DEVELOPMENT OF A MIX DESIGN PROCESS FOR COLD-IN-PLACE REHABILITATION USING FOAMED ASPHALT

Final Report
for
TR-474 Phase I

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1. EVALUATION OF CURRENT PRACTICE OF CIR WITH EMULSION

The need to provide a safe, efficient, and cost-effective roadway system has led to a significant increase in the demand for ways to rehabilitate existing pavement. In the last several decades, asphalt recycling has grown to become the preferred method for restoring existing pavements. This study evaluates one of the recycling techniques used to rehabilitate pavement, called Cold In-Place Recycling (CIR).

CIR is a recycling process that evolved during the late 1980s. It is one of the fastest growing road rehabilitation techniques because it is quick and cost-effective. Currently the process requires a curing period of about two days to one week before a thin surface of new hot mix asphalt can be applied on top of the recycled pavement. The CIR process continues to evolve, however, and the need for a CIR mixture with specific engineering properties calls for the use of a mix design. The engineered CIR mixture will allow the pavement designer to take the mixture properties into account when determining the necessary overlay thickness. It is generally recommended that before hot asphalt is applied, the CIR "free moisture" content must be between 0.3% and 1.5%. Typical asphalt emulsion, cement, or lime contents range from 1-3% by weight of the reclaimed asphalt pavement (RAP). There is currently no nationally accepted method for CIR design (ARRA, 2001).

Most agencies have their own mix design procedure that determines the amount of emulsion based on a mix design using recycled material sampled from the roadway. Based on a survey of 24 states (out of a total of 46 respondents), Lee et al. (2002) reported that 11 states use the Marshall mix design, three use Hveem, four use a gyratory compactor, seven use "other" processes, and four states use none at all. Reihe and Apilo (1995), for example, developed a design method in Finland suitable for softer emulsion with a viscosity of 1000 to 3000 mm^2/sec at 60 ˚C (140 ˚F). Khosla and Bienvenu (1996) developed a cold mix design process that uses CMS and HFRA emulsions as recycling agents. AASHTO-AGC-ARTBA Joint Committee Task Force 38 (1998) published a design procedure for both Marshall and Hveem equipment, which was adopted or modified by many state agencies. To improve on this modified Marshall, Lee et al. (2002) developed a new volumetric design for CIR utilizing the SuperPave gyratory compactor. However, the design variability associated with five different types of emulsion (HFMS-2T, CSS-1h, HF150P, Cyclogen ME, and HFE150-P) was not addressed.

A recent survey by the Rocky Mountain User Producer Group of 38 states reported some consistency problems due to the lack of standard design and testing methods, which had resulted in raveling, minor segregation, isolated rutting, extended curing time, compaction problems, thermal cracking, and disintegration under traffic (RMAUPG 1999). Based on an extensive literature review, current practices of CIR with emulsion are summarized below.

1.1 Emulsion type

Cationic slow-setting (CSS) emulsion typically contains about 65% asphalt and 35% water—although a few emulsions can be up to 75% asphalt. Salomon and Newcomb (2000) evaluated three emulsions, CSS-1 (cationic slow-setting emulsion), HFMS-2s (high-float medium-setting emulsion with a residue of relatively low viscosity), and HFMS-2p (high-float medium-setting emulsion modified with a polymer). They found that the HFMS-2p emulsion gave the lowest overall air voids, and recommended that the Minnesota DOT use it until more precise PG binder information could be collected on the aged asphalt from RAP.

Lee et al. (2002) reported that most states use high-float type emulsion; a few exceptions prefer slow- or medium-setting cationic emulsions. Several states include lime, fly ash and Portland cement as an additive. Before 1988, the Oregon DOT used CMS-2s (now called CMS-2RA). Since 1988, they have employed HFE-150. The province of Ontario, Canada also uses HFE-150 (Murphy and Emery, 1996). The Pennsylvania DOT uses CMS-2 emulsion with an asphalt residue of 100 to 120 penetration. When the penetration of the recovered asphalt is in the range of 15–20, CSS-1h emulsion with an asphalt residue of 40–90 penetration is used to achieve softer recovered asphalt (Epps, 1990). To address the problem of rutting, reflective cracking and moisture damage, the New Mexico DOT has elected to use high-float polymer-modified emulsion instead of SS-1 and CMS-2S (McKeen et al., 1997). The Asphalt Institute (AI) recommends uising the heaviest asphalt that can be worked, while advocating the use of low-viscosity asphalt for fine aggregates and high-viscosity asphalt for coarse aggregates (TAI 1979).

1.2 Emulsion and water content

Lee et al. (2002) indicated that in the U.S., the different specifications for how much water and emulsion should be use are too numerous to summarize. They applied their new volumetric design to the RAP materials and asphalt emulsions supplied by five states and reported that optimum emulsion contents varied from 1.1% to 2.6% (with optimum water contents ranging from 1.8% to 2.9%). In general, most states define emulsion and water contents as a total liquid content and determine the optimum liquid level using density curves. The Oregon DOT uses an empirical procedure for estimating an initial asphalt emulsion content of 1.2%, which is then adjusted based on gradation, residual asphalt content, and penetration (or viscosity) of the recovered asphalt (Rogge et al., 1990; 1992).

Hveem stability and resilient modulus at 25˚C (77 ˚F) were used to establish the optimum emulsion content. None of the mix property tests, however, accurately predicted the same emulsion content as their estimated emulsion content formula.

The California DOT (Epps 1990) determines the total bitumen requirement using an aggregate surface area formula and then subtracts the residual asphalt content from the total to arrive at the needed amount of recycling agent. Optimum emulsion content is determined based on requirements of a minimum 4% air voids and 30 Hveem stability at 60˚C (140 ˚F). Chevron (1982) recommended a minimum of 2% emulsion and an optimum emulsion content based on resilient modulus ranging from 150 to 600 ksi at 23˚C (73 ˚F), a minimum Hveem stability of 30, and a cohesion meter value of 100 at 60˚C (140 ˚F). The Pennsylvania DOT specified a constant emulsion of 2.5% with varying water content (Kandhal and Koehler, 1987). Ontario suggested that emulsion contents should test in the range of 0.5% to 2.5%, with a total liquid content of 4.5% (Murphy and Emery, 1996). Salomon and Newcomb (2002) concluded that the emulsion content should not exceed 3%.

1.3 RAP gradation

A statistical analysis conducted by Castedo (1987) revealed significant variation in the asphalt content, aggregate gradation, and asphalt penetration within a single section of road in Indiana. The survey conducted by Lee et al. (2002) found that maximum RAP size could range from 19 to 75 mm (0.75 to 3 inches), although 31.75 mm (1.25 inch) is most common. Four states did not specify a maximum RAP size. However, 24 of 25 states performed one or more of the following tests on RAP: RAP gradation, extracted gradation, extracted asphalt content, viscosity, or penetration.

1.4 Compaction

Salomon and Newcomb (2000) recommended that CIR mixtures be compacted with gyratory compactors that produce consistent air voids. They reported that density became constant after about 60 gyrations. At 10 gyrations, relative densities were in the range of 85 to 90% of the maximum density, and at 60 gyrations, they were between 90 and 95% of maximum density. To achieve a desired density of 130 pcf for a laboratory test specimen, Lee et al. (2003) recommended 37 gyrations. Thomas and Kadrmas (2003) suggested 30 gyrations.

1.5 Curing condition after compaction

There is considerable variation in the curing temperature and time adopted for mix design processes (Lee et al., 2002). Most states use a curing temperature of either 60˚C (140˚F) or room temperature (25˚C), and curing times that ranging from two hours to three days. Lee et al. (2003) recommend curing times of six hours and 24 hours to simulate short-term and long-term curing in the field at 60˚C (140 ˚F), a typical hot summer day's pavement temperature, and at 25˚C (77˚F), a typical summer night's pavement temperature.

1.6 Additives

Issa et al. (2001) conducted a study to examine the behavior of RAP when rejuvenated with high-float emulsion and Portland cement to produce a cement-emulsion mix. They reported that 2% emulsion produced the highest gain in soaked stability because of the addition of the cement. Some emulsion CIR projects exhibit rutting and asphalt stripping problems. As a result, the Kansas DOT specified Class C fly ash as the only approved recycling additive for CIR (Thomas, Huffman and Kadrmas, 2000). It was observed, however, that the fly ash section had nearly twice the amount of cracking as a section emulsified with lime slurry. Wu (1999) reported that pavement sections with the fly-ash-stabilized RAP base showed very uniform distribution of shear strains within pavement layers, and had the smallest rut depths among all sections studied in Kansas. Valkonen and Nieminen (1995) found that a small amount of Portland cement—but not lime or gypsum—improved early strength and water resistance.

