**	**11.1**	**2.117**	**9.9**	**9.00**	**1020**	**645**	**88**
	Stdev	**1.43**	**0.023**	**1.0**	**0.013**	**0.6**	**---**	**---**	**---**	**---**
All	**Avg**	**81.11**	**2.057**	**12.5**	**2.091**	**11.0**	**9.36**	**878**	**659**	**87**
	Stdev	**1.72**	**0.036**	**1.5**	**0.032**	**1.4**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-29. Slab Data for *Mixture* 2, Subjected to *STAP* 2, Control Mixture

		Height[1]	Dimensional		Vacuum Seal		Rut	Dry S_t	Wet S_t	Sat[2]
Rep	**Core**	**(mm)**	D_{b-c}	V_{a-b}	G_{mb}	V_a	**(mm)**	**(kPa)**	**(kPa)**	**(%)**
1	1	79.93	2.034	13.5	2.068	12.0	12.05	---	---	---
	2	82.19	2.019	14.1	2.051	12.7	11.71	---	---	---
	3	82.42	2.031	13.6	2.071	11.9	---	---	738	90
	4	83.17	2.036	13.4	2.072	11.8	---	---	664	89
	5	81.67	2.024	13.9	1.949	17.1	---	781	---	---
	6	82.60	2.032	13.5	2.076	11.6	---	790	---	---
	Avg	**82.00**	**2.029**	**13.6**	**2.048**	**12.9**	**11.88**	**786**	**701**	**89**
	Stdev	**1.13**	**0.007**	**0.3**	**0.049**	**2.1**	**---**	**---**	**---**	**---**
2	1	78.18	2.098	10.7	2.136	9.1	8.38	---	---	---
	2	79.28	2.111	10.2	2.150	8.5	8.16	---	---	---
	3	79.06	2.119	9.8	2.159	8.1	---	---	863	93
	4	79.69	2.112	10.1	2.159	8.1	---	---	802	94
	5	78.33	2.124	9.6	2.167	7.8	---	1050	---	---
	6	78.98	2.139	9.0	2.176	7.4	---	1078	---	---
	Avg	**78.92**	**2.117**	**9.9**	**2.158**	**8.2**	**8.27**	**1064**	**833**	**94**
	Stdev	**0.58**	**0.014**	**0.6**	**0.014**	**0.6**	**---**	**---**	**---**	**---**
3	1	83.81	2.081	11.4	2.116	10.0	9.35	---	---	---
	2	77.63	2.037	13.3	2.076	11.7	9.17	---	---	---
	3	81.54	2.093	11.0	2.108	10.3	---	---	631	92
	4	80.41	2.066	12.1	2.091	11.0	---	---	609	89
	5	81.90	2.064	12.2	2.093	10.9	---	942	---	---
	6	80.27	2.058	12.4	2.090	11.0	---	981	---	---
	Avg	**80.93**	**2.066**	**12.1**	**2.096**	**10.8**	**9.26**	**962**	**620**	**90**
	Stdev	**2.06**	**0.019**	**0.8**	**0.014**	**0.6**	**---**	**---**	**---**	**---**
All	**Avg**	**80.61**	**2.071**	**11.9**	**2.101**	**10.6**	**9.80**	**937**	**718**	**91**
	Stdev	**1.85**	**0.039**	**1.7**	**0.055**	**2.3**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-30. Slab Data for *Mixture* 2, Subjected to *STAP* 3, Control Mixture

		Height[1]	Dimensional		Vacuum Seal		Rut	Dry S_t	Wet S_t	Sat[2]
Rep	**Core**	**(mm)**	D_{b-c}	V_{a-b}	G_{mb}	V_a	**(mm)**	**(kPa)**	**(kPa)**	**(%)**
1	1	81.05	2.041	13.2	2.078	11.6	11.05	---	---	---
	2	79.19	2.099	10.7	2.110	10.2	10.76	---	---	---
	3	81.44	2.062	12.3	2.093	10.9	---	---	782	90
	4	80.69	2.092	11.0	2.105	10.4	---	---	810	91
	5	80.88	2.069	12.0	2.102	10.6	---	930	---	---
	6	80.58	2.113	10.1	2.123	9.7	---	972	---	---
	Avg	**80.64**	**2.079**	**11.5**	**2.102**	**10.6**	**10.90**	**951**	**796**	**91**
	Stdev	**0.77**	**0.027**	**1.1**	**0.015**	**0.6**	**---**	**---**	**---**	**---**
2	1	81.56	2.115	10.0	2.059	12.4	10.45	---	---	---
	2	81.34	2.063	12.2	2.091	11.0	10.71	---	---	---
	3	81.36	2.029	13.7	2.068	12.0	---	---	744	89
	4	82.11	2.015	14.3	2.063	12.2	---	---	744	87
	5	81.41	2.060	12.3	2.099	10.7	---	923	---	---
	6	81.58	2.069	12.0	2.097	10.8	---	835	---	---
	Avg	**81.56**	**2.058**	**12.4**	**2.079**	**11.5**	**10.58**	**879**	**744**	**88**
	Stdev	**0.29**	**0.035**	**1.5**	**0.018**	**0.8**	**---**	**---**	**---**	**---**
3	1	82.82	2.041	13.2	2.082	11.4	5.31	---	---	---
	2	79.55	2.051	12.7	2.094	10.9	5.28	---	---	---
	3	82.32	2.079	11.5	2.105	10.4	---	---	554	90
	4	80.99	2.099	10.7	2.111	10.2	---	---	569	90
	5	82.17	2.058	12.4	2.083	11.4	---	923	---	---
	6	81.00	2.045	13.0	2.085	11.3	---	848	---	---
	Avg	**81.47**	**2.062**	**12.2**	**2.093**	**10.9**	**5.29**	**886**	**562**	**90**
	Stdev	**1.20**	**0.022**	**1.0**	**0.012**	**0.5**	**---**	**---**	**---**	**---**
All	**Avg**	**81.22**	**81.22**	**2.067**	**12.1**	**2.092**	**8.92**	**905**	**700**	**90**
	Stdev	**0.90**	**0.90**	**0.028**	**1.2**	**0.017**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-31. Slab Data for *Mixture* 2, Subjected to *STAP* 1, Sequential Mixing

Rep	Core	Height[1] (mm)	Dimensional $D_{b\text{-}c}$	Dimensional $V_{a\text{-}b}$	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	79.85	2.006	14.6	2.044	13.0	10.57	---	---	---
	2	84.84	2.028	13.7	2.056	12.5	10.72	---	---	---
	3	81.36	2.002	14.8	2.052	12.7	---	---	637	89
	4	82.84	2.059	12.4	2.075	11.7	---	---	708	93
	5	81.10	2.045	13.0	2.089	11.1	---	805	---	---
	6	83.37	2.034	13.4	2.070	11.9	---	732	---	---
	Avg	**82.23**	**2.029**	**13.7**	**2.064**	**12.2**	**10.65**	**769**	**672**	**91**
	Stdev	**1.80**	**0.022**	**0.9**	**0.017**	**0.7**	**---**	**---**	**---**	**---**
2	1	79.83	2.072	11.8	2.188	6.9	2.95	---	---	---
	2	77.60	2.154	8.3	2.208	6.0	2.99	---	---	---
	3	76.83	2.172	7.6	2.209	6.0	---	---	1083	93
	4	77.41	2.187	6.9	2.224	5.3	---	---	1138	96
	5	76.26	2.187	7.0	2.213	5.8	---	1119	---	---
	6	76.79	2.193	6.7	2.233	5.0	---	1147	---	---
	Avg	**77.45**	**2.161**	**8.0**	**2.213**	**5.9**	**2.97**	**1133**	**1111**	**94**
	Stdev	**1.26**	**0.046**	**1.9**	**0.015**	**0.7**	**---**	**---**	**---**	**---**
All	**Avg**	**79.84**	**2.095**	**10.9**	**2.138**	**9.0**	**6.81**	**951**	**891**	**93**
	Stdev	**2.90**	**0.077**	**3.3**	**0.079**	**3.4**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350
1) Average of 4 measurements.
2) Degree of saturation.

Table H-32. Slab Data for *Mixture* 2, Subjected to *STAP* 2, Sequential Mixing

Rep	Core	Height[1] (mm)	Dimensional $D_{b\text{-}c}$	Dimensional $V_{a\text{-}b}$	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	79.90	2.040	13.2	2.076	11.7	6.06	---	---	---
	2	81.08	2.056	12.5	2.097	10.8	6.14	---	---	---
	3	81.26	2.064	12.2	2.088	11.2	---	---	748	94
	4	82.44	2.063	12.2	2.091	11.0	---	---	688	93
	5	82.64	2.026	13.8	2.098	10.7	---	827	---	---
	6	80.77	2.088	11.1	2.105	10.4	---	791	---	---
	Avg	**81.35**	**2.056**	**12.5**	**2.092**	**11.0**	**6.10**	**809**	**718**	**94**
	Stdev	**1.04**	**0.022**	**0.9**	**0.010**	**0.4**	**---**	**---**	**---**	**---**
2	1	80.29	2.006	14.6	2.045	13.0	10.64	---	---	---
	2	83.54	2.007	14.6	2.050	12.8	10.85	---	---	---
	3	82.29	2.021	14.0	2.057	12.5	---	---	688	88
	4	82.90	2.027	13.8	2.048	12.9	---	---	658	87
	5	81.80	2.058	12.4	2.092	11.0	---	747	---	---
	6	83.50	2.065	12.1	2.084	11.3	---	716	---	---
	Avg	**82.39**	**2.031**	**13.6**	**2.063**	**12.2**	**10.74**	**731**	**673**	**88**
	Stdev	**1.23**	**0.025**	**1.1**	**0.020**	**0.9**	**---**	**---**	**---**	**---**
All	**Avg**	**81.87**	**2.043**	**13.0**	**2.078**	**11.6**	**8.42**	**770**	**696**	**91**
	Stdev	**1.21**	**0.026**	**1.1**	**0.022**	**0.9**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350
1) Average of 4 measurements.
2) Degree of saturation.

Table H-33. Slab Data for *Mixture* 2, Subjected to *STAP* 3, Sequential Mixing

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	79.59	2.096	10.8	2.118	9.9	7.60	---	---	---
	2	77.99	2.095	10.8	2.112	10.1	7.80	---	---	---
	3	80.50	2.105	10.4	2.138	9.0	---	---	881	93
	4	80.55	2.094	10.9	2.138	9.0	---	---	845	94
	5	79.45	2.097	10.8	2.123	9.7	---	912	---	---
	6	79.56	2.114	10.1	2.137	9.1	---	929	---	---
	Avg	**79.60**	**2.100**	**10.6**	**2.128**	**9.5**	**7.70**	**921**	**863**	**93**
	Stdev	**0.93**	**0.008**	**0.3**	**0.011**	**0.5**	**---**	**---**	**---**	**---**
2	1	80.32	2.095	10.9	2.124	9.6	6.62	---	---	---
	2	77.66	2.134	9.2	2.163	8.0	6.80	---	---	---
	3	80.37	2.107	10.3	2.151	8.5	---	---	924	91
	4	79.23	2.125	9.6	2.150	8.5	---	---	904	91
	5	79.38	2.111	10.2	2.152	8.4	---	983	---	---
	6	78.52	2.133	9.2	2.159	8.1	---	1012	---	---
	Avg	**79.25**	**2.117**	**9.9**	**2.150**	**8.5**	**6.71**	**997**	**914**	**91**
	Stdev	**1.05**	**0.016**	**0.7**	**0.014**	**0.6**	**---**	**---**	**---**	**---**
All	**Avg**	**79.42**	**2.109**	**10.3**	**2.139**	**9.0**	**7.21**	**959**	**889**	**92**
	Stdev	**0.96**	**0.015**	**0.6**	**0.017**	**0.7**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-34. Slab Data for *Mixture* 2, Subjected to *STAP* 1, Sasobit®

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	77.18	2.154	8.4	2.180	7.2	5.20	---	---	---
	2	77.40	2.163	7.9	2.207	6.1	5.11	---	---	---
	3	77.18	2.187	6.9	2.207	6.1	---	---	1072	88
	4	77.17	2.173	7.5	2.211	5.9	---	---	1046	92
	5	77.16	2.174	7.5	2.209	6.0	---	985	---	---
	6	76.94	2.171	7.6	2.207	6.1	---	1042	---	---
	Avg	**77.17**	**2.170**	**7.6**	**2.203**	**6.2**	**5.16**	**1013**	**1059**	**90**
	Stdev	**0.15**	**0.011**	**0.5**	**0.011**	**0.5**	**---**	**---**	**---**	**---**
2	1	75.88	2.133	9.2	2.179	7.3	3.57	---	---	---
	2	77.32	2.168	7.8	2.208	6.0	3.58	---	---	---
	3	76.03	2.163	8.0	2.192	6.7	---	---	964	85
	4	77.19	2.180	7.2	2.217	5.7	---	---	1063	92
	5	76.33	2.166	7.8	2.199	6.4	---	1098	---	---
	6	77.15	2.170	7.7	2.212	5.9	---	1011	---	---
	Avg	**76.65**	**2.163**	**7.9**	**2.201**	**6.3**	**3.57**	**1054**	**1014**	**88**
	Stdev	**0.64**	**0.016**	**0.7**	**0.014**	**0.6**	**---**	**---**	**---**	**---**
All	**Avg**	**76.91**	**2.167**	**7.8**	**2.202**	**6.3**	**4.36**	**1034**	**1036**	**89**
	Stdev	**0.52**	**0.014**	**0.6**	**0.012**	**0.5**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-35. Slab Data for *Mixture* 2, Subjected to *STAP* 2, Sasobit®

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	76.43	2.132	9.3	2.158	8.2	3.10	---	---	---
	2	77.87	2.155	8.3	2.171	7.6	3.08	---	---	---
	3	77.99	2.142	8.9	2.174	7.5	---	---	918	86
	4	77.42	2.187	6.9	2.183	7.1	---	---	964	86
	5	77.52	2.151	8.5	2.180	7.2	---	934	---	---
	6	78.10	2.163	7.9	2.162	8.0	---	945	---	---
	Avg	**77.55**	**2.155**	**8.3**	**2.171**	**7.6**	**3.09**	**940**	**941**	**86**
	Stdev	**0.61**	**0.019**	**0.8**	**0.010**	**0.4**	**---**	**---**	**---**	**---**
2	1	77.55	2.134	9.2	2.154	8.3	5.41	---	---	---
	2	76.68	2.147	8.6	2.170	7.7	5.31	---	---	---
	3	77.90	2.158	8.2	2.187	7.0	---	---	942	92
	4	78.11	2.167	7.8	2.167	7.8	---	---	957	79
	5	77.53	2.172	7.6	2.179	7.3	---	989	---	---
	6	78.52	2.177	7.4	2.200	6.4	---	1022	---	---
	Avg	**77.71**	**2.159**	**8.1**	**2.176**	**7.4**	**5.36**	**1006**	**949**	**86**
	Stdev	**0.63**	**0.016**	**0.7**	**0.016**	**0.7**	**---**	**---**	**---**	**---**
All	**Avg**	**77.63**	**2.157**	**8.2**	**2.174**	**7.5**	**4.22**	**973**	**945**	**86**
	Stdev	**0.60**	**0.017**	**0.7**	**0.013**	**0.5**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350
1) Average of 4 measurements.
2) Degree of saturation.

Table H-36. Slab Data for *Mixture* 2, Subjected to *STAP* 3, Sasobit®

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	79.80	2.068	12.0	2.121	9.7	7.04	---	---	---
	2	78.78	2.085	11.3	2.112	10.1	6.98	---	---	---
	3	80.52	2.108	10.3	2.145	8.7	---	---	1020	98
	4	80.57	2.135	9.1	2.154	8.3	---	---	874	96
	5	80.35	2.090	11.1	2.120	9.8	---	892	---	---
	6	80.46	2.099	10.7	2.135	9.1	---	923	---	---
	Avg	**80.08**	**2.097**	**10.7**	**2.131**	**9.3**	**7.01**	**907**	**947**	**97**
	Stdev	**0.70**	**0.023**	**1.0**	**0.016**	**0.7**	**---**	**---**	**---**	**---**
2	1	80.97	2.069	12.0	2.100	10.6	4.44	---	---	---
	2	79.52	2.042	13.1	2.065	12.1	4.45	---	---	---
	3	81.50	2.104	10.5	2.121	9.8	---	---	859	88
	4	81.37	2.090	11.1	2.125	9.6	---	---	758	94
	5	81.28	2.072	11.8	2.100	10.6	---	813	---	---
	6	81.21	2.081	11.4	2.113	10.1	---	799	---	---
	Avg	**80.97**	**2.076**	**11.6**	**2.104**	**10.5**	**4.45**	**806**	**809**	**91**
	Stdev	**0.74**	**0.021**	**0.9**	**0.022**	**0.9**	**---**	**---**	**---**	**---**
All	**Avg**	**80.53**	**2.087**	**11.2**	**2.118**	**9.9**	**5.73**	**857**	**878**	**94**
	Stdev	**0.83**	**0.024**	**1.0**	**0.023**	**1.0**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350
1) Average of 4 measurements.
2) Degree of saturation.

Table H-37. Slab Data for *Mixture* 2, Subjected to *STAP* 1, Evotherm 3G™

Rep	Core	Height[1] (mm)	Dimensional $D_{b\text{-}c}$	Dimensional $V_{a\text{-}b}$	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	80.72	2.105	10.4	2.129	9.4	9.66	---	---	---
	2	77.40	2.096	10.8	2.125	9.6	9.74	---	---	---
	3	80.18	2.095	10.9	2.149	8.6	---	---	917	93
	4	79.77	2.090	11.1	2.151	8.5	---	---	879	92
	5	79.95	2.075	11.7	2.134	9.2	---	874	---	---
	6	79.36	2.091	11.0	2.143	8.8	---	881	---	---
	Avg	**79.56**	**2.092**	**11.0**	**2.139**	**9.0**	**9.70**	**878**	**898**	**92**
	Stdev	**1.15**	**0.010**	**0.4**	**0.011**	**0.5**	**---**	**---**	**---**	**---**
2	1	79.41	2.063	12.2	2.128	9.5	7.83	---	---	---
	2	76.80	2.120	9.8	2.178	7.3	7.99	---	---	---
	3	78.03	2.112	10.1	2.176	7.4	---	---	1007	94
	4	77.91	2.172	7.6	2.214	5.8	---	---	1090	98
	5	77.77	2.119	9.8	2.170	7.6	---	1059	---	---
	6	77.74	2.157	8.2	2.200	6.4	---	991	---	---
	Avg	**77.94**	**2.124**	**9.6**	**2.178**	**7.3**	**7.91**	**1025**	**1048**	**96**
	Stdev	**0.84**	**0.038**	**1.6**	**0.030**	**1.3**	**---**	**---**	**---**	**---**
3	1	80.27	2.112	10.1	2.143	8.8	11.33	---	---	---
	2	77.44	2.134	9.2	2.130	9.4	11.06	---	---	---
	3	79.70	2.118	9.9	2.139	9.0	---	---	669	93
	4	79.60	2.118	9.9	2.141	8.9	---	---	703	89
	5	80.01	2.115	10.0	2.133	9.2	---	1025	---	---
	6	79.28	2.119	9.8	2.138	9.0	---	989	---	---
	Avg	**79.38**	**2.119**	**9.8**	**2.137**	**9.1**	**11.19**	**1007**	**686**	**91**
	Stdev	**1.01**	**0.008**	**0.3**	**0.005**	**0.2**	**---**	**---**	**---**	**---**
All	**Avg**	**78.96**	**2.112**	**10.1**	**2.151**	**8.5**	**9.60**	**970**	**877**	**93**
	Stdev	**1.21**	**0.026**	**1.1**	**0.026**	**1.1**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-38. Slab Data for *Mixture* 2, Subjected to *STAP* 2, Evotherm 3G™

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	78.73	2.143	8.8	2.171	7.6	6.90	---	---	---
	2	75.56	2.143	8.8	2.188	6.9	6.88	---	---	---
	3	78.37	2.177	7.4	2.207	6.1	---	---	1038	97
	4	77.78	2.173	7.5	2.203	6.3	---	---	1027	94
	5	78.14	2.166	7.8	2.199	6.4	---	988	---	---
	6	77.35	2.154	8.3	2.197	6.5	---	997	---	---
	Avg	**77.65**	**2.159**	**8.1**	**2.194**	**6.6**	**6.89**	**993**	**1033**	**96**
	Stdev	**1.13**	**0.015**	**0.6**	**0.013**	**0.5**	**---**	**---**	**---**	**---**
2	1	78.37	2.105	10.4	2.140	8.9	5.81	---	---	---
	2	77.45	2.133	9.3	2.180	7.2	5.89	---	---	---
	3	78.66	2.154	8.3	2.194	6.6	---	---	1016	96
	4	78.60	2.165	7.9	2.199	6.4	---	---	1068	94
	5	78.41	2.153	8.4	2.197	6.5	---	1038	---	---
	6	78.26	2.161	8.0	2.191	6.8	---	1059	---	---
	Avg	**78.29**	**2.145**	**8.7**	**2.184**	**7.1**	**5.85**	**1048**	**1042**	**95**
	Stdev	**0.44**	**0.023**	**1.0**	**0.022**	**1.0**	**---**	**---**	**---**	**---**
All	**Avg**	**77.97**	**2.152**	**8.4**	**2.189**	**6.9**	**6.37**	**1021**	**1037**	**95**
	Stdev	**0.88**	**0.020**	**0.8**	**0.018**	**0.8**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-39. Slab Data for *Mixture* 2, Subjected to *STAP* 3, Evotherm 3G™

Rep	Core	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a	Rut (mm)	Dry S_t (kPa)	Wet S_t (kPa)	Sat[2] (%)
1	1	78.08	2.051	12.7	2.098	10.7	9.86	---	---	---
	2	79.18	2.110	10.2	2.153	8.4	9.82	---	---	---
	3	79.30	2.090	11.1	2.142	8.8	---	---	884	89
	4	79.56	2.125	9.6	2.163	8.0	---	---	846	97
	5	78.89	2.099	10.7	2.145	8.7	---	922	---	---
	6	79.33	2.081	11.5	2.139	9.0	---	846	---	---
	Avg	**79.05**	**2.092**	**11.0**	**2.140**	**8.9**	**9.84**	**884**	**865**	**93**
	Stdev	**0.53**	**0.026**	**1.1**	**0.022**	**0.9**	**---**	**---**	**---**	**---**
2	1	82.91	2.064	12.2	2.114	10.0	8.35	---	---	---
	2	77.46	2.023	13.9	2.090	11.1	8.43	---	---	---
	3	81.52	2.069	12.0	2.184	7.1	---	---	792	129
	4	80.41	2.074	11.8	2.119	9.8	---	---	819	92
	5	81.22	2.073	11.8	2.118	9.9	---	913	---	---
	6	80.07	2.074	11.8	2.118	9.9	---	892	---	---
	Avg	**80.60**	**2.063**	**12.2**	**2.124**	**9.6**	**8.39**	**903**	**806**	**111**
	Stdev	**1.83**	**0.020**	**0.8**	**0.032**	**1.3**	**---**	**---**	**---**	**---**
All	**Avg**	**79.83**	**2.078**	**11.6**	**2.132**	**9.3**	**9.11**	**893**	**835**	**102**
	Stdev	**1.52**	**0.027**	**1.1**	**0.027**	**1.2**	**---**	**---**	**---**	**---**

Note: G_{mm} = 2.350

1) Average of 4 measurements.

2) Degree of saturation.

Table H-40. Slab Data Summary of Average V_a Data for *Mixture* 1

Compaction Scenario	*STAP*	Slab Rep	Height[1] (mm)	Dimensional		Vacuum Seal	
				D_{b-c}	V_{a-b}	G_{mb}	V_a
Control	1	1	82.48	2.204	13.0	2.247	11.3
		2	78.95	2.157	14.9	2.224	12.2
		3	84.25	2.142	15.5	2.182	13.9
		4	81.27	2.220	12.4	2.274	10.3
		Avg	**81.74**	**2.181**	**13.9**	**2.232**	**11.9**
	2	1	84.50	2.128	16.0	2.176	14.1
		2	83.23	2.139	15.6	2.200	13.2
		3	83.86	2.158	14.8	2.199	13.2
		Avg	**83.86**	**2.142**	**15.5**	**2.191**	**13.5**
	3	1	85.95	2.174	14.2	2.176	14.1
		2	83.09	2.137	15.7	2.188	13.6
		3	86.36	2.100	17.1	2.141	15.5
		Avg	**85.13**	**2.137**	**15.7**	**2.169**	**14.4**
Seq. Mix	1	1	88.09	2.061	18.7	2.126	16.1
		2	84.97	2.111	16.7	2.170	14.4
		Avg	**86.53**	**2.086**	**17.7**	**2.148**	**15.2**
	2	1	85.18	2.134	15.8	2.194	13.4
		2	88.63	2.095	17.3	2.153	15.0
		Avg	**86.90**	**2.115**	**16.5**	**2.173**	**14.2**
	3	1	87.88	2.049	19.1	2.109	16.8
		2	83.13	2.167	14.5	2.220	12.4
		3	84.27	2.157	14.9	2.181	13.9
		Avg	**85.09**	**2.124**	**16.2**	**2.170**	**14.4**
Sasobit®	1	1	81.33	2.101	17.1	2.163	14.7
		2	82.45	2.090	17.5	2.154	15.0
		3	83.11	2.186	13.7	2.216	12.6
		4	79.76	2.263	10.7	2.314	8.7
		Avg	**81.66**	**2.160**	**14.8**	**2.212**	**12.7**
	2	1	86.78	2.099	17.2	2.156	14.9
		2	84.87	2.121	16.3	2.177	14.1
		3	84.08	2.152	15.1	2.182	13.9
		4	78.80	2.285	9.8	2.333	7.9
		Avg	**83.63**	**2.164**	**14.6**	**2.212**	**12.7**
	3	1	85.60	2.107	16.8	2.145	15.4
		2	85.60	2.067	18.4	2.126	16.1
		3	82.99	2.179	14.0	2.208	12.9
		4	81.58	2.209	12.8	2.267	10.5
		Avg	**83.94**	**2.140**	**15.5**	**2.186**	**13.7**
Evotherm 3G™	1	1	80.50	2.183	13.8	2.235	11.8
		2	78.58	2.176	14.1	2.226	12.2
		Avg	**79.54**	**2.180**	**14.0**	**2.231**	**12.0**
	2	1	83.35	2.148	15.2	2.207	12.9
		2	83.53	2.152	15.1	2.203	13.1
		Avg	**84.15**	**2.153**	**15.0**	**2.181**	**13.9**
	3	1	83.68	2.151	15.1	2.197	13.3
		2	83.36	2.175	14.2	2.213	12.7
		3	82.74	2.180	14.0	2.229	12.0
		Avg	**83.05**	**2.177**	**14.1**	**2.221**	**12.3**