1.7 Performance

One cold recycled mixture was used as a surface layer in Israel, and when subjected to low-volume traffic for one year performed well without any kind of distortion (Cohen et al. 1989). In another study, Castedo (1987) concluded that a stable and sound pavement could generally be obtained using cold-mix recycling techniques. Mamlouk and Ayoub (1983) evaluated the long-term behavior of an artificially aged cold recycled asphalt mixture (cured at 60˚C [140˚F] for up to 60 days) using both creep and Marshall stability and flow tests at 24˚C (75˚F). There was no large difference in the creep behavior of the virgin and recycled mixtures, and they concluded that the emulsified asphalt did not have a long-term softening effect on the old asphalt binder. To improve the field performance of CIR, Thomas and Kadrmas (2003) proposed performance-related tests and specifications for CIR including a raveling test, an indirect tensile test at a low temperature for thermal cracking, and Marshall testing of gyratory compacted specimens.

2. LITERATURE REVIEW FOR RESEARCH ON FOAMED ASPHALT

Csanyi (1960) developed the original foaming process in which steam was injected into hot asphalt through a specially designed nozzle so that asphalt was ejected as foam. Due to the awkwardness of this process, the comparatively low cost of asphalt and energy, and the availability of quality aggregates, it was not widely implemented until 1968. At that time, Mobil Oil Australia modified the original process by adding cold water rather than steam to allow for practical foaming operations in the field. A controlled flow of cold water was introduced into a hot asphalt stream, passed through a suitable mixing chamber, and then delivered through a nozzle as asphalt foam. Advancements since then have included improved foaming nozzles, the development of admixtures for better foaming, and more installations of field projects.

Despite such progress, the use of foamed asphalt has been limited because of the lack of a standardized mix design procedure. Foamed asphalt technology is popular in and has been used successfully throughout Europe and South Africa. Its acceptance in these countries is due to reasons of economy, scarcity of paving materials, and the environmental friendliness of the process, which causes little evaporation of volatile, runoff and leaching from mixtures. In the 1980s, several full depth reclamation projects (FDR-Foam) were conducted using foamed asphalt in Colorado and Wyoming. A demonstration project was constructed in 1998 in Jefferson County, Wisconsin, using a new European process. Foamed asphalt was also used as a stabilizing agent in 2002 in FDR on Route 8 in Belgrade, Maine (Brian et al. 2003). Cold In-place Recycling (CIR-Foam) projects constructed using foamed asphalt as a stabilizing agent have been limited. Both US-61 (2000) and IA-78 (2001) were rehabilitated using the CIR-Foam technique in Iowa. In 2002, one section of highway US-20, at the east end of highway 187 in Buchanan County, Iowa, was recycled using two different stabilizing agents in CIR: engineered emulsion ReFlex® and foamed asphalt.

Over the years, numerous studies have sought to evaluate and improve the foamed asphalt mixture design procedures for full depth reclamation (FDR-Foam). Bowering (1970, 1976), Acott (1979), Rucket et al. (1980), and Lee (1981) all studied foamed asphalt mixtures using virgin materials. Foamed asphalt is now beginning to be implemented into the FDR process of old asphalt pavement. Van Wijk and Wood (1982), Van Wijk et al. (1983), Brennen et al. (1983), Tia and Wood (1984), Engelbrecht (1985) and Akeroyd (1988) have all researched the design procedure and the performance of FDR using foamed asphalt mixtures (FDR-Foam). Maccarrone et al. (1994) introduced a new "FOAMSTAB" process with several advantages, such as a superior fatigue property, less sensitivity to extreme weather and rapid curing.

Recently, advancements in foaming methods and equipment have allowed CIR-Foam to be tried in the field. The optimum design procedure for CIR-Foam, however, has not been developed. The Association Mondiale de la Route (AIPCR) and World Road Association (PIARC) published a draft report in 2002 on the CIR of pavements using emulsion or foamed bitumen. This report was not intended as a specification, however, but only to provide information about the approaches used in different countries. In the following sections, research efforts on foamed asphalt are summarized for eight different design factors.

2.1 Foaming water content and temperature

A higher foaming temperature results in a higher expansion ratio and lower half-life. High water content has an effect similar to temperature but different in degree. Brennen et al. (1983) suggested foaming conditions at 160˚C (325˚F) with a water content of 2% for optimum expansion ratio and half-life. Maccarrone et al (1994) showed that a mix of 2.6% water and 0.7% additives was best for achieving the optimum expansion ratio and half-life. Ruckel et al. (1980; 1982) recommended limiting the expansion ratio to 8-15 and allowing at least 20 seconds for the half-life to obtain the optimum foaming water content. CSIR Transportek (1999) recommended lower limits of 10 for the expansion ratio and 12 seconds for the half-life. Nataatmadja (2001) concluded that the foaming water content should generally be in the range of 2.0% to 2.5%. Somewhat outside of this range, Mohammad et al. (2003) established an optimum water content of 2.75% (for PG 58-28 binder) at 160˚C. Marquis et al. (2003) used an even higher optimum water content of 3% (for PG 64-28), which achieved an expansion ratio of 11 and half-life of 8.5 seconds at 160˚C.

2.2 Effects of compaction methods

Brennen et al. (1983) studied the effects of compaction methods on stability values. When twenty gyrations under a pressure of 200 psi were compared to 75 blows of the Marshall hammer, it was found that the stability values of the gyratory compacted specimens were two to three times higher than those of the Marshall hammer compacted specimens. Even seventy-five blows of the Marshall hammer did not provide sufficient compaction to simulate initial compaction after construction. Despite its higher density, the gyratory compacted specimens exhibited lower resilient modulus values than those compacted by Marshall hammer, possibly due to changes in particle rearrangement (Nataatmadja 2001).

2.3 Foamed asphalt content

Brennen et al. (1983) recommended that the optimum foamed asphalt content for FDR projects should be between 0.5% and 1% to achieve the maximum stability value. AC-20 (42 penetrations) and AP-4 (69 penetrations) showed the highest expansion ratio and longest half-life, with 2% water foaming at 160˚C (325˚F). Others also found optimum contents of foamed asphalt ranging from 0.5% to 1% (Castedo and Wood, 1983; Tia and Wood, 1983; Roberts et al., 1984). Akeroyd and Hicks (1988) proposed the use of a proportional binder-fines relationship to select the binder content, which ranged from 3.5% binder for 5% fines content up to 5% binder for 20% fines content. Nataatmadja (2001) concluded that the optimum foamed asphalt content is generally on the order of 3% to 4%. Mohammad et al. (2003) recommended a 2% foamed asphalt content with 1.5% Portland cement, which achieved a maximum retained indirect tensile strength of 108%. For aggregates composed of 60% RAP, 25% crusher dust and 15% gravel base course, the optimum foamed asphalt content was determined to be 2.5% in the presence of 1.5% Portland cement (Marquis et al., 2003). Roberts et al. (1984) reported an optimum foamed asphalt content that was lower than the optimum amount of cutback or emulsion. However, Tia and Wood (1983) found that slightly more asphalt content was needed for foamed asphalt mixtures compared with the optimum amount of emulsion.

Ruckel et al. (1982) suggested the following table as a guide for selecting the appropriate foamed asphalt binder content as a function of the amount of coarse and fine aggregates in an FDR-foam project. As can be seen from Table 2-1, the finer the aggregates the more foamed asphalt content was recommended.

Table 2-1. Foamed asphalt content (Ruckel et al., 1982)

Percent passing No.4 sieve	Percent passing No.200 sieve	Foamed asphalt content (%)
< 50 (gravels)	3 ~ 5	3
	5 ~ 7.5	3.5
	7.5 ~ 10	4
	> 10	4.5
> 50 (sands)	3 ~ 5	3.5
	5 ~ 7.5	4
	7.5 ~ 10	4.5
	> 10	5

2.4 RAP gradation

Foamed asphalt mixtures need a critical amount of fines to achieve high strengths (Maccarrone, 1994; Sakr and Manke, 1985; Bissada, 1987; Bowering and Martin, 1976). Maccarrone (1994) recommended a minimum of 8 % fines. Ruckle et al. (1983) advised that the fines content should be above 5%. Sakr and Manke (1985) showed that the stability of foamed asphalt mixtures is more affected by aggregate interlock than by the viscosity of the binder. As a result, foamed asphalt mixtures may not be as susceptible to temperature as hot-mix asphalt mixtures.