Table H-41. Slab Data Summary of Average V_a Data for *Mixture* 2

Compaction Scenario	*STAP*	Slab Rep	Height[1] (mm)	Dimensional D_{b-c}	Dimensional V_{a-b}	Vacuum Seal G_{mb}	Vacuum Seal V_a
Control	1	1	80.43	2.065	12.1	2.103	10.5
		2	82.83	2.016	14.2	2.054	12.6
		3	80.07	2.089	11.1	2.117	9.9
		Avg	**81.11**	**2.057**	**12.5**	**2.091**	**11.0**
	2	1	82.00	2.029	13.6	2.048	12.9
		2	78.92	2.117	9.9	2.158	8.2
		3	80.93	2.066	12.1	2.096	10.8
		Avg	**80.61**	**2.071**	**11.9**	**2.101**	**10.6**
	3	1	80.64	2.079	11.5	2.102	10.6
		2	81.56	2.058	12.4	2.079	11.5
		3	81.47	2.062	12.2	2.093	10.9
		Avg	**81.22**	**2.067**	**12.1**	**2.092**	**11.0**
Seq. Mix	1	1	82.23	2.029	13.7	2.064	12.2
		2	77.45	2.161	8.0	2.213	5.9
		Avg	**79.84**	**2.095**	**10.9**	**2.138**	**9.0**
	2	1	81.35	2.056	12.5	2.092	11.0
		2	82.39	2.031	13.6	2.063	12.2
		Avg	**81.87**	**2.043**	**13.0**	**2.078**	**11.6**
	3	1	79.60	2.100	10.6	2.128	9.5
		2	79.25	2.117	9.9	2.150	8.5
		Avg	**79.42**	**2.109**	**10.3**	**2.139**	**9.0**
Sasobit®	1	1	77.17	2.170	7.6	2.203	6.2
		2	76.65	2.163	7.9	2.201	6.3
		Avg	**76.91**	**2.167**	**7.8**	**2.202**	**6.3**
	2	1	77.55	2.155	8.3	2.171	7.6
		2	77.71	2.159	8.1	2.176	7.4
		Avg	**77.63**	**2.157**	**8.2**	**2.174**	**7.5**
	3	1	80.08	2.097	10.7	2.131	9.3
		2	80.97	2.076	11.6	2.104	10.5
		Avg	**80.53**	**2.087**	**11.2**	**2.118**	**9.9**
Evotherm 3G™	1	1	79.56	2.092	11.0	2.139	9.0
		2	77.94	2.124	9.6	2.178	7.3
		3	79.38	2.119	9.8	2.137	9.1
		Avg	**78.96**	**2.112**	**10.1**	**2.151**	**8.5**
	2	1	77.65	2.159	8.1	2.194	6.6
		2	78.29	2.145	8.7	2.184	7.1
		Avg	**77.97**	**2.152**	**8.4**	**2.189**	**6.9**
	3	1	79.05	2.092	11.0	2.140	8.9
		2	80.60	2.063	12.2	2.124	9.6
		Avg	**79.83**	**2.078**	**11.6**	**2.132**	**9.3**

SGC Data

Results of samples compacted in the Superpave Gyratory Compactor (*SGC*) and subjected to *APA* rut testing are shown in the Tables H-42 through H-45. A total of 96 specimens were fabricated and tested in this portion of the research.

Table H-42. *APA* Results for *Mixture 1* at 7% Target V_a

STAP	**Mixture Type**	**Rep**	**Sample Mass (g)**	**Gyrations to 75 mm**	**Rut Depth (mm)**
4	Control	1	3059.8	46	2.38
		2	3058.8	39	2.44
		Avg	**---**	**43**	**2.41**
	Seq. Mix	1	3058.7	35	3.83
		2	3058.5	44	3.98
		Avg	**---**	**40**	**3.90**
	Sasobit®	1	3058.3	28	3.87
		2	3057.6	30	3.83
		Avg	**---**	**29**	**3.85**
	Evotherm 3G™	1	3059.3	50	3.66
		2	3058.2	31	3.77
		Avg	**---**	**41**	**3.72**
5	Control	1	3059.5	61	3.02
		2	3060.8	66	3.06
		Avg	**---**	**64**	**3.04**
	Seq. Mix	1	3059.4	56	4.02
		2	3060.0	48	4.03
		Avg	**---**	**52**	**4.02**
	Sasobit®	1	3059.2	37	4.27
		2	3059.5	32	4.17
		Avg	**---**	**35**	**4.22**
	Evotherm 3G™	1	3060.4	42	2.48
		2	3059.7	39	2.50
		Avg	**---**	**41**	**2.49**
6	Control	1	3060.5	60	3.15
		2	3060.0	66	3.17
		Avg	**---**	**63**	**3.16**
	Seq. Mix	1	3060.5	53	4.87
		2	3059.2	55	4.83
		Avg	**---**	**54**	**4.85**
	Sasobit®	1	3059.5	48	4.18
		2	3059.6	63	4.12
		Avg	**---**	**56**	**4.15**
	Evotherm 3G™	1	3060.3	53	3.05
		2	3059.9	64	3.09
		Avg	**---**	**59**	**3.07**

Table H-43. *APA* Results for *Mixture 1* at 10% Target V_a

STAP	**Mixture Type**	**Rep**	**Sample Mass (g)**	**Gyrations to 75 mm**	**Rut Depth (mm)**
4	Control	1	2928.7	11	5.07
		2	2929.2	13	5.21
		Avg	**---**	**12**	**5.14**
	Seq. Mix	1	2929.4	14	5.02
		2	2928.6	14	4.94
		Avg	**---**	**14**	**4.98**
	Sasobit®	1	2929.4	10	5.27
		2	2927.0	12	5.17
		Avg	**---**	**11**	**5.22**
	Evotherm 3G™	1	2927.7	14	6.20
		2	2926.4	18	6.43
		Avg	**---**	**16**	**6.31**
5	Control	1	2930.1	17	5.67
		2	2929.9	19	5.72
		Avg	**---**	**18**	**5.69**
	Seq. Mix	1	2929.8	16	4.81
		2	2928.1	15	4.61
		Avg	**---**	**16**	**4.71**
	Sasobit®	1	2929.7	15	5.11
		2	2930.1	15	5.04
		Avg	**---**	**15**	**5.07**
	Evotherm 3G™	1	2928.6	16	5.93
		2	2929.3	22	6.04
		Avg	**---**	**19**	**5.98**
6	Control	1	2930.3	16	6.05
		2	2929.2	17	6.00
		Avg	**---**	**17**	**6.02**
	Seq. Mix	1	2929.8	20	5.40
		2	2930.1	17	5.36
		Avg	**---**	**19**	**5.38**
	Sasobit®	1	2930.1	20	5.18
		2	2930.7	26	5.07
		Avg	**---**	**23**	**5.12**
	Evotherm 3G™	1	2930.2	17	7.89
		2	2930.0	19	7.91
		Avg	**---**	**18**	**7.90**

Table H-44. *APA* Results for *Mixture 2* at 7% Target V_a

STAP	**Mixture Type**	**Rep**	**Sample Mass (g)**	**Gyrations to 75 mm**	**Rut Depth (mm)**
4	Control	1	2850.0	32	3.35
		2	2846.7	31	3.4
		Avg	---	**32**	**3.38**
	Seq. Mix	1	2847.7	27	5.22
		2	2847.2	37	5.19
		Avg	---	**32**	**5.20**
	Sasobit®	1	2846.7	28	4.97
		2	2846.6	29	4.95
		Avg	---	**29**	**4.96**
	Evotherm 3G™	1	2848.1	47	4.80
		2	2847.5	38	4.64
		Avg	---	**43**	**4.72**
5	Control	1	2847.8	38	3.64
		2	2848.5	34	3.66
		Avg	---	**36**	**3.65**
	Seq. Mix	1	2848.2	41	5.22
		2	2847.7	36	5.23
		Avg	---	**39**	**5.22**
	Sasobit®	1	2847.8	49	5.47
		2	2847.9	61	5.34
		Avg	---	**55**	**5.40**
	Evotherm 3G™	1	2848.7	54	4.01
		2	2848.1	32	4.06
		Avg	---	**43**	**4.04**
6	Control	1	2848.4	53	3.98
		2	2848.1	45	3.97
		Avg	---	**49**	**3.97**
	Seq. Mix	1	2848.8	44	5.79
		2	2848.6	53	5.74
		Avg	---	**49**	**5.76**
	Sasobit®	1	2847.6	62	5.96
		2	2848.0	59	5.94
		Avg	---	**61**	**5.95**
	Evotherm 3G™	1	2848.9	85	4.16
		2	2848.5	62	4.21
		Avg	---	**74**	**4.18**

Table H-45. *APA* Results for *Mixture 2* at 10% Target V_a

STAP	Mixture Type	Rep	Sample Mass (g)	Gyrations to 75 mm	Rut Depth (mm)
4	Control	1	2750.8	15	6.29
		2	2750.6	13	6.29
		Avg.	---	**14**	**6.29**
	Seq. Mix	1	2751.2	16	4.67
		2	2751.4	14	4.60
		Avg.	---	**15**	**4.63**
	Sasobit®	1	2751.8	11	5.74
		2	2751.8	14	5.72
		Avg.	---	**13**	**5.73**
	Evotherm 3G™	1	2751.0	16	8.18
		2	2751.6	16	7.96
		Avg.	---	**16**	**8.07**
5	Control	1	2752.3	16	6.50
		2	2751.2	16	6.50
		Avg.	---	**16**	**6.50**
	Seq. Mix	1	2752.1	27	5.24
		2	2752.2	26	5.10
		Avg.	---	**27**	**5.17**
	Sasobit®	1	2752.3	24	6.24
		2	2752.1	22	6.18
		Avg.	---	**23**	**6.21**
	Evotherm 3G™	1	2751.6	14	7.78
		2	2752.1	16	7.84
		Avg.	---	**15**	**7.81**
6	Control	1	2752.5	18	9.51
		2	2752.2	21	9.33
		Avg.	---	**20**	**9.42**
	Seq. Mix	1	2752.8	19	6.64
		2	2752.1	19	6.67
		Avg.	---	**19**	**6.65**
	Sasobit®	1	2751.7	24	7.70
		2	2752.2	23	7.66
		Avg.	---	**24**	**7.68**
	Evotherm 3G™	1	2752.1	26	8.99
		2	2752.4	25	9.10
		Avg.	---	**26**	**9.04**

Data Analysis

The focus of the analysis was on 64 of the 79 slabs and the 96 *SGC* compacted specimens. The 15 preliminary slabs were used to establish the properties of the remaining 64 slabs and were not considered in analysis, though test results were provided.

Analysis of Air Voids (V_a) Data

In general the slab produced specimens had much higher V_a values than did the *SGC* produced specimens. The range of average V_a values from a given slab were 7.9 to 16.8% for *Mixture 1* and 5.9 to 12.9% for *Mixture 2*. Average V_a values from all slab testing are shown in Figure H-15. Relative to the control specimens, sequential mixing was shown to be very erratic and performed worse than the control specimens in terms of compactability in many instances. At standard hot mix compaction temperatures (i.e. *STAP* 1), *Mixture 1* control specimens performed the best while *Mixture 2* control specimens performed the worst. Both warm mix additives out performed the control specimens for *STAP* 2 and 3, which are the conditions of interest to this research. From a compactability standpoint, both additives provided superior performance to control specimens.

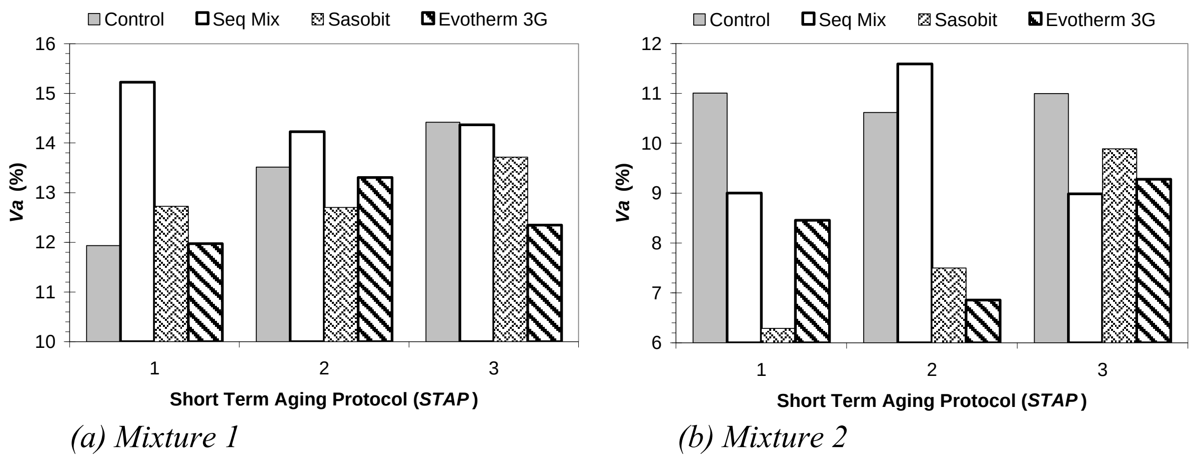
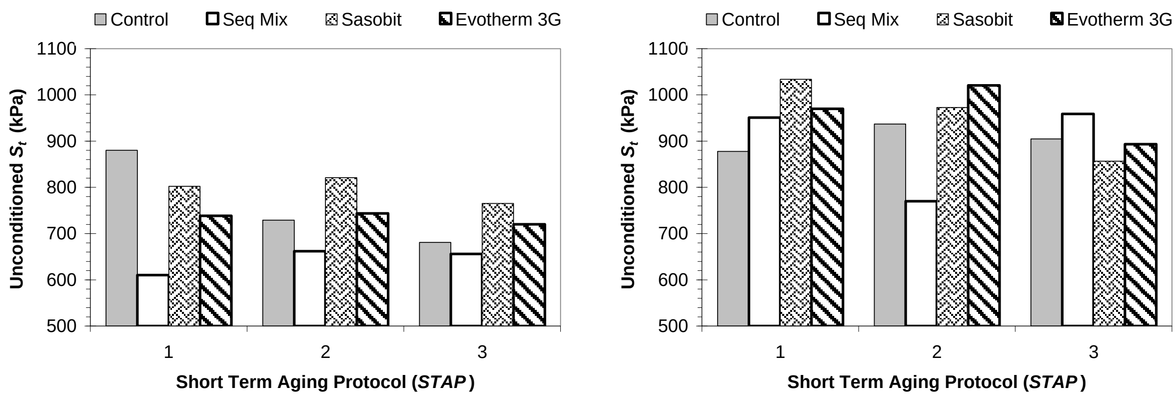


Figure H-15. Average Slab Va Test Results

Analysis of Indirect Tensile Strength (S_t) and Tensile Strength Ratio (TSR) Data

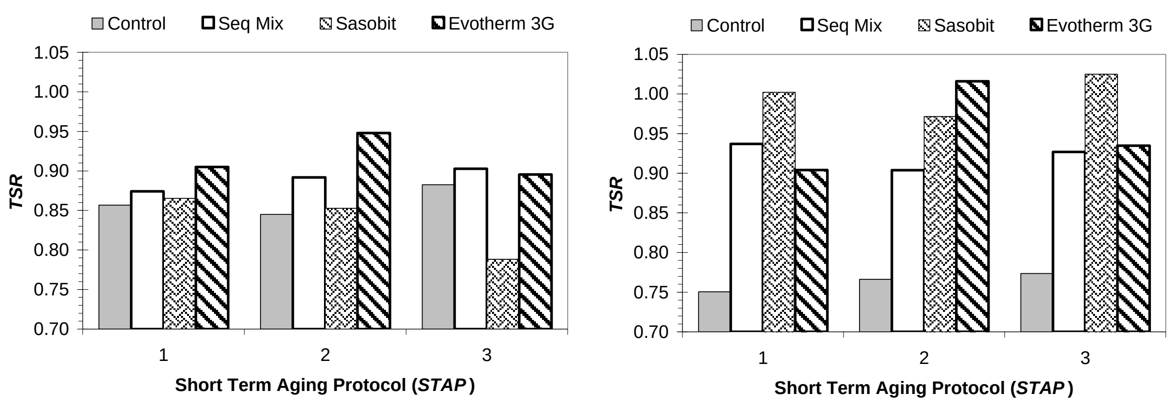
Figure H-16 plots average unconditioned S_t values for both mixtures. As a reference, compacted warm mix asphalt control specimens had S_t values at the same temperature of the data in Figure H-16 of 900 to 1,000 kPa at *Va* levels of 3.1 to 4.7% (*15*). *Mixture 1* test results were lower than this range, while *Mixture 2* test results were equivalent to slightly lower than this range. This level of tensile strength is adequate for a temporary application, especially in absence of freeze/thaw behaviors.

Figure H-17 plots average *TSR* data for all mixtures and aging/compaction protocols using all data replicates collected; only slab compacted specimens were available. There was a moderate trend of *TSR* data increasing with a decrease in V_a, which was not plotted for brevity. The majority of the specimens tested had *TSR* values in excess of the minimum *T 283* value of 0.80. In general the control specimens had lower *TSR* values than did the sequentially mixed or warm mix additive supplemented mixtures when all replicates were considered. Four of the twenty-four combinations had average *TSR* values below 0.80.



(a) Mixture 1 *(b) Mixture 2*

Figure H-16. Average Slab S_t Test Results (Unconditioned)



(a) Mixture 1 *(b) Mixture 2*

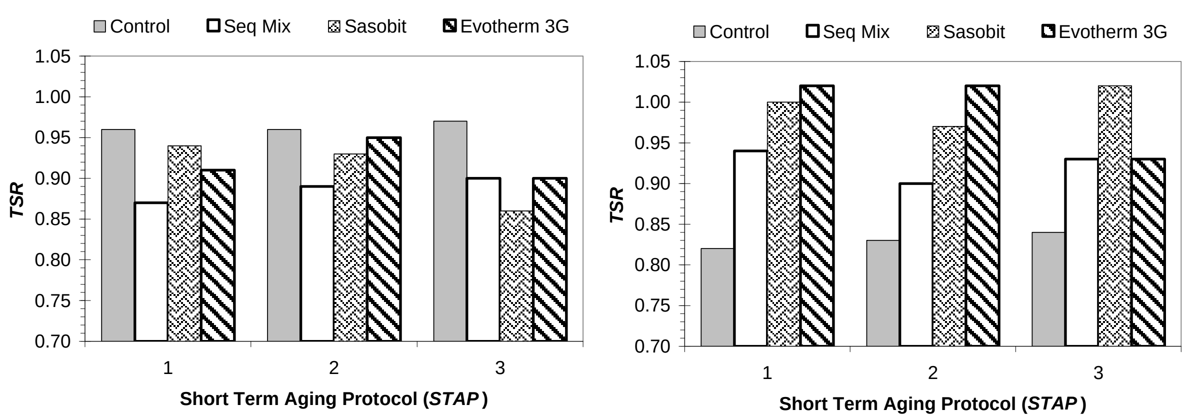
Figure H-17. Average Slab TSR Test Results Incorporating All Replicates

Individual *TSR* values below 0.80 were typically from the last replicate of a given combination and were as low as 0.63. Table H-46 provides details of all individual *TSR* data points below 0.80 (12 of 64 points were below 0.80). The research team considered this trend suspect and investigated possible causes. It was found that the ten data points that were from the last replicate and appreciably below 0.80 were mixed in succession in the testing program. It is very likely that the hydrated lime was inadvertently omitted from these slabs during batching though no conclusive evidence could be obtained. Ten slabs would be a typical batching duty for one operator working the entire day. Hydrated lime has a distinct smell that if omitted could be noticed by the laboratory operator during mixing. A meeting with those involved did not recall such an event, but the evidence of Table H-46 is fairly strong and points toward a laboratory error causing the low *TSR* values from the ten data points of the table that occurred on the last slab replicate.

Table H-46. *TSR* Test Results Below 0.80

Mixture	*STAP*	Type	Last Replicate	*TSR*
1	1	Control	Yes	0.65
	2	Control	Yes	0.66
	3	Control	Yes	0.71
	1	Sasobit®	Yes	0.73
	2	Sasobit®	Yes	0.73
	3	Sasobit®	Yes	0.64
	3	Sequential Mixing	No	0.79
2	1	Control	Yes	0.63
	2	Control	Yes	0.64
	3	Control	Yes	0.63
	1	Evotherm 3G™	Yes	0.68
	2	Control	No	0.78

Figure H-18 omits the ten data points believed to be erroneous and plots the remaining *TSR* data in a similar manner as in Figure H-17. All conditions plot above the *T 283* minimum value of 0.80. With the corrected data, the control specimens for *Mixture 1* had higher *TSR* values than the other combinations, whereas for *Mixture 2*, the reverse occurred. The conclusion related to moisture damage was that for a temporary application in a hot and wet condition (e.g. Gulf Coast hurricane) these materials should perform in an acceptable manner in relation to moisture damage when compacted to an elevated air void content.



(a) Mixture 1 *(b) Mixture 2*

Figure H-18. Average Slab TSR Test Results Incorporating Select Replicates

<u>*Analysis of APA Rut Test Data at 8,000 Cycles*</u>

APA testing has been conducted since the mid 1990's. Lower test temperatures (e.g. 50 C) were more common in that time period. A pass fail criteria when testing at 50 C was 5 mm for Georgia DOT work according to Zhang et al. (2005). Brown et al. (2001) suggested an 8 mm rut depth as the pass/fail criteria in the APA for high traffic materials tested at the high temperature grade of the binder with a 445 N wheel load and 690 kPa hose pressure.

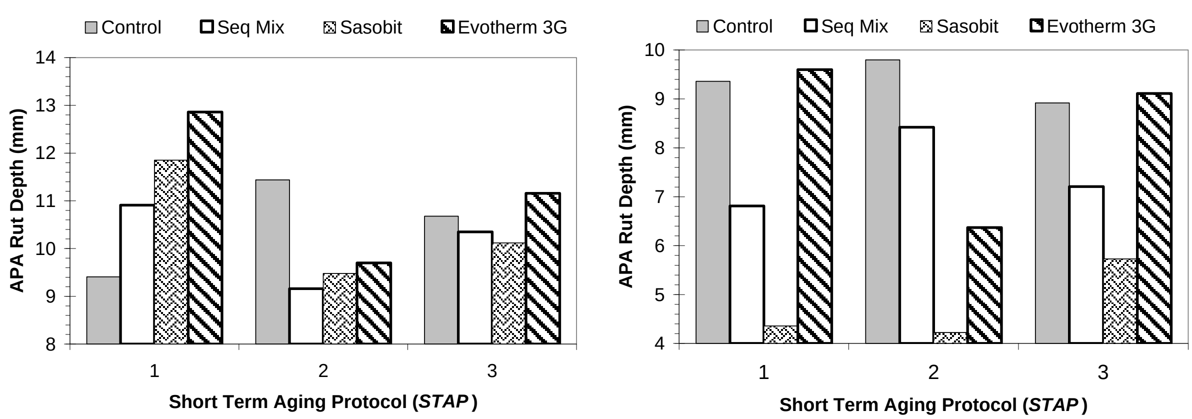
The test conditions in this research were also a 445 N wheel load and 690 kPa hose pressure. Zhang et al. (2005) provides a detailed review of performance tests for hot mixed asphalt and makes note of the 8 mm value suggested by Brown et al. (2001).

Buchanan et. al. (2004) conducted a field and laboratory study to recommend acceptable *APA* rut depth criteria for *MDOT* HMA surface mixtures. Twenty-four field locations between 2 and 5 years post construction were selected for evaluation that encompassed the range of aggregate types, aggregate sizes, binder grades, and design traffic levels common in Mississippi. *APA* rut depth results from both field samples and laboratory-compacted mix were compared to field rut measurements. Test parameters were the same as in this study. Based on the results a maximum *APA* rut depth of 12 mm for low and medium design traffic levels (ST and MT) and 6 mm for high traffic (HT) was recommended for mix design evaluation.

Kandhal and Cooley (2003) recommended a 9.5 mm pass/fail criteria for 4% air voids samples to be used in conjunction with 2 million Equivalent Single Axle Loads (ESALs). Two million ESALs was the lowest level of traffic considered. The pass/fail rut criterion was reduced with increasing traffic.

Failure criteria for an emergency construction material are not readily available. In that the goal of these materials is performance over a brief anticipated service life in absence of freeze/thaw conditions, a failure criterion that is less rigid than that suggested for high trafficked permanent pavement is appropriate. A failure criterion of 10 to 12 mm is suggested as a very reasonable value for emergency construction when tested in the APA under the aforementioned conditions. This is not to say that a 13 mm rut depth wouldn't work reasonably well in a temporary application after a disaster, rather it is to say that anything less than 10 to 12 mm would work reasonably well after a disaster.

Figure H-19 plots average APA rut depths from slabs after 8,000 cycles of testing. As seen, the average rut depths were mostly below the 10 to 12 mm threshold of the previous paragraph. The only exception would be non control specimens of *Mixture 1* conditioned using *STAP* 1.



(a) Mixture 1 *(b) Mixture 2*

Figure H-19. Average Slab APA Rut Test Results at 8,000 Cycles

The total depth of the APA mold is 76 mm and the groove is 10 mm deep measured from the top of the mold, which allows for 10 mm of rutting in a sample that is 76 mm thick before the pressurized hose comes in contact with the mold. Excessive rut depths could conceivably cause a concave shaped rut pattern due to the hose resting on the groove and preventing rutting at the edge of the specimens. Some of the slab specimens tested in this project had significant rutting, though as seen in Figure H-20 the deformation was uniform along the length of the samples indicating reliable data.

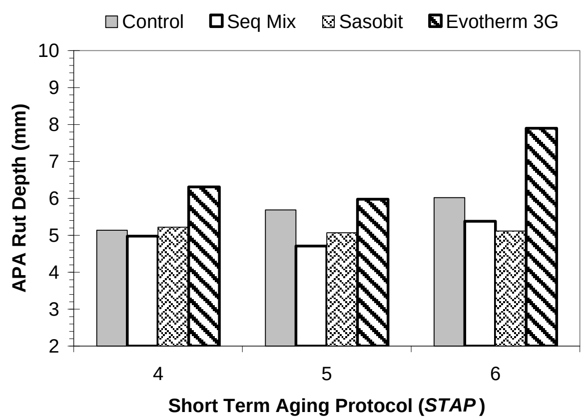
Figure H-20. APA Slab Specimens Indicating Uniform Deformation

Figure H-21 provides rut depth test results of all *SGC* compacted specimens. *Mixture 1* compacted to V_a of 7% (Figure H-21a) had very low rutting in the APA. The control mixture only had 2.4 mm of rutting. The highest rutting was seen in the sequential mixing condition at the lowest temperature, but this was still less than 5 mm of rutting. There was very little practical difference between the rutting potential for sequential mixing and the warm mix additives at lower compaction temperatures (i.e. *STAP* 6) for purposes of this research. Looking at each Figure H-21a individual process it can be seen that the mix compacted at the highest temperature has the lowest rutting with exception of Evotherm 3G™ where rutting decreased with compaction temperature. At the lower compaction temperature Evotherm 3G™ actually had results similar to the standard hot mix control in *STAP* 4. The highest rutting was seen with the sequential mixing followed by the Sasobit®. The increased rutting with the Sasobit® is surprising in that this material is also used as a binder additive to increase stiffness for rutting resistance; see Table H-6 where Sasobit® modified binder had the highest $G^*/\sin\delta$). The average increase in rutting relative to the *STAP 4* control mixture for the remaining eleven Figure H-21a conditions was 1.3 mm, with the maximum difference for any one condition being sequential mixing for *STAP* 6 at 2.4 mm higher than the *STAP* 4 control.