2.5 Moisture content

Lee (1981) found the optimum mixing moisture content to be in the range of 65% to 85% of the modified AASHTO optimum moisture content (OMC) for aggregates. This range was later confirmed by Bissada (1987). Castedo and Wood (1983) concluded that the best compactive moisture condition occurs when the total fluid content (moisture + asphalt) is approximately equal to the OMC. CSIR Transportek (1999) recommended that the moisture content for mixing and compaction be set at OMC minus asphalt content for Marshall compaction. In 1984, Roberts et al. found that high tensile strength could be achieved at a total fluid content of 1.5%. Van Wijk and Wood (1983), on the other hand, established an optimum compaction moisture content of 2.4% based on the Marshall stability value.
Sakr and Manke (1985) developed the following relationship (Eq. 1) to determine the moisture content for maximum density of foamed asphalt mixes (*MMC*) as a function of the modified AASHTO OMC (*OMC*), percentage of fines (*PF*) of the aggregate and the bitumen content (*BC*).

$$MMC = 8.92 + 1.48OMC + 0.4PF - 0.39BC \qquad (1)$$

Brennen et al. (1983) reported that the effect of water decreased as the amount of foamed asphalt increased. Following the AASHTO T 180 modified proctor, Mohammad et al. (2003) determined the OMC of RAP to be 8%.

2.6 Curing Condition after Compaction

Previous researchers have tended to adopt the laboratory curing procedure proposed by Bowering (1970)—i.e., three days oven curing at 60˚C. CSIR Transportek (1999) recommended the same procedure. In 1998, Lewis suggested drying the foamed asphalt in the oven at only 40˚C. Ruckle et al. (1988) had previously recommended a temperature of 40˚C for one-day intermediate and three-day long-term curing. Castedo and Wood (1983) reported that foamed asphalt strengths increased with curing time, particularly from one to three days. In studying the effects of curing environments on tensile strength, Roberts et al. (1984) and found that the strength of dry-cured specimens is about two times higher than that of wet-cured specimens.

2.7 Strength and layer coefficients

Tia and Wood (1983) determined that the layer coefficients of CIR-foam range from 0.25 to 0.40. Looking at field data, Wijk et al. (1983) found a wide range of layer coefficients, from 0.05 to 0.44 for foamed asphalt layers, depending on the curing time. Similar ranges—from 0.20 to 0.42—of layer coefficients for both foamed and emulsified asphalt sections were also observed by Wijk (1984). Roberts et al. (1984) reported that using foamed asphalt (AC-5) produced strength values equal to or higher than those of cutback (MC-800) or two emulsions (EA-11M and AES-300).

2.8 Performance

In their 1984 study, Van Wijk et al. found that the strength of foamed-asphalt sections increased more rapidly than that of emulsion sections during the first 250 days. Differences, however, were small. They also indicated that while water-sensitivity durability was low, it could be improved by adding 1-2% lime. Based on artificially aged paving mixtures, Tia and Wood (1983) found, that foamed asphalt and emulsion recycling mixtures exhibited equivalent strengths. Castedo and Wood (1983) discovered that foamed asphalt mixture was significantly affected by water infiltration, such that saturated strengths were much lower than corresponding cured strengths. Specimens fabricated at the highest bitumen content showed a greater resistance to water. Mohammad et al. (2003) reported that foamed-asphalt-treated RAP materials, including 1.5% Portland cement, showed higher in-situ stiffness values than those of a limestone base layer, which had been measured at the construction stage.

3. FOAMING EXPERIMENT

3.1. Introduction

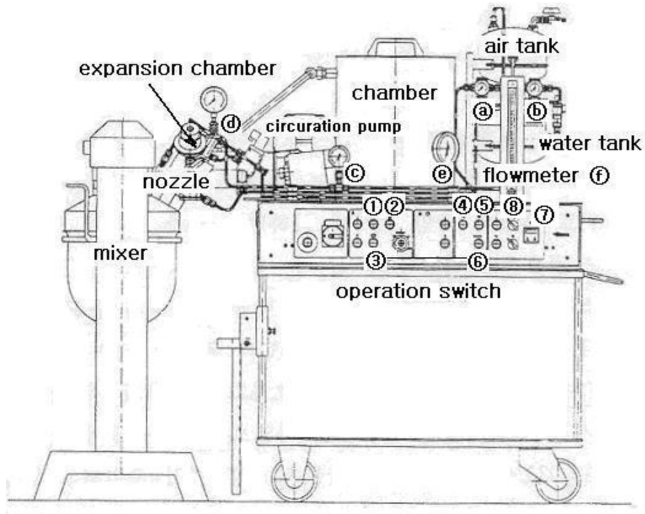
This foaming experiment sought to evaluate the accuracy of the Wirtgen laboratory foaming equipment. The performance of the Wirtgen equipment was evaluated with respect to water discharge rate, pressure gauges, and foamed asphalt discharge rate.

3.2 Operation of Laboratory Foaming Equipment

Figure 3-1 presents a picture of the Wirtgen laboratory foaming equipment; its schematic diagram appears below in Figure 3-2.

Figure 3-1. Wirtgen foaming equipment

As may be seen in Figure 3-2, the foaming equipment has four valves and one timer: water release valve ④, air release valve ⑤, asphalt release valve ⑥, discharge duration timer ⑦, and automatic release valve ⑧. To set air pressure to a desired level, the operator first adjusts the air manometer (a) while pushing the air pressure valve ⑤. To then set water flow rate to a desired level, the operator adjusts flowmeter ⓐ while pushing both air and water pressure valves (④ and ⑤). Given the fixed discharge rate of 100 g per second and the foamed asphalt demand for the mix design, discharge duration of foamed asphalt is then set using the discharge duration timer ⑦. Finally, the operator pushes the automatic release button ⑧ (shown in Figure 3-3) to inject asphalt into the expansion chamber through a 2.5 mm nozzle, while cold water is supplied under air pressure. Foamed asphalt is then immediately released into the mixer through the 6 mm nozzle.



a Air manometer

b Water manometer

c Water pressure gauge during foaming operation

d Asphalt pressure gauge during foaming operation

e Asphalt thermometer

f Flow meter

1 Nozzle sensor

2 Pump sensor

3 Temperature sensor

4 Water release valve

5 Air release valve

6 Asphalt release valve

7 Discharge duration timer

8 Automatic release valve

Figure 3-2. Schematic of foaming equipment

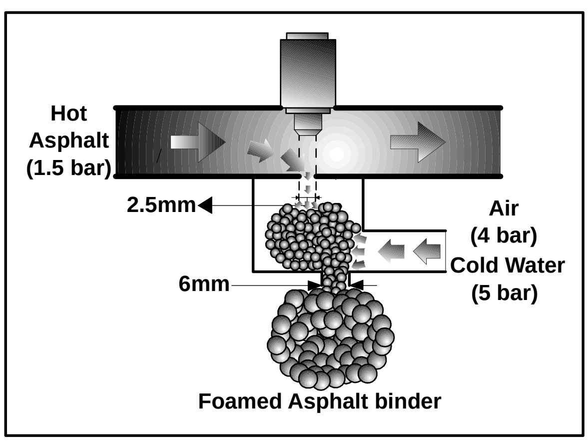


Figure 3-3. Production of foamed asphalt in the expansion chamber (Wirtgen 2002)

3.3 Determination of optimum foaming asphalt and water contents

To determine the optimum percentage of foaming asphalt and water, the operator performs the foaming process described below.

Step 1. Select the asphalt binder grade—for example, PG 58-28.

Step 2. Heat asphalt to the appropriate temperature (160°C, 170°C, or 180°C) and maintain it for at least five minutes before beginning the foaming process.

Step 3. Set the air pressure to four bars and water pressure to five bars (water pressure must be higher than air pressure by one bar).

Step 4. Press the automatic release button.

Step 5. Measure the expansion ration and half-life for varying water contents from 1% to 4%, at 1% increments.

For five seconds, the equipment will produce foamed asphalt and discharge it into a container with a diameter of 27 cm (500 g of asphalt binder). The expansion ratio is determined by measuring the maximum height of the foamed asphalt in this container with a dipstick. As shown in Figure 3-4, the expansion ratio is determined by dividing the maximum expansion volume (V_{max}) by the original asphalt volume (V_{min}). The half-life is defined by the duration in seconds from maximum expansion to one half of maximum expansion.