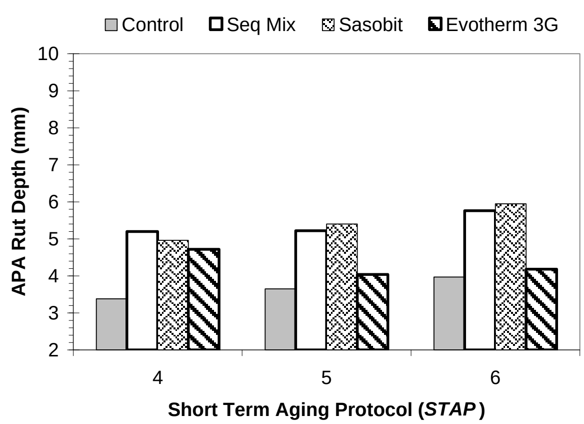
Mixture 1 compacted to V_a of 10% (Figure H-21b) did not show the same rutting trends as the samples compacted to V_a of 7%. The 10% void samples all had about the same amount of rutting for the different compaction temperatures and the warm mix additives except for Evotherm 3G™. All the samples except the Evotherm 3G™ had between 5 and 6 mm of rutting with no variation that could be related to compaction temperature. The Evotherm 3G™ samples had 1.2, 0.3, and 1.9 mm higher rutting than the control specimens in *STAP* 4, 5, and 6, respectively. The Evotherm 3G™ samples had between 6 and 8 mm of rutting.

The measured difference between 10% V_a rut depths relative to the *STAP* 4 control show a change in the mix types that exhibited larger differences from the control (Figure H-21b data). At 7% voids it was the sequential mixing and Sasobit® mixes that had higher rutting than the *STAP* 4 control. At 10% voids the sequential mixing and Sasobit® mixes show no increase in rutting and in some cases show a very miner reduction in rutting. The control compacted at lower temperature and the Evotherm 3G™ samples all indicate some increase in rutting, but less than 1 mm except for the Evotherm 3G™ from *STAP* 6 which had almost a 3 mm increase in rutting over the *STAP* 4 control. The overall rutting was relatively low with only minimal difference between the various warm mix additives and compaction temperatures. The most interesting observation was the reversal of the mixes that indicate the greater difference from the control.

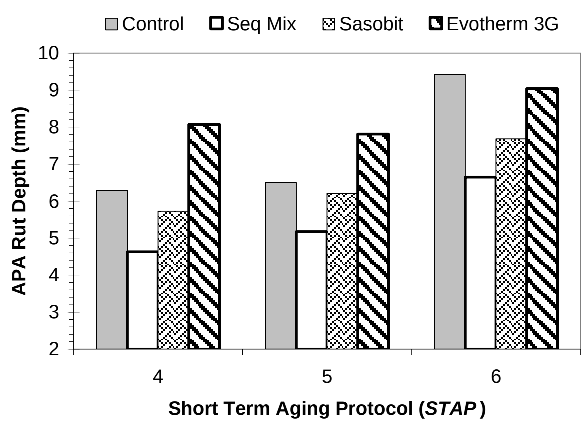
(a) Mixture 1 at V_a of 7%



(b) Mixture 1 at V_a of 10%



(c) Mixture 2 at Va of 7%



(d) Mixture 2 at Va of 10%

Figure H-21. APA SGC Rut Test Results at 8,000 Cycles

A comparison of the 7% and 10% voids data for *Mixture 1* rutting provides some very interesting data (Figures H-21a and H-21b). When comparing the control and Evotherm 3G™ mixes there is typically a 3 mm increase in rutting from 7% V_a samples to 10% V_a samples. The sequentially mixed samples and Sasobit® mixes only exhibited a 1 mm or less increase in rutting from the 7% V_a samples to the 10% V_a samples. It would be assumed that rutting would increase with increased V_a, which did happen, but it would also be assumed that the mixes with the higher rutting at lower V_a values would have a larger increase in rutting with an increase in V_a which did not happen. Sasobit® and Evotherm 3G™ had smaller rut depth increases and exhibited very little difference between the 7% and 10% voids. This will take further testing to explain. The increased $G^*/\sin\delta$ due to Sasobit® (Table H-6) could have affected the rutting more noticeably when the air voids were increased causing additional reliance on the binder to prevent rutting.

Figure H-21c provides rutting test results of *Mixture 2* at 7% V_a compacted by the *SGC*. As with *Mixture 1* at 7% voids the differences in compaction temperature are seen for each of the four conditions. The mix compacted at the hottest temperature had lower rutting than the mix compacted at the lower temperatures. What is very interesting is as with *Mixture 1* the Evotherm 3G™ compacted at the highest temperature had higher rutting than the Evotherm 3G™ mix compacted at the lowest temperature. This indicates that there could be some issue with compacting Evotherm 3G™ at higher temperatures. *Mixture 2* is produced with completely different aggregate as compared to *Mixture 1* so it is not likely that some type of interaction between the Evotherm 3G™ and the aggregate is the cause. Another similarity to *Mixture 1* is that the control had the lowest rutting followed by the Evotherm 3G™ with the sequential mixing and Sasobit® mixes with higher rutting. Again it would be assumed that the stiffening effect of the Sasobit® would reduce rutting, but at 7% voids it exhibits this highest rutting. The overall rutting of *Mixture 2* was slightly higher than *Mixture 1* by about 1 mm for each mixing process and compaction temperature.

The maximum difference in rutting for *Mixture 2* at 7% voids relative to the *STAP* 4 control is the *STAP* 6 Sasobit® at 2.6 mm higher. The average difference of all mixes relative to the *STAP* 4 control was 1.4 mm higher. All mixes rutted more than the *STAP* 4 control.

Mixture 2 compacted to 10% voids (Figure H-21d) had similar rutting results as *Mixture 1* at 10% voids. *Mixture 2* had a reversal in ranking as did *Mixture 1*. At 10% voids the sequential mixing and Sasobit® mixes had less rutting than the control and Evotherm 3G™ mixes. The change in compaction temperature can be seen with the mixes compacted at higher temperatures having less rutting. This difference, however, is small especially *STAP* 4 and 5 where there is less than 1 mm increase in rutting with the decrease in compaction temperature. There was a larger increase in rutting with the decrease in compaction temperature from *STAP* 5 to 6, which was typically over 1 mm. The difference from the least rutting for the *STAP* 4 sequential mixing to the highest rutting for the *STAP* 6 control mix was apparent at 4.8 mm. The sequential mixing and Sasobit® mixes have less rutting than the *STAP* 4 control for both *STAP* 4 and 5, but for *STAP* 6 they both have a slight increase in rutting over the *STAP* 4 control. However, the sequential mixing and Sasobit® mixes from *STAP* 6 have less rutting than the *STAP 6* control.

As with *Mixture 1*, there was an increase in rutting from 7% to 10% voids for the control and Evotherm 3G™ mixes, however there was only a very minor increase in rutting from 7% to 10% voids for the sequential mixing and Sasobit® mixes. This verifies that there is something about the sequential mixing and Sasobit® that allows for more rutting at lower voids, but does not seem to increase rutting substantially at higher voids. Since *Mixture 1* and *Mixture 2* are from completely different material it is likely the mixing process and additive are causing the behavior rather than an issue related to aggregate composition or gradation. The 10% voids *Mixture 2* as with the 7% voids *Mixture 2* have slightly higher rutting than *Mixture 1*.

<u>*Rutting Rate Analysis of APA Test Data*</u>

The 64 slabs used for standard data analysis were also used for rutting rate analysis. Data was averaged from a given mixture, *STAP*, and type of process as with the analysis of total rut depths provided in the previous section. *SGC* data was also included in rutting rate analysis. All 24 factor-level combinations were incorporated into the analysis.

Data at 0, 2, 4, 6, and 8 thousand cycles was used for the analysis. Members of the research team have been involved with use of the APA since its inception in the mid 1990's, and the experiences over that time were used to select the data intervals, in particular the first data point being at 2,000 cycles. During early cycles sample seating and consolidation occur; the two behaviors cannot be decoupled. Typically, a break in the data occurs between 1,000 and 1,500 cycles depending on mixture properties and compaction, making 2,000 to 8,000 cycles an appropriate range to evaluate rate of rutting of any given mixture.

Figures H-22 through H-27 plot rutting rate for all 24 factor-level combinations at the three air void levels (7%, 10%, and slab). As seen, there is a noticeable break in the curve at 2,000 cycles and thereafter the relationship is essentially linear. It can also be seen that for many of the mixtures the slope of the plot beyond 2,000 cycles is reasonable between the various aging protocols.

Tables H-47 through H-49 summarize Figures H-22 through H-27 and provide the rutting rate prior to and after 2,000 cycles. Summary statistics of all conditions are provided at the end of each table. As the air void level increases the data shows an increase in the rut rate from 0 to 2,000 cycles (1.39, 2.15, and 3.02 mm per 1,000 passes, respectively) as well as in the rut rate from 2,000 to 8,000 cycles (0.23, 0.33, and 0.48 mm per 1,000 passes, respectively). The ratio of average rutting rate during the first 2,000 cycles and the rutting rate from 2,000 to 8,000 cycles were 6.0, 6.5, and 6.3 for Tables H-47 through H-49, respectively, indicating that it is likely that some of the characteristics allowing high rutting during early portions of testing remain and affect rutting behavior in later portions of testing. For example, rutting behavior in early stages is often dominated by densification of a specimen, which could be continuing into later stages of the test albeit to a much lesser extent.

The rut rate from 2,000 to 8,000 cycles is arguably one of the best indicators of long term performance of a mixture when constructability is not a factor (i.e. mixture is compacted to a given air void level). In that the goal of the analysis was to evaluate temporary applications and the industry standard is to use total rut depth to quantify mixtures, total rut depth was used in this analysis as well. This position is supported by the aforementioned ratios of rutting pre and post 2,000 cycles having similar ratios as the air void levels increased. An additional complexity of using any parameter other than total rut depth would be data to use to assess a pass/fail criterion. Data for emergency applications is essentially non-existent and the criterion for this analysis was estimated based exclusively on data from total rut depth measurements.

At 7% voids, Sasobit® had the highest rut rate from 2,000 to 8,000 cycles in both *Mixture 1* and *Mixture 2*. At 10% voids, the control had the highest rate for *Mixture 1*, while Evotherm 3G™ had the highest rate for *Mixture 2*. In the slabs (highest void levels), Evotherm 3G™ had the highest rate for *Mixture 1*, while the control had the highest rate for *Mixture 2*.

The most valuable contribution of the rutting rate analysis to the current work was that the samples could be estimated to rut approximately six times faster during early trafficking than during later trafficking. A rut will almost certainly appear quickly in service, but traffic can continue since as the material densifies the rate of rutting should slow considerably.

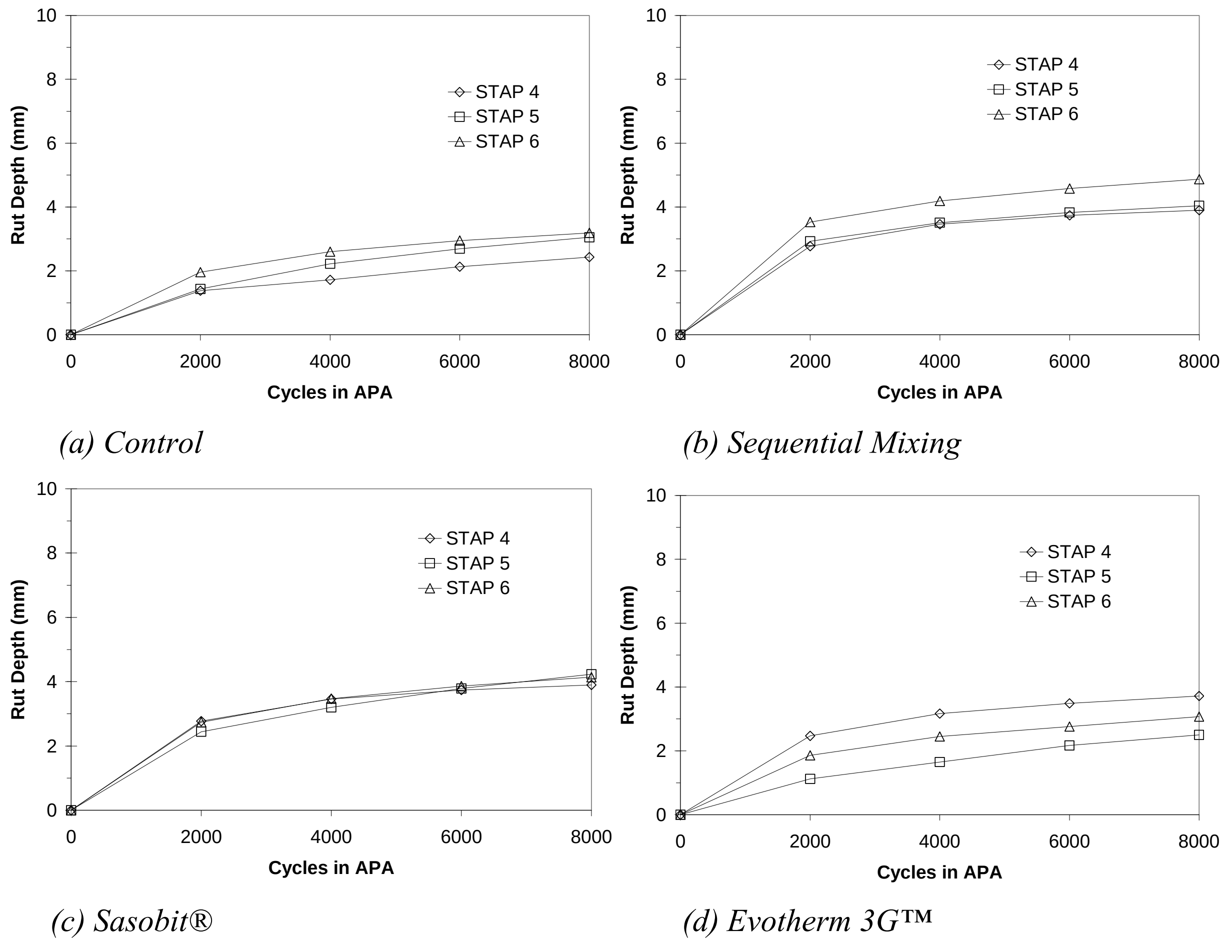
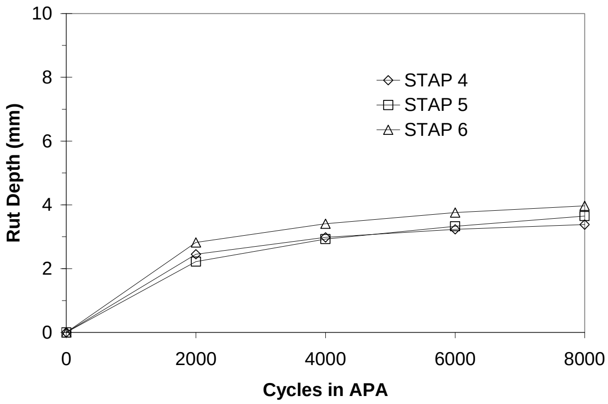
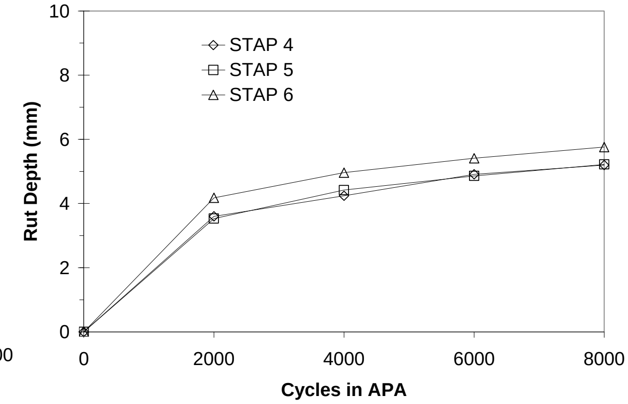