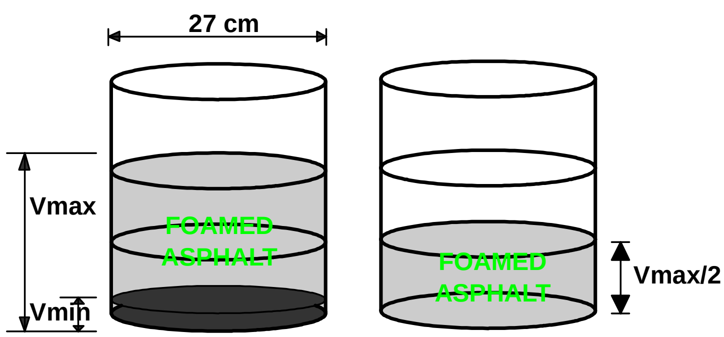


Figure 3-4. Description of expansion ratio and half-life

Step 6. Plot expansion ratio and half-life against water content.

Perform three measurements of expansion ration and half-life for each percentage of water content from 1% to 4% at 1% increments. The average of the three test results should be then plotted against water content (see Figure 3-5). Optimum water content is determined at the intersection of the graphs of the expansion ratio and half-life against water content.

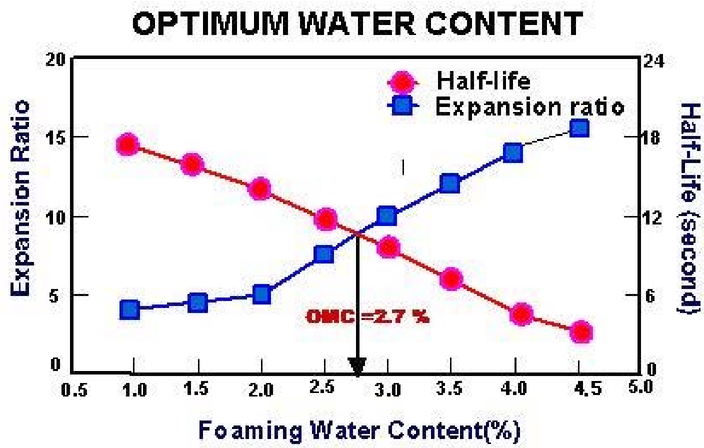


Figure 3-5. Relationship between expansion ratio and half-life

3.4 Evaluation of laboratory foaming equipment

The laboratory foaming equipment is evaluated with respect to four criteria: (1) water discharge rate with no air, (2) water discharge rate with air, (3) verification of manometer readings, and (4) foamed asphalt discharge rate. First, for 10 seconds without an air supply, the foaming equipment discharged 20-50 g of water for a water content of between 2% and 5%. We observed the water pressure increasing from 1.0 bar to 1.6 bars as the water content increased from 2 to 5%. Figure 3-6 shows relationship between the actual amount of water discharged and water content specified by the equipment without an air supply. Although there was a slight fluctuation in the amount of water discharged for a given water content, the test results seemed consistent with the varying water contents.

Next, for 10 seconds with an air supply, the foaming equipment discharged 20-50 g of water, again for a water content of between 2 and 5%. With an air pressure of 1 bar and water pressure of 2 bars, we observed the constant water pressure of 1.5 bars as the water content increased from 2% to 5%. Similarly, when the air pressure was 2 bars and the water pressure 3 bars, we observed a constant water pressure of 2.4 bars as the water content increased. Figure 3-7 shows the relationship between the actual amount of water discharged and water content specified in the equipment with the air supply. The result was quite satisfactory and very similar to the previous one without air.

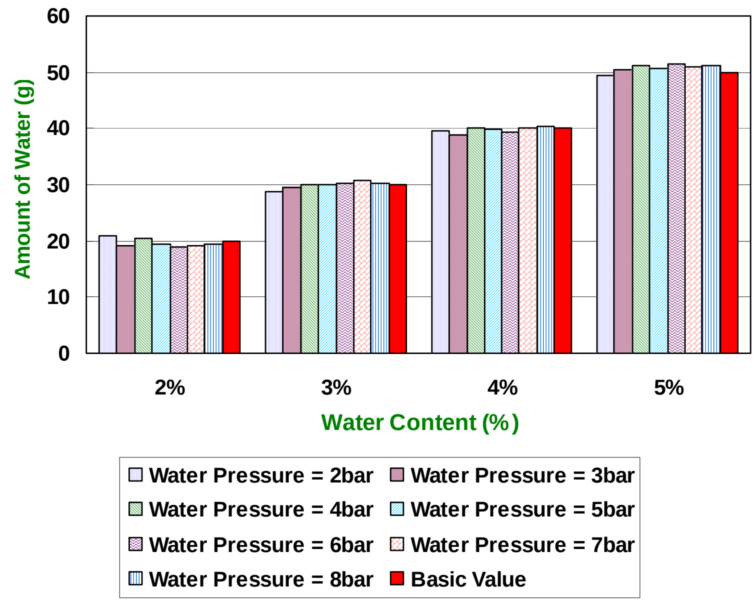


Figure 3-6. Amount of water vs water content (without air)

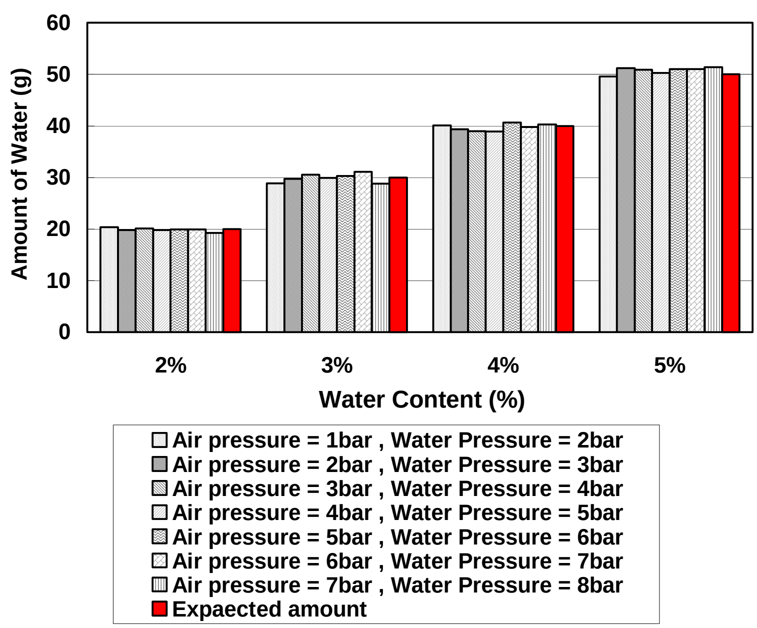


Figure 3-7. Amount of water vs water content (with air)

For the third test, for 5 seconds, five hundred grams of foamed asphalt were discharged at 180° C at a fixed rate of 100 g per second. Water pressure was the same as for the previous tests without asphalt. For air pressure between 3 and 8 bars, the foaming appeared satisfactory. Figure 3-8 indicates that the asphalt pressure remained constant at 1.5 bars as the air pressure was increased from 1 bar to 7 bars. Although the water pressure was set to be 1 bar above the air pressure, the actual air pressure was just 0.2 bars to 0.5 bars above the water pressure.

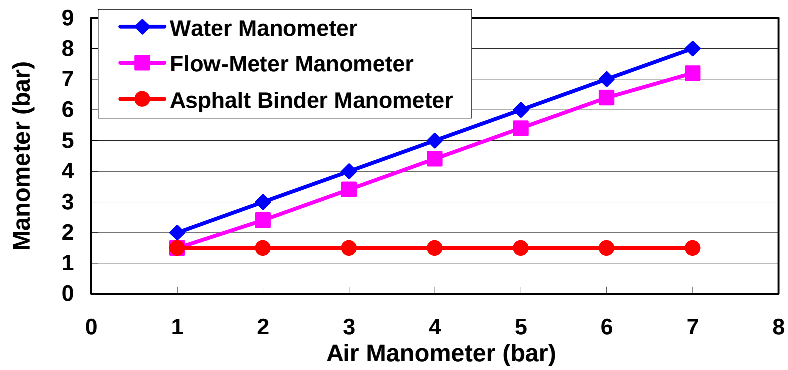


Figure 3-8. Variation of manometers during foamed production

Finally, the total foamed asphalt contents were measured with the varying water contents. As shown in Figure 3-9, the actual weights of foamed asphalt were very consistent with the given water contents. However, the weight of the foamed asphalt did increase slightly as the water content increased. This may have been caused by excess water remaining in the foamed asphalt after evaporation.

3.5 Summary

This concludes our discussion of the design and operating procedures for the Wirtgen laboratory foaming equipment. The equipment was evaluated with respect to water discharge rate, pressure gauges, and foamed asphalt discharge rate. Test results revealed that the Wirtgen laboratory foaming equipment is very consistent in producing the amount of foamed asphalt specified by the mix design.