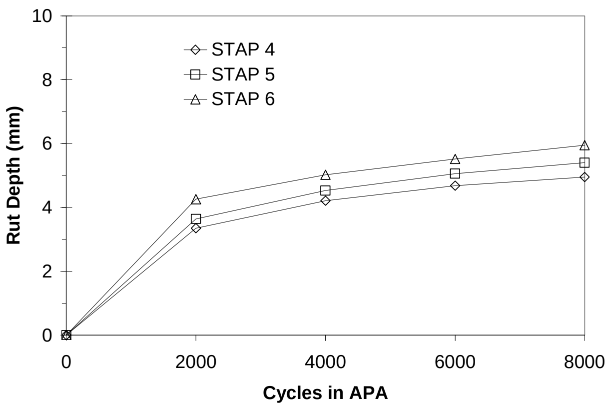
Figure H-22. Rate of Rutting for Mixture 1 Compacted in SGC to 7% Voids



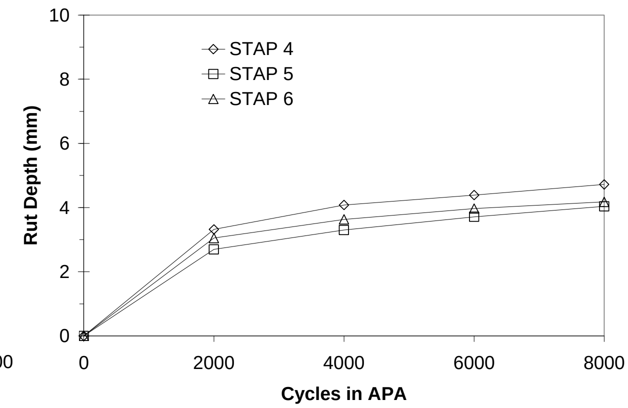
(a) Control



(b) Sequential Mixing

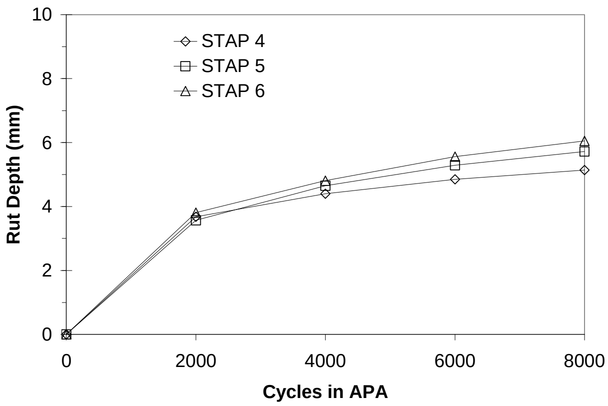


(c) Sasobit®

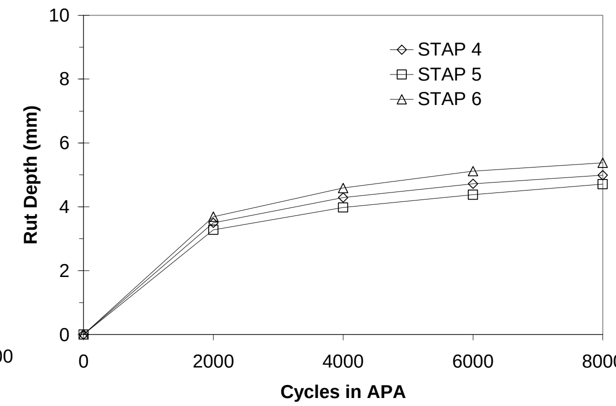


(d) Evotherm 3G™

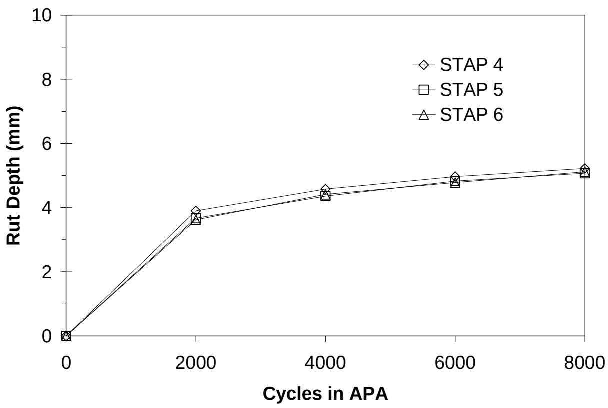
Figure H-23. Rate of Rutting for Mixture 2 Compacted in SGC to 7% Voids



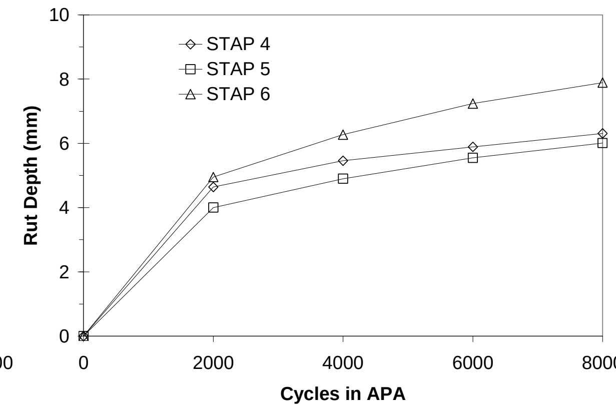
(a) Control



(b) Sequential Mixing

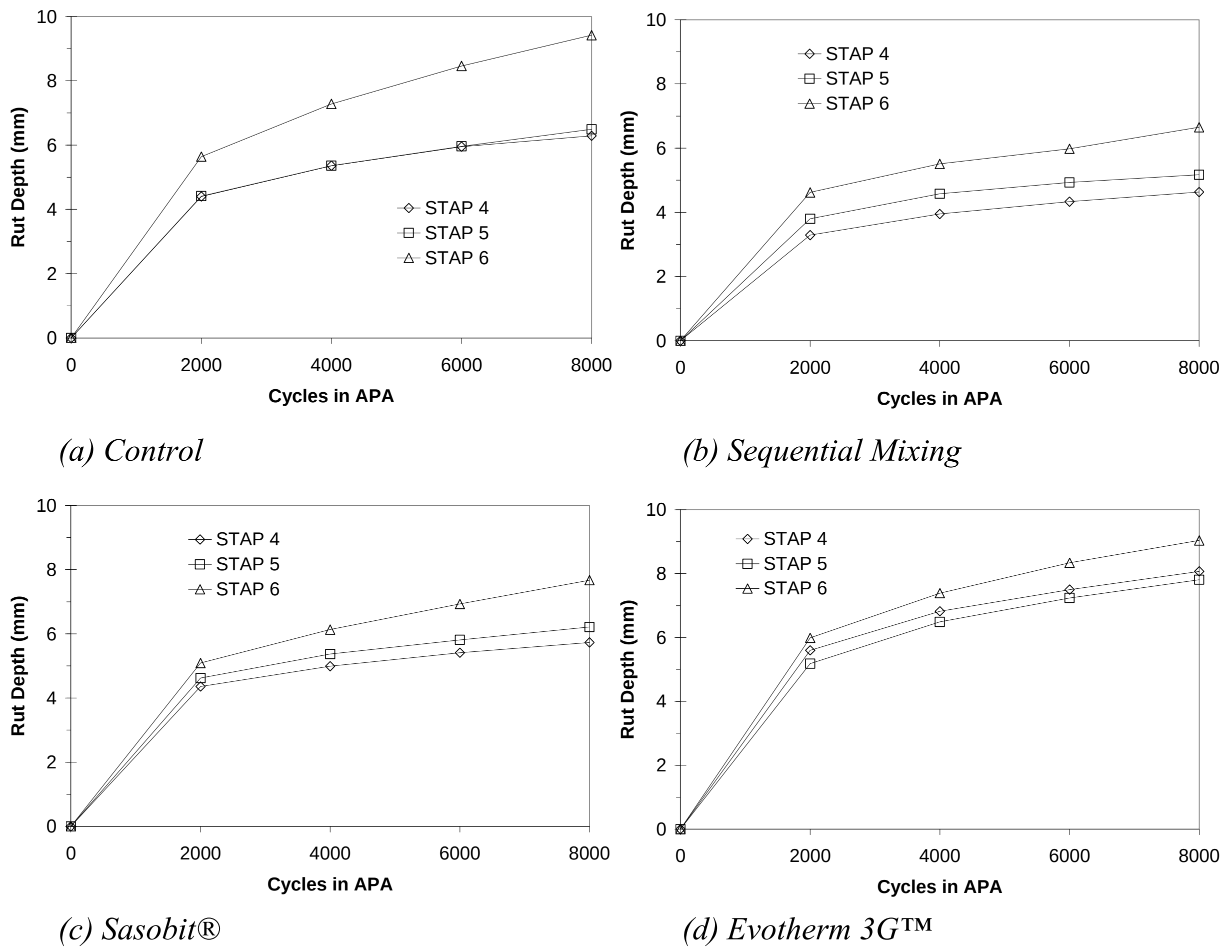


(c) Sasobit®



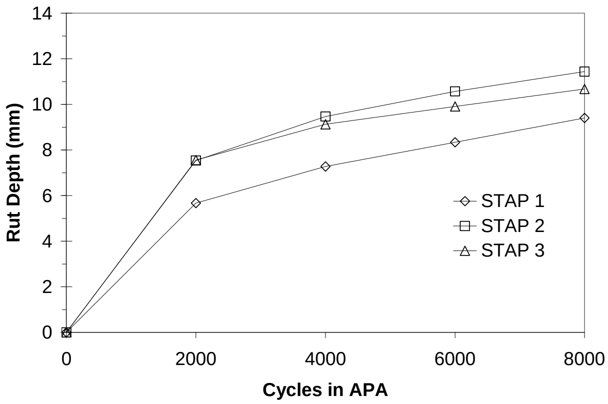
(d) Evotherm 3G™

Figure H-24. Rate of Rutting for Mixture 1 Compacted in SGC to 10% Voids

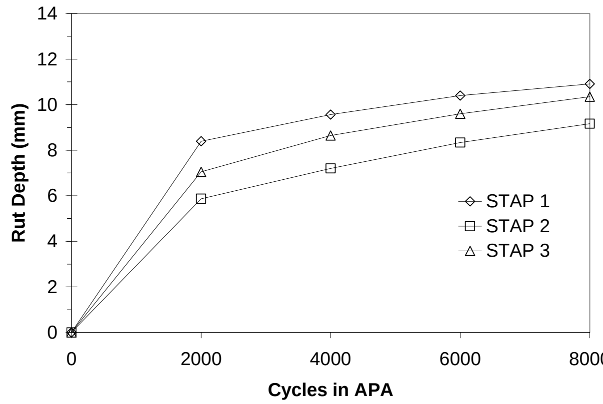


(a) Control *(b) Sequential Mixing* *(c) Sasobit®* *(d) Evotherm 3G™*

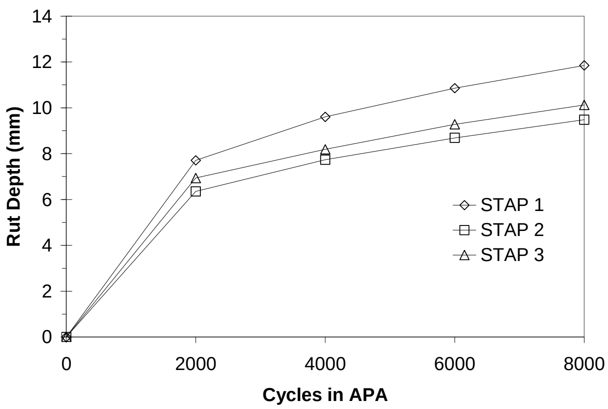
Figure H-25. Rate of Rutting for Mixture 2 Compacted in SGC to 10% Voids