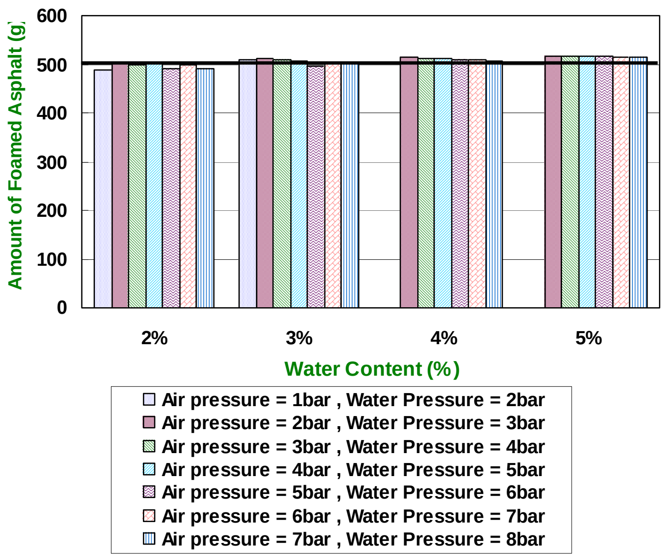


Figure 3-9. Amount of foamed asphalt vs. water content

4. FIELD DATA COLLECTION AND COMPACTION STUDY

4.1 Introduction

Six thousand pounds of milled RAP samples were collected from the CIR-Foam construction project on Highway US-20 in Iowa on July 15, 2002. The samples were sorted according to collection time and location to determine if there were any changes in gradation depending on milling time and specific position in the lane. An additional 1,000 pounds of foam-treated RAP samples were collected from the same project site before they were compacted. These samples were used to determine the effect on density and Marshall stability of different levels of compaction effort using a Marshall hammer. The same sample was also compacted using a gyratory compactor to determine the number of gyrations needed to produce a density equivalent to 75 blows of the Marshall hammer.

4.2 Job mix formula for US-20 project

The job mix formula for the project specifies 3% foaming moisture at 160°C, an expansion ratio of 20 and half-life of 4 seconds, 2.7% foamed asphalt content (applied at the rate of 0.31 gal/sy-in), and an optimum moisture content of 4.5-5%.

4.3 Collection of RAP samples in the field

As shown in Figure 4-1, Zone A represents a newly constructed CIR section using foamed asphalt and Zone B the milled RAP materials. RAP were collected from the westbound section of the US-20 CIR construction site, which is about 4 miles west of the intersection of US-20 and Highway 13 near city of Manchester, Iowa.

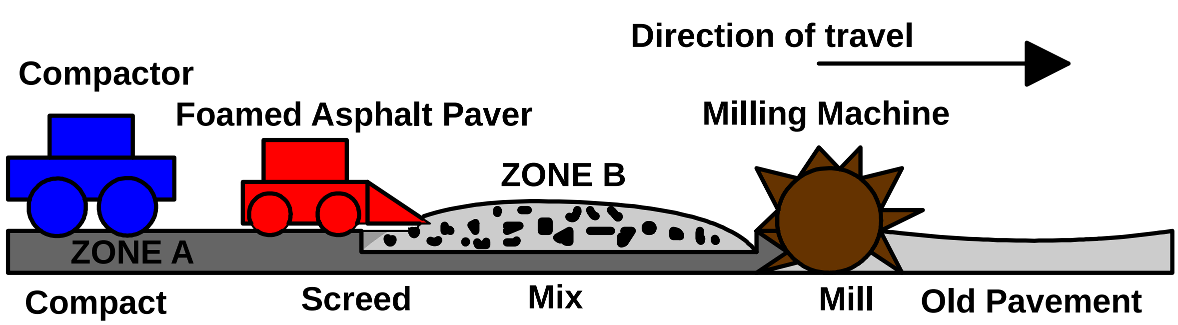


Figure 4-1. Schematic diagram of the CIR-Foam construction site

Collection of samples from both Zone A and Zone B began at 7:30 a.m. and ended at 4:00 p.m., following the milling and construction operation. Detailed descriptions of the samples from Zone A and B are given below.

- ZONE A (Collection of CIR-Foam mixtures)
  - Time of collection: 9:00 a.m., 12:00 p.m. and 3:30 p.m.
  - Temperature of CIR-Foam mixtures: 35° C (9:00 a.m.), 42° C (12:00 p.m.), and 49° C (3:30 p.m.)
  - Samples were collected from the edge of the traffic lane to minimize damage to the constructed foamed asphalt mat.
  - Six 50-lb bags of the CIR-Foam mixture were collected for each time period (total 18 bags)
- ZONE B (Collection of milled RAP)
  - Time of collection: 7:30 a.m., 12:30 p.m. and 4:00 p.m.
  - Temperature of RAP: 25–28° C (7:30 a.m.), 49–52° C (12:30 p.m.), and 46–50° C (4:00 p.m.)
  - Forty 50-lb bags of RAP were collected for each time period (total 120 bags). Four bags were collected at approximately every 100 ft, and each bag collected across the lane width—left edge, left center, right center, and right edge)

4.4 Compaction test of the CIR-Foam mixtures collected from Zone A

CIR-foam mixtures collected from Zone A were compacted at the L.L. Pelling Company's asphalt laboratory from July 17th through the 31st. To study the repeatability of the compaction, six samples were made for five different compactions efforts (see Table 4-1). Six samples were prepared for the Marshall test under two compaction efforts (50 and 75 blows). The number of samples produced for each category is summarized in Table 4-2.

Table 4-1. Number of Samples Needed for Compaction Study and Mechanical Tests

Compaction study					
Numbers of blow per side	30	40	50	60	75
Numbers of specimen	6	6	6	6	6
Mechanical test					
Indirect tensile test(wet/dry)	-	-	6	-	6
Marshall stability test(wet/dry)	-	-	6	-	6
Total numbers of specimen	6	6	18	6	18

Table 4-2. Compacted samples and their curing condition

Date		July 17	July 18	July 19	July 22
Moisture content		3.0 %	3.9 %	1.5 %	3.8 % (2 % added)
No. of samples	30 blows	6		6	
	40 blows	6		6	
	50 blows	9	17	11	15
	60 blows	6		6	
	75 blows	9	17	6	15
Curing condition		16 hrs oven curing in molds at 40° C and 7 days room curing (one day in the air for dry and one day under water for wet)			

The bulk specific gravities of the Marshall mixtures (G_{mb}) were estimated by measuring the volume of the Marshall specimens using a caliper. Table 4-3 summarizes the results. Figure 4-2 shows a plot of the estimated bulk specific gravities against various compaction efforts. As expected, the bulk density steadily increased as the compaction efforts increased at a constant rate from 40 to 70 blows (and at a higher constant rate from 30 to 40 blows). The bulk specific gravities were also measured in the laboratory for 50- and 75-blow samples, and are higher than the estimated ones as expected (need measured data here). Table 4-4 summarizes the maximum specific gravities measured using a Rice method.

Table 4-3. Estimated (dimensional) G_{mb} of CIR-Foam mixtures collected from Zone A (9:00 a.m.)

Blows / No. of sample	30	40	50	60	75
1	1.999	2.107	2.125	2.140	2.151
2	2.050	2.100	2.106	2.138	2.146
3	2.045	2.116	2.128	2.114	2.140
4	2.042	2.083	2.103	2.124	2.167
5	2.030	2.070	2.119	2.162	2.142
6	2.043	2.102	2.120	2.126	2.175
Average	2.035	2.096	2.117	2.143	2.153
Standard dev.	0.019	0.017	0.010	0.017	0.015
G_{mb}(measured)	-	-	2.138	-	2.168

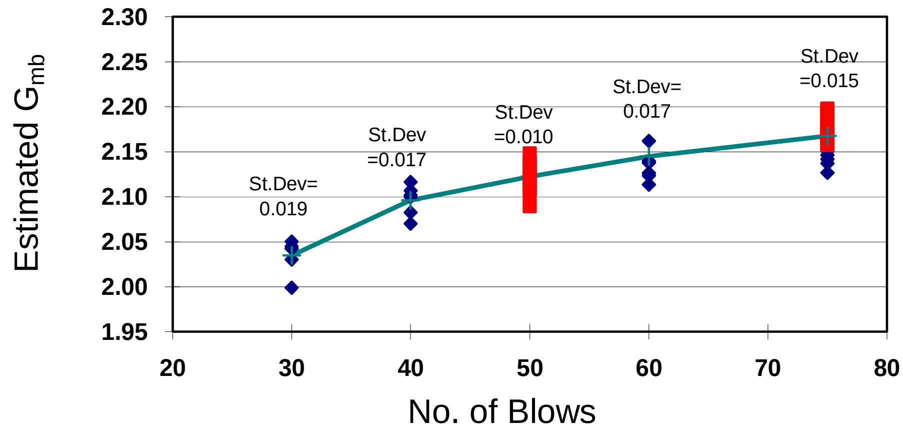


Figure 4-2. Estimated G_{mb} vs compaction efforts

Table 4-4. Maximum specific gravities measured from CIR-Foam mixtures

Time of collection / No. of samples	**Loose samples (morning sample)**	**Loose samples (evening sample)**
1	2.284	2.269
2	2.274	2.280
3	2.270	n.a.
Average	2.276	2.275
Standard deviation	0.007	0.008

As shown in Table 4-5, the 6-inch samples from Zone A were compacted with up to 150 gyrations using a gyratory compactor. To determine how many gyrations were needed to produce the same density as 75 blows of the Marshall hammer, density values from both the gyratory compactor and Marshall hammer were plotted (see Figure 4-3). As may be seen in the figure, approximately 25 gyrations were needed to produce the equivalent density of 75 blows of the Marshall hammer.

Table 4-5. Estimated (dimensional) Gmb of CIR-Foam mixtures compacted by a gyratory compactor (Zone A: 9:00 a.m.)

Gyrations \ No. of sample	1	2	3	4	Average
5	2.037	1.992	1.994	1.987	2.002
8	2.083	2.041	2.043	2.033	2.050
15	2.145	2.107	2.109	2.095	2.114
20	2.174	2.137	2.139	2.123	2.143
30	2.210	2.178	2.179	2.163	2.182
40	2.235	2.204	2.208	2.189	2.209
50	2.255	2.223	2.227	2.208	2.228
60	2.269	2.239	2.243	2.223	2.243
70	2.279	2.251	2.255	2.237	2.255
80	2.289	2.261	2.267	2.247	2.266
95	2.302	2.275	2.279	2.261	2.279
100	2.306	2.279	2.283	2.265	2.283
110	2.312	2.285	2.291	2.273	2.290
120	2.316	2.291	2.297	2.279	2.296
130	2.327	2.297	2.304	2.285	2.303
150	2.331	2.308	2.312	2.295	2.311

4.5 Marshall stability test

CIR-Foam mixtures collected from Zone A were compacted at room temperature (25°C) and cured in the oven at 40°C for 16 hours (from 6:00 p.m. to 10 a.m.) in a mold. Curing was then completed in the air for seven days. The curing procedure was changed for RAP materials collected from Zone B by increasing the curing time in the 40°C oven from 16 hours to three days (16 hours in the mold and 58 hours after the mold was removed). Half of the samples were dry-cured in the air one more day, while the other half were wet-cured under water at 25°C (Figure 4-4). Marshall stability tests were performed at room temperature (25°C).

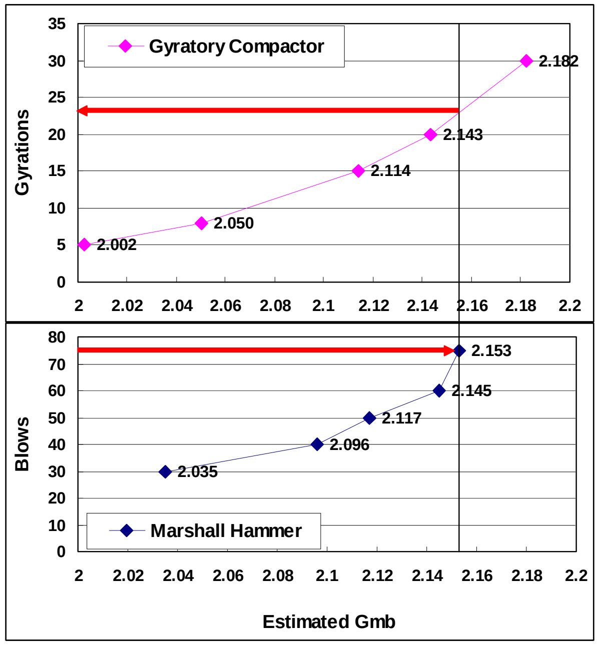


Figure 4-3. Plots of Marshall blows and gyrations versus estimated density

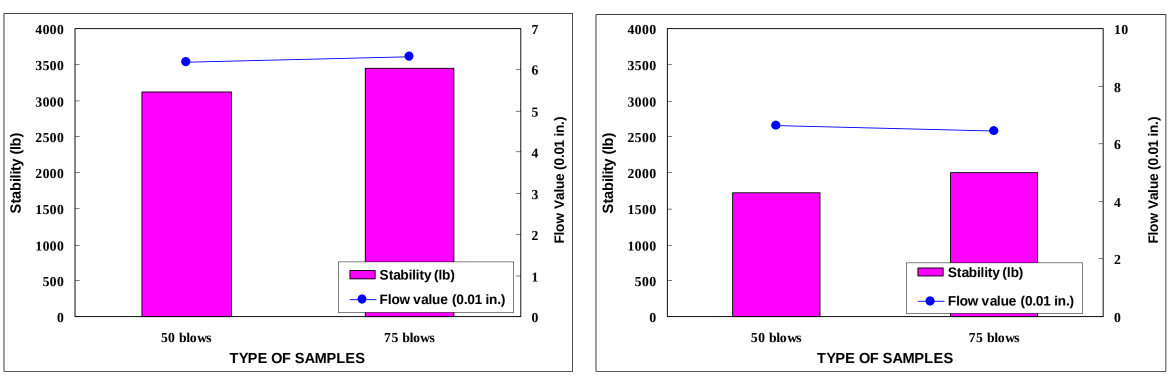
(a) Dry (b) Wet

Figure 4-4. Zone A samples for Marshall tests

Marshall stability tests were performed using the compression machine to produce a load versus a deformation curve. Results from the tests are summarized in Table 4-6. As the Marshall stabilities were measured at room temperature (25°C), they were higher than typical HMA stability values measured at 60°C. It was difficult to measure the flow values because the load did not drop as the deformation increased. It can be postulated that this was caused by the yielding behavior of CIR-Foam mastic, which is similar to CIR-Emulsion. The flow was therefore measured at the intersection of the tangent line of the loading curve and its maximum plateau. As may be seen in Figure 4-5, the wet samples produced lower stability and higher flow values than the dry samples. As expected, the samples subjected to higher compaction procedures demonstrated higher stability values.

Table 4-6. Marshall stability test results of the CIR-Foam mixtures collected from Zone A

Stability & flow / Blow	Stability (lb)		Flow value (0.01 in.)	
	Dry	Wet	Dry	Wet
50 blows	3310	1710	6.55	6.62
	2950	1830	6.28	6.67
	3090	1630	5.75	6.65
Average	3117	1723	6.19	6.65
Standard deviation	181.5	100.7	0.41	0.03
75 blows	3120	2170	6.25	6.40
	3590	2170	6.15	6.45
	3640	1650	6.55	6.55
Average	3450	1997	6.32	6.47
Standard deviation	286.9	300.2	0.21	0.08



(a) Dry (b) Wet

Figure 4-5. Marshall stability values and flows for (a) Dry and (b) Wet condition

Table 4-7 shows the temperature of the RAP measured in the field. RAP temperatures ranged between 25°C and 30°C in the morning, and increased over time. The highest temperature of 54.8°C was measured at 13:20 p.m.

Table 4-7. Temperature of the RAP

Number of section	**Section**					
	Morning samples		Afternoon samples		Evening samples	
	Time	Temperature (˚C)	Time	Temperature (˚C)	Time	Temperature (˚C)
S-1	7:40	25.2	12:50	49.0	15:55	50.0
S-2	7:50	25.8	12:55	51.0	16:00	46.8
S-3	7:55	26.0	13:00	52.0	16:05	34.4
S-4	8:00	26.0	13:15	50.8	16:10	45.5
S-5	8:05	26.0	13:20	54.8	16:15	46.0
S-6	8:15	25.4	13:30	51.6	16:20	46.2
S-7	8:25	27.0	13:35	52.8	16:30	46.2
S-8	8:30	28.0	13:45	53.0	16:35	45.8
S-9	8:40	28.6	13:50	43.0	16:40	45.0
S-10	8:50	30.4	13:55	52.2	16:50	44.2

4.6 RAP gradation

Gradation tests were conducted to see if any differenced in gradation had occurred due to differences in milling time. Some contractors indicated that they had experienced finer RAP gradation in the afternoon compared to in the morning. RAP samples were dried in the laboratory for three days, and a cooling fan was used to speed up the drying process. The moisture content of the dry RAP was between 0.3% and 0.5% once this process was complete. Since the samples were collected from four different locations and at three different time periods, a total of 12 gradation tests were conducted.