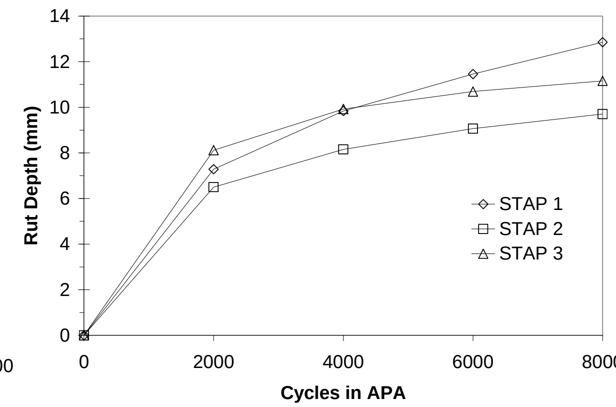
(a) Control



(b) Sequential Mixing

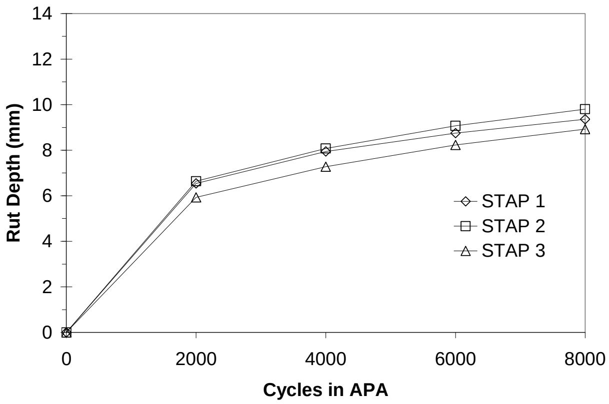


(c) Sasobit®

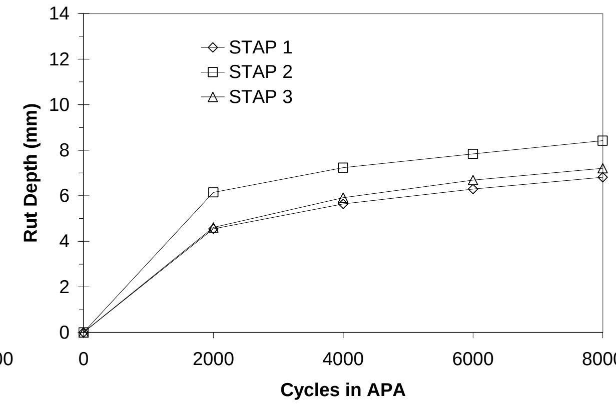


(d) Evotherm 3G™

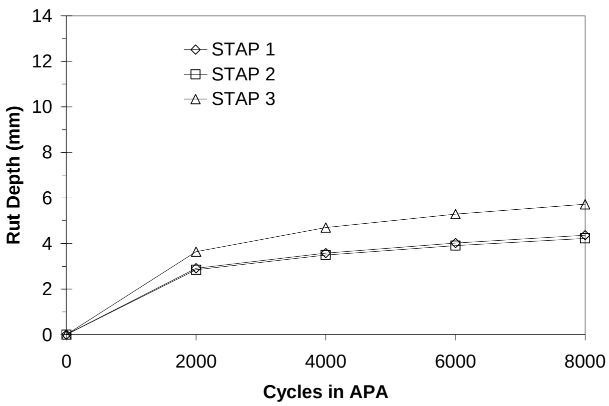
Figure H-26. Rate of Rutting for Mixture 1 Compacted Slab Sawn Specimens



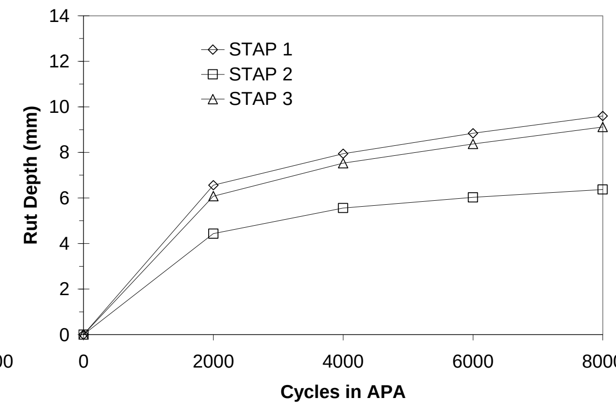
(a) Control



(b) Sequential Mixing



(c) Sasobit®



(d) Evotherm 3G™

Figure H-27. Rate of Rutting for Mixture 2 Compacted Slab Sawn Specimens

Table H-47. Rutting Rate per 1,000 APA Cycles from *SGC* Specimens at 7% Voids

			0 to 2,000 Cycles	2,000 to 8,000 Cycles	
			Rut Rate	**Rut Rate**	R^2
Mix	**Type**	**STAP**	**(mm)**	**(mm)**	**(---)**
1	Control	4	0.69	0.18	0.99
		5	0.72	0.27	0.97
		6	0.98	0.20	0.95
1	Sequential Mixing	4	1.39	0.18	0.90
		5	1.47	0.18	0.95
		6	1.77	0.22	0.97
1	Sasobit®	4	1.39	0.18	0.90
		5	1.22	0.30	0.99
		6	1.37	0.23	0.95
1	Evotherm 3G™	4	1.24	0.20	0.93
		5	0.56	0.23	0.99
		6	0.93	0.20	0.97
2	Control	4	1.23	0.15	0.93
		5	1.11	0.24	0.96
		6	1.41	0.19	0.95
2	Sequential Mixing	4	1.80	0.27	0.98
		5	1.77	0.28	0.95
		6	2.09	0.26	0.97
2	Sasobit®	4	1.68	0.26	0.94
		5	1.82	0.29	0.96
		6	2.13	0.28	0.98
2	Evotherm 3G™	4	1.66	0.23	0.95
		5	1.35	0.22	0.98
		6	1.53	0.19	0.95
All	***All***	***Avg***	***1.39***	***0.23***	
		St Dev	***0.42***	***0.04***	
		Cov	***30***	***19***	
		Range	***1.57***	***0.15***	

Table H-48. Rutting Rate per 1,000 APA Cycles from *SGC* Specimens at 10% Voids

			0 to 2,000 Cycles	2,000 to 8,000 Cycles	
			Rut Rate	**Rut Rate**	R^2
Mix	**Type**	**STAP**	**(mm)**	**(mm)**	**(---)**
1	Control	4	1.84	0.24	0.96
		5	1.79	0.35	0.96
		6	1.91	0.37	0.98
1	Sequential Mixing	4	1.75	0.25	0.95
		5	1.64	0.24	0.97
		6	1.85	0.28	0.94
1	Sasobit®	4	1.95	0.22	0.95
		5	1.84	0.23	0.96
		6	1.81	0.24	0.95
1	Evotherm 3G™	4	2.32	0.27	0.97
		5	2.00	0.33	0.98
		6	2.48	0.49	0.98
2	Control	4	2.20	0.31	0.95
		5	2.21	0.34	0.98
		6	2.82	0.63	0.99
2	Sequential Mixing	4	1.65	0.33	0.99
		5	1.90	0.22	0.97
		6	2.31	0.22	0.97
2	Sasobit®	4	2.18	0.23	0.98
		5	2.31	0.26	0.98
		6	2.55	0.43	0.99
2	Evotherm 3G™	4	2.80	0.41	0.97
		5	2.59	0.43	0.96
		6	3.00	0.51	0.98
All	***All***	***Avg***	***2.15***	***0.33***	
		St Dev	***0.39***	***0.11***	
		Cov	***18***	***33***	
		Range	***1.36***	***0.41***	

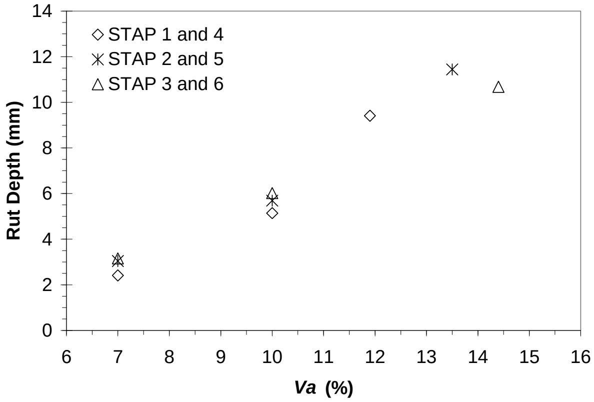
Table H-49. Rutting Rate per 1,000 APA Cycles from Slab Specimens

			0 to 2,000 Cycles	2,000 to 8,000 Cycles	
Mix	**Type**	**STAP**	**Rut Rate (mm)**	**Rut Rate (mm)**	**R^2 (---)**
1	Control	1	2.84	0.61	0.99
		2	3.16	0.55	0.97
		3	3.78	0.51	0.96
1	Sequential Mixing	1	4.20	0.42	0.97
		2	2.94	0.55	0.99
		3	3.53	0.54	0.97
1	Sasobit®	1	3.86	0.68	0.98
		2	3.47	0.52	0.98
		3	3.18	0.53	0.99
1	Evotherm 3G™	1	3.65	0.92	0.98
		2	3.25	0.53	0.95
		3	4.06	0.49	0.91
2	Control	1	3.27	0.46	0.96
		2	3.32	0.52	0.98
		3	2.97	0.50	0.98
2	Sequential Mixing	1	2.28	0.37	0.97
		2	3.08	0.37	0.97
		3	2.31	0.43	0.96
2	Sasobit®	1	1.46	0.24	0.98
		2	1.43	0.23	0.97
		3	1.82	0.34	0.96
2	Evotherm 3G™	1	3.28	0.50	0.98
		2	2.22	0.32	0.92
		3	3.04	0.50	0.97
All	***All***	***Avg***	***3.02***	***0.48***	
		St Dev	***0.75***	***0.14***	
		Cov	***25***	***29***	
		Range	***2.77***	***0.69***	

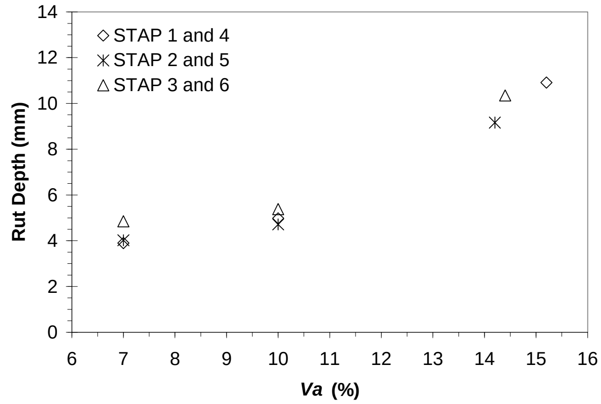
Correlation of Air Voids and Rut Depths

Figures H-28 and H-29 plot rut depth versus air voids by combining test data from slab and *SGC* compacted APA testing. The average rut depth and air voids from slab testing were used (i.e. data from Figure H-15 and Figure H-19). When separated by mixture, approach (i.e. control, sequential mixing, Sasobit®, and Evotherm 3G™), and aging protocol (*STAP*) the trend of rut depths increasing with air voids was, in general, observed.

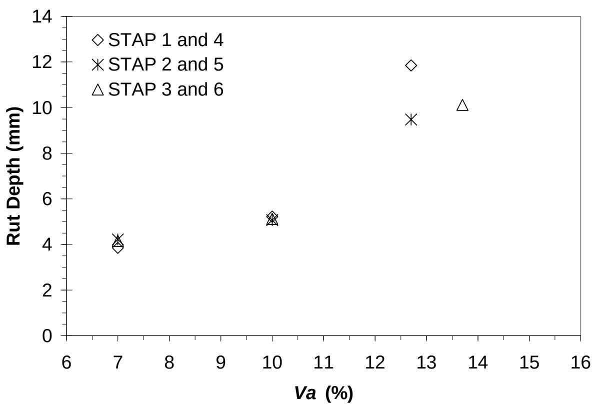
It has been well established that different compactors typically develop different aggregate structures that have different mechanical responses. Combining data from two compaction approaches should be understood to produce only an estimate of behavior. For this application, however, *SGC* specimens appeared to produce lower rutting than did slab compacted specimens when compacted to similar V_a levels, or when extrapolating the behavior of *SG*C specimens between 7 and 10 % voids to higher void levels. This would be expected based on the historical behavior of the *SGC* in that it is very robust and produces stiff mixtures. Combining slab data would therefore be expected to be as conservative, if not more conservative, than incorporating a third *SGC* compacted data point at elevated air voids.