Tables 4-8 to 4-13 show the gradation test results of the samples collected in the morning, afternoon and evening, from two test sections, respectively. All six gradations are plotted in Figure 4-6. As may be seen in the figure, there is no significant variation among these gradations. Therefore, for this test section, we concluded that time of milling (temperature of pavement during the milling process) did not affect gradation.

Table 4-8. Gradation of RAP (Section 4) collected at 9:30 A.M.

Location / Sieve size (mm)	Passing percentage (%)			
	Left-edge	Left-center	Right-center	Right-edge
38.1	100.00	100.00	100.00	100.00
25.0	100.00	100.00	99.17	100.00
19.0	97.62	97.61	96.50	98.21
12.5	86.60	85.31	88.14	85.47
9.5	74.60	71.93	78.99	75.68
4.75 (No.4)	47.93	45.16	57.39	47.18
2.36 (No. 8)	30.12	29.27	40.25	29.17
1.18 (No. 16)	18.31	18.70	26.70	17.34
0.6 (No. 30)	9.64	10.29	15.55	9.20
0.3 (No.50)	3.11	3.45	5.71	3.09
0.15 (No. 100)	0.60	0.59	1.24	0.59
0.075 (No.200)	0.18	0.12	0.32	0.16

Table 4-9. Gradation of RAP (Section 4) collected at 12:00 P.M.

Location / Sieve size (mm)	Passing percentage (%)			
	Left-edge	Left-center	Right-center	Right-edge
38.1	100.00	100.00	100.00	100.00
25.0	98.17	100.00	100.00	98.81
19.0	97.15	99.19	96.93	95.93
12.5	86.01	91.83	86.52	85.44
9.5	73.58	81.40	76.08	75.28
4.75 (No.4)	47.56	55.10	49.81	46.26
2.36 (No. 8)	31.40	36.37	30.42	28.05
1.18 (No. 16)	19.75	22.83	18.33	17.15
0.6 (No. 30)	9.98	11.07	9.06	8.76
0.3 (No.50)	2.78	2.92	2.50	2.63
0.15 (No. 100)	0.46	0.43	0.38	0.51
0.075 (No.200)	0.11	0.10	0.10	0.15

Table 4-10. Gradation of RAP (Section 4) collected at 3:30 P.M.

Location / Sieve size (mm)	Passing percentage (%)			
	Left-edge	Left-center	Right-center	Right-edge
38.1	100.00	100.00	100.00	100.00
25.0	100.00	100.00	98.99	97.49
19.0	96.02	98.69	95.66	96.38
12.5	85.99	85.17	89.18	83.00
9.5	75.38	73.74	79.74	72.22
4.75 (No.4)	49.12	48.12	52.78	42.25
2.36 (No. 8)	31.47	30.91	32.58	24.67
1.18 (No. 16)	18.72	19.03	19.14	13.77
0.6 (No. 30)	8.45	8.93	8.95	5.90
0.3 (No.50)	2.04	2.19	2.25	1.37
0.15 (No. 100)	0.34	0.31	0.32	0.22
0.075 (No.200)	0.10	0.07	0.07	0.06

Table 4-11. Gradation of RAP (Section 10) collected at 9:30 A.M.

Location / Sieve size (mm)	Passing percentage (%)			
	Left-edge	Left-center	Right-center	Right-edge
38.1	100	100	100	100
25.0	100	99	100	98.8
19.0	96.9	97.7	96.8	96.2
12.5	82.6	88.2	84	84.5
9.5	72.6	80.3	74.8	74.4
4.75 (No.4)	45.9	54.7	50	49.9
2.36 (No. 8)	28.9	34.8	32.8	32.8
1.18 (No. 16)	17.9	20.9	20.8	20.5
0.6 (No. 30)	9.8	10.6	11.2	11.1
0.3 (No.50)	3.4	3.3	3.8	3.7
0.15 (No. 100)	0.7	0.6	0.9	0.8
0.075 (No.200)	0.2	0.1	0.3	0.2

Table 4-12. Gradation of RAP (Section 10) collected at 12:00 P.M.

Location / Sieve size (mm)	Passing percentage (%)			
	Left-edge	Left-center	Right-center	Right-edge
38.1	100	100	100	100
25.0	100	100	100	100
19.0	97.4	94	96.7	95.9
12.5	83.8	87.3	87.9	86.6
9.5	72.7	79.4	80.5	78.7
4.75 (No.4)	48.7	58.1	58.6	57
2.36 (No. 8)	32.2	40.9	39.9	38.5
1.18 (No. 16)	20.4	26.4	25.5	24.6
0.6 (No. 30)	10.4	13	12.7	12.4
0.3 (No.50)	3	3.4	3.5	3.4
0.15 (No. 100)	0.6	0.5	0.6	0.6
0.075 (No.200)	0.1	0.1	0.1	0.2

Table 4-13. Gradation of RAP (Section 10) collected at 3:30 P.M.

Location / Sieve size (mm)	Passing percentage (%)			
	Left-edge	Left-center	Right-center	Right-edge
38.1	100	100	100	100
25.0	99.2	99	98.9	100
19.0	95.9	98.4	96.8	93.0
12.5	81.9	89.1	84.5	88.2
9.5	72.5	78.2	74.1	80.0
4.75 (No.4)	46.8	53	45.8	54.4
2.36 (No. 8)	29.2	32.8	26.1	33.4
1.18 (No. 16)	16.9	18.5	13.6	18.5
0.6 (No. 30)	7.5	8.1	5.4	8.0
0.3 (No.50)	1.9	2.1	1.4	2.1
0.15 (No. 100)	0.4	0.4	0.3	0.4
0.075 (No.200)	0.1	0.1	0.1	0.1

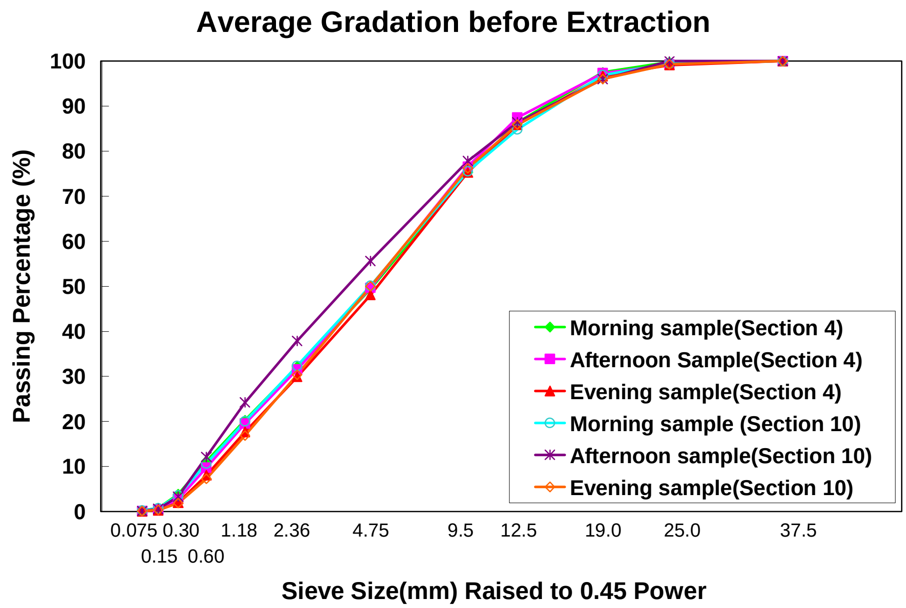


Figure 4-6. Gradations of six RAP samples

4.7 Summary

Based on the samples collected during one hot summer day in July, there was no apparent change in the milled RAP gradation throughout the day. Neither was there a difference in gradation among the samples collected from different parts of the pavement, for example, from the edge versus the center lane. Both density and Marshall stability of CIR-Foam mixtures collected from the field steadily increased as Marshall compaction efforts increased from 30 blows to 75 blows. It was determined that, for the given CIR-Foam mixtures, 25 gyrations would produce a density equivalent to that of the 75-blow Marshall samples.

5. DETERMINATION OF MIX DESIGN PARAMETERS FOR CIR WITH FOAMED ASPHALT: FIRST ROUND

5.1 Introduction

In this study, numerous mixture components were analyzed in the laboratory. Figure 5-1 shows a foamed asphalt mix design process flowchart, which helps identify the critical mix design parameters. As may be seen in the figure, we examined the foaming process, distribution and amount of asphalt, RAP gradation, compaction, curing, and mixture strength. The mix design parameters for the first round are summarized in Table 5-1.