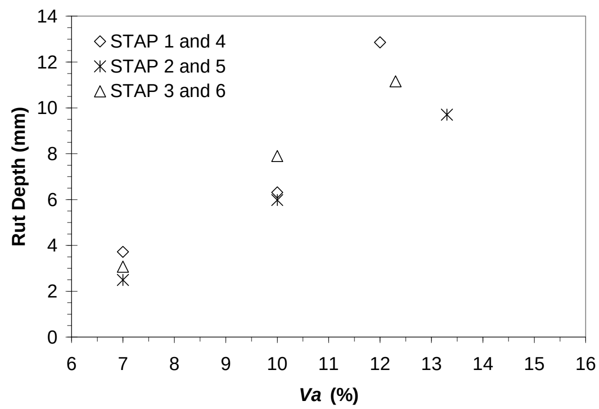
(a) Control



(b) Sequential Mixing



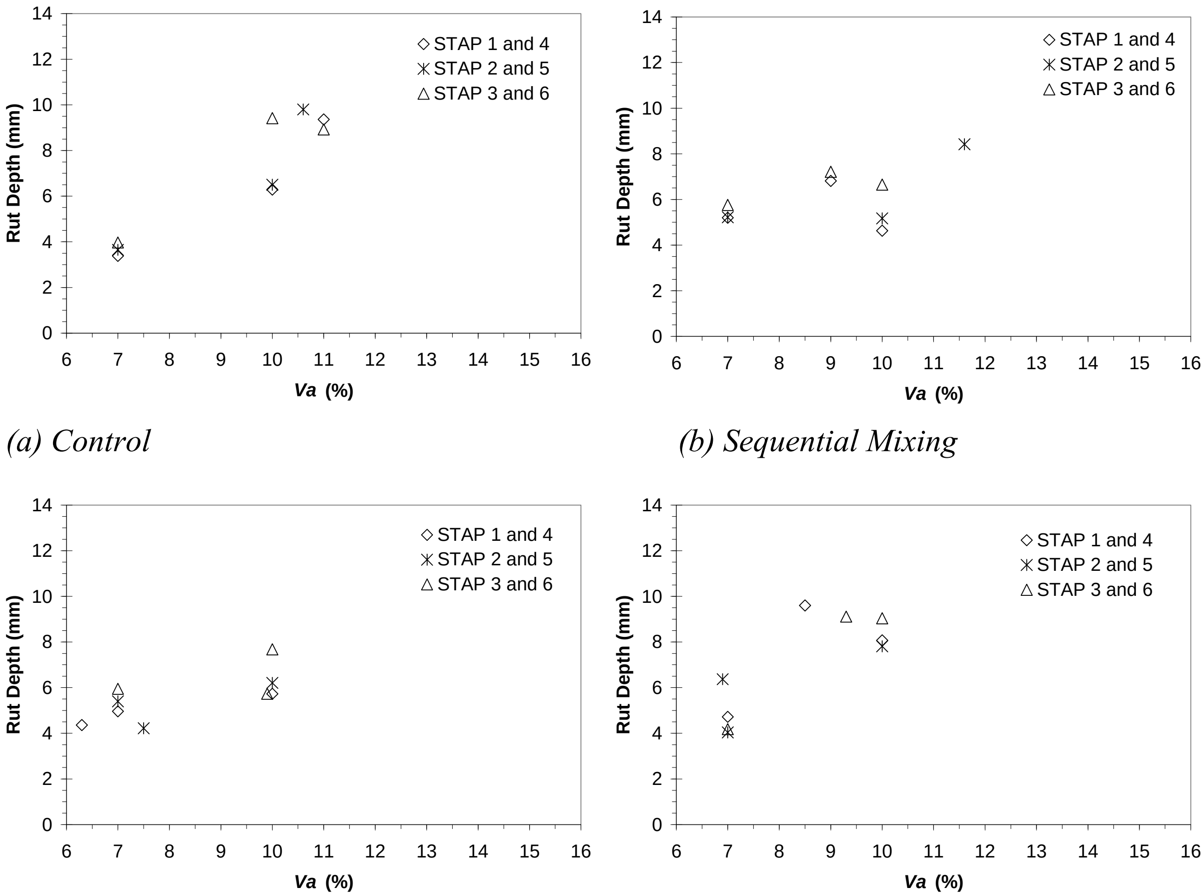
(c) Sasobit®



(d) Evotherm 3G™

Figure H-28. Correlation of Air Voids and Rut Depths for *Mixture 1*

Linear regression equations were developed for each of the 24 factor-level combinations shown in Figures H-28 and H-29 and are provided in Table H-50. Also provided in Table H-50 are the estimated air voids ($V_{a\text{-}est}$) where a given factor level combination would have 10 mm of rutting in the APA. Rutting of 10 mm was previously established as a reasonable to conservative lower end performance criterion for short term emergency asphalt mixtures to respond to a Gulf Coast hurricane. Estimates of air voids were only provided for factor level combinations where R^2 was 0.80 or greater.



(a) Control *(b) Sequential Mixing*

(c) Sasobit® *(d) Evotherm 3G™*

Figure H-29. Correlation of Air Voids and Rut Depths for *Mixture 2*

Visual comparison of the predictions in Table H-50 and measured data in Figures H-15 and H-19 agreed with each other in general terms, which should not be interpreted as anything more than a rudimentary check since the data in Figures H-15 and H-19 are part of the Table H-50 predictions. The primary purpose of the check was to provide some confidence in combining *SGC* and slab compacted data into a single prediction.

Data from *Mixture 2* was not able to predict a threshold air void level for 10 mm of rutting using the aforementioned approach but on six of the twelve factor level combinations, while *Mixture 1* was able to provide a prediction for all twelve of its factor-level combinations. The outer limits of V_a values for *Mixture 1* to provide acceptable performance was 11 to 16%, while the range was 10 to 23% for *Mixture 2*. The majority of the data indicates that compaction in the field to V_a values of 11 to 14% would provide acceptable performance. Typical construction would require compaction to V_a levels of 6 to 9%, indicating compaction requirements for emergency construction can be lessened substantially, which provides the approach investigated in this research a relatively high probability of success if implemented.

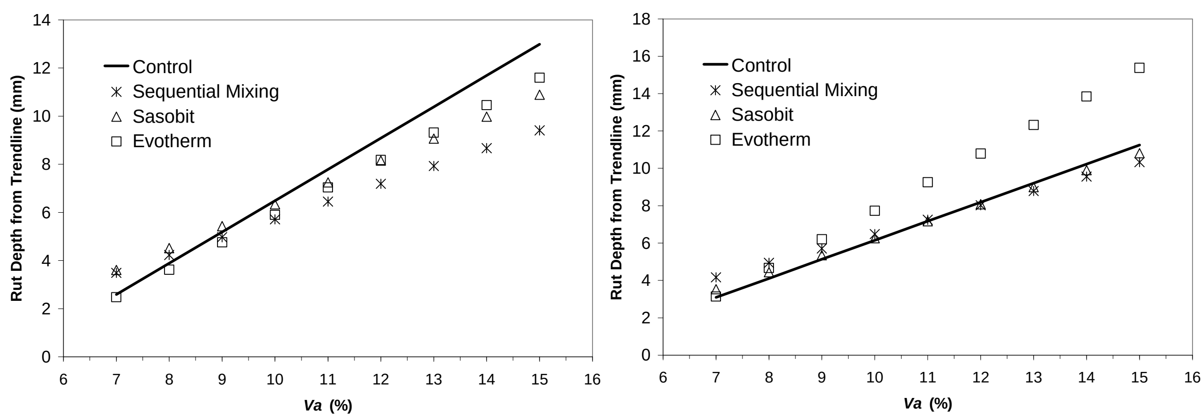
Figure H-30 plots the regression equations of Table H-50 for *STAP* 2 and 5 as well as *STAP* 3 and 6 for *Mixture 1*. Insufficient data was available to produce these plots for *Mixture 2*. As seen, the rut resistance for all approaches was superior to the control for *STAP*

2 and 5 if the specimens were compacted to the same air void level. For *STAP* 3 and 6, Evotherm 3G™ performed worse than the control for a given air void level, but this should be understood in the context of the following paragraph.

Table H-50. Linear Regression Predictions of Air Voids at 10 mm Rut

Mixture (---)	Type (---)	*STAP* (---)	Slope (*m*)	Intercept (*b*)	R^2 (---)	V_{a-est} (%)[1]
1	Control	1 and 4	1.38	-7.66	0.94	12.8
		2 and 5	1.30	-6.51	0.97	12.7
		3 and 6	1.02	-4.05	0.99	13.8
	Sequential Mixing	1 and 4	0.89	-2.92	0.95	14.5
		2 and 5	0.74	-1.69	0.91	15.8
		3 and 6	0.77	-1.22	0.90	14.6
	Sasobit®	1 and 4	1.39	-6.75	0.85	12.1
		2 and 5	0.91	-2.76	0.85	14.0
		3 and 6	0.91	-2.84	0.91	14.1
	Evotherm 3G™	1 and 4	1.75	-9.30	0.88	11.0
		2 and 5	1.14	-5.50	0.99	13.6
		3 and 6	1.53	-7.57	0.99	11.5
2	Control	1 and 4	1.37	-6.48	0.91	12.0
		2 and 5	1.46	-6.82	0.84	11.5
		3 and 6	1.37	-5.36	0.90	11.2
	Sequential Mixing	1 and 4	-0.05	5.96	0.00	---
		2 and 5	0.60	0.51	0.57	---
		3 and 6	0.36	3.44	0.56	---
	Sasobit®	1 and 4	0.34	2.40	0.93	22.4
		2 and 5	0.44	1.69	0.50	---
		3 and 6	0.27	4.01	0.19	---
	Evotherm 3G™	1 and 4	1.12	-2.03	0.45	---
		2 and 5	0.83	-0.58	0.60	---
		3 and 6	1.75	-7.90	0.94	10.2

1: V_{a-est} calculated by solving: Rut Depth = $m(V_{a-est})+b$ =10 mm



(a) STAP 2 and 5 *(b) STAP 3 and 6*

Figure H-30. Comparison of Regression Equation Predicted Rut Depths of Mixture 1

One should be mindful that for a given mixture the same compactive effort was applied to the slabs, so a direct assessment of rut depth versus air voids correlation should also consider the ease to which a given level of air voids can be achieved and not compare mixes solely on their air void versus rut depth trends. For example a mixture that cannot be compacted to lower air voids should not be penalized in the assessment for this application if it exhibits adequate rut resistance for the same compactive effort as another mixture. The data presented in Figure H-30 is one assessment tool for the approach, but should not be used as the only assessment tool.

Summary Conclusions and Recommendations

The conclusions and recommendations provided in this appendix should not be extended beyond the constraints provided without additional examination. The approaches suggested in this appendix are only valuable in areas without sufficient power and/or asphalt plant infrastructure. The purpose of the hot mixed warm compacted asphalt is a quick deployment temporary paving material with an estimated 30 to 45 day service life. The focus of the work presented in this appendix was compaction and short term performance in a warm and possibly wet environment. A total of 24 factor-level combinations were tested: 2 aggregate gradations (limestone and gravel); four types of mixture (control, sequential mixing, Sasobit®, and Evotherm 3G™); and 3 short term aging protocols each for slab and *SGC* prepared specimens.

Limited data was found in literature related to the topic though what was found did not refute the concept investigated in this appendix. *SGC* specimens were evaluated for a quick opening to traffic and were thus never cooled below the test temperature. Little data exists for this condition. Test results indicated traffic could be placed on the mixture very shortly after compaction (e.g. 30 min).

Field procedures for using the approaches developed would be straight forward to experienced asphalt paving groups. A trial run of material should immediately be sent to the site (a moderate number of truck loads of material) to investigate if the material will work in conjunction with site specific conditions, equipment, and personnel. The haul time and on ground temperature should be carefully noted during the trial run (first day). Once compacted, cores should be sawn for immediate measurement of bulk density and subsequent measurement of air voids. Nuclear density gages could also be used if available. Provided performance is acceptable, significant amounts of the mixture can be delivered beginning on the second day of the response. At the asphalt plant, Sasobit® is provided in pellets that can be introduced into the mixture relatively easily, and Evotherm 3G™ can be pre-mixed into the asphalt binder.

Mixtures rutted on the order of six times faster during early portions of the test as they did in later portions of the test. If these mixtures are used in service a rut will almost certainly appear relatively quickly. Traffic can continue on these mixtures as the rate of rutting is expected to drastically decrease after a fair amount of densification has taken place. This is evidenced by the rutting rate analysis performed in this appendix.

Incorporation of warm mix additives was, in general, preferred for the application. Air voids (V_a) were lower at longer aging (i.e. cooler temperatures) in mixtures with warm mix additives than in the control mixtures. S_t and *TSR* values with warm mix additives were, in general, higher than the control for the gravel aggregate (*Mixture 2*). The reverse was true for the limestone aggregate (*Mixture 2*), where S_t and *TSR* values with warm mix additives were, in general, lower than the control. Both warm mix additives had smaller rut depth increases and exhibited little difference in *SGC* specimens relative to control mixtures. Relative behaviors at elevated air voids did not necessarily follow trends at lower air voids indicating that historical behaviors for permanent applications do not necessarily translate to temporary applications.

A ranking system was initially considered to evaluate mixtures, but did not materialize after the performance of the mixes was at a level where conceivably any of the approaches could be used in short term emergency construction. Evotherm 3G™ was by comparison easy to compact but rutted more for *Mixture 1*; insufficient data was obtained to make any assessment for *Mixture 2*. Overall Evotherm 3G™ was the worst performer in terms of rut depth but was still acceptable. Sasobit® was easier to compact at warm compaction temperatures relative to control mixtures and had comparable to superior rut resistance.

The objective of the work conducted in this appendix was successful in that the concept of very long haul distances was shown to be feasible. Quantifiable on site performance data was beyond the scope of the laboratory study. The overall conclusion of the research is that the concept of hot mixed warm compacted asphalt is viable for emergency conditions. The technology appears ready for implementation, but should be demonstrated at full scale prior to deployment.

Field conditions for adequate performance with the materials tested are on ground mix temperatures in excess of 105 C and compaction of 11 to 14% air voids. Mixture specific void and temperature levels could also be estimated based on the information in this appendix. The key is that compaction requirements in an emergency could be lessened as evidenced by the data in this appendix, which greatly increases the probability of success of the concept of hot mixed warm laid asphalt for emergency use.

Two key issues remain in terms of the practicality and feasibility of the research: 1) can the mixture of interest be delivered to the location of interest at a temperature at or in excess of 105 C; and 2) can the mixture delivered be compacted to 11 to 14% air voids? If the answer to these questions are both yes and the mixtures tested in this research are representative of the materials available the techniques in this research are recommended for emergency construction for short term use in a warm and wet environment.

It is recommended to instrument trucks of fully heated asphalt in the presence of different air temperatures to establish cooling rates and haul distances for the material. The material should be compacted at the conclusion of the cooling rate experiments at a test section that subsequently is trafficked with fully loaded trucks at elevated air temperatures (e.g. above 30 C) to establish the life of the material. Instrumentation should be used during testing alongside specimens sawn from the test section to provide a qualitative assessment of performance at full scale conditions. A test of this nature would fully establish feasibility of the emergency construction material investigated in this appendix. The key questions to be answered are: 1) how long can a mix be hauled; and 2) once it arrives can it be compacted in a manner that will perform acceptably in a temporary disaster environment?

The material placed for emergency use has notable residual value. A permanent pavement will most likely be constructed at the location of the temporary pavement and emergency material could effectively be incorporated into the design of the permanent pavement in the form of a high reclaimed asphalt pavement (RAP) mix design, hot in place recycling (HIPR), or in a full depth reclamation (FDR). The residual value of mixtures placed in this environment should be studied. A logical approach would be to fabricate slab specimens that simulate emergency use, age them to simulate 30 to 45 days of service, and use the materials in new laboratory mix designs to investigate the properties that can be obtained for permanent paving.

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