Table 5-1. Mix design parameters (first round)

Items	First round
Asphalt binder	PG 52-34
Number of samples	2 samples per set
Water content of RAP	Fine gradation (5.1 % (OMC), 4.6%, 4.1%, and 3.9%) Field gradation (5.0 % (OMC), 4.5%, 4.0%, and 3.5%) Coarse gradation (3.9 % (OMC), 3.4%, 2.9%, and 2.4%)
Dry curing condition	72 hours in 40°C oven
Wet curing condition	Soaking for 24 hours
Extra curing condition	29 days
Paper disk	Used

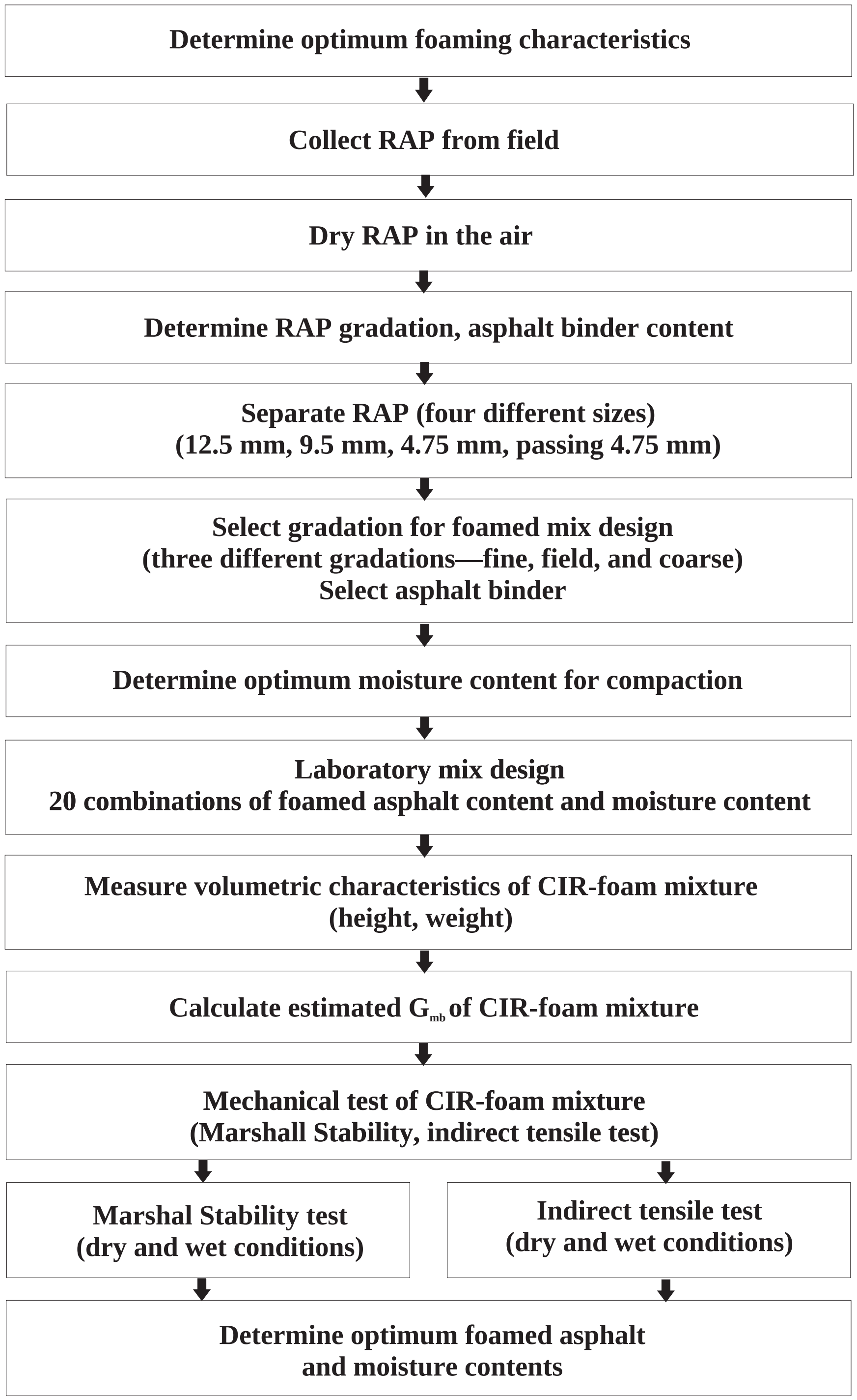


Figure 5-1. Foamed asphalt mix design process flowchart

5.2 Determination of optimum foaming water content

Asphalt binders with a low-viscosity foam more readily produce a higher expansion ratio and a longer half-life than asphalt binders with a high-viscosity foam. A good foaming can be achieved at temperatures at or above 150°C. As foaming temperature and water content increases, the expansion ratio increases but half-life decreases. Foamed asphalt tests were conducted to determine the optimum foaming water content under the following test conditions.

- Asphalt: PG 52-34
- Air pressure: 4 bars
- Water pressure: 5bars
- Asphalt binder pressure: 1.5 bars
- Temperature of asphalt binder: 160°C to 180°C, at 10°C increments
- Water content: 1% to 5%, at 1% increments

Both expansion ratio and half-life were measured at water contents varying from 1% to 5%, at 1% increments. Three measurements were made for each percentage level. Table 5-2 shows test results of foaming characteristics at an asphalt temperature of 160°C. Figure 5-2 illustrates the optimum water content of 1.5% at an expansion ratio of 10 and a half-life of 12 seconds.

Table 5-2. Test results of foaming characteristics at 160°C

Water content (%)	Flow (l/h)	1		2		3		Average	
		Measurement		Measurement		Measurement			
		Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life
1.0	3.6	9.2	13	7.7	14	7.7	15	8.2	14.0
2.0	7.2	12.3	11	13.1	10	13.1	10	12.8	10.3
3.0	10.8	16.9	7	20.0	5	19.2	5	18.7	5.7
4.0	14.4	22.3	4	23.1	4	23.1	4	22.8	4.0
5.0	18.0	23.8	3	24.6	4	24.6	3	24.4	3.3

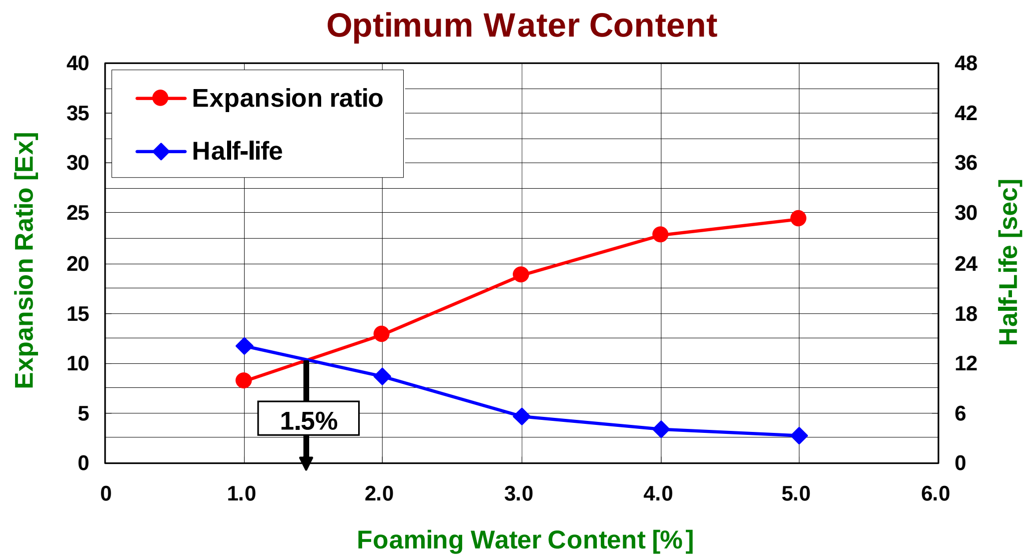


Figure 5-2. Plot of expansion ratio and half-life against water content at 160°C

Table 5-3 shows test results of foaming characteristics at an asphalt temperature of 170°C. Figure 5-3 illustrates the optimum water content of 1.3% at an expansion ratio of 12.5 and a half-life of 15 seconds.

Table 5-3. Test results of foaming characteristics at 170°C

Water content (%)	Flow (l/h)	1 Measurement		2 Measurement		3 Measurement		Average	
		Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life
1.0	3.6	9.0	17	12.2	18	9.0	17	10.1	17.3
2.0	7.2	21.0	9	20.0	12	19.0	10	20.0	10.3
3.0	10.8	31.1	5	28.9	6	28.9	4	29.6	5.0
4.0	14.4	33.3	5	34.4	4	34.4	5	34.1	4.7
5.0	18.0	-	-	-	-	-	-	-	-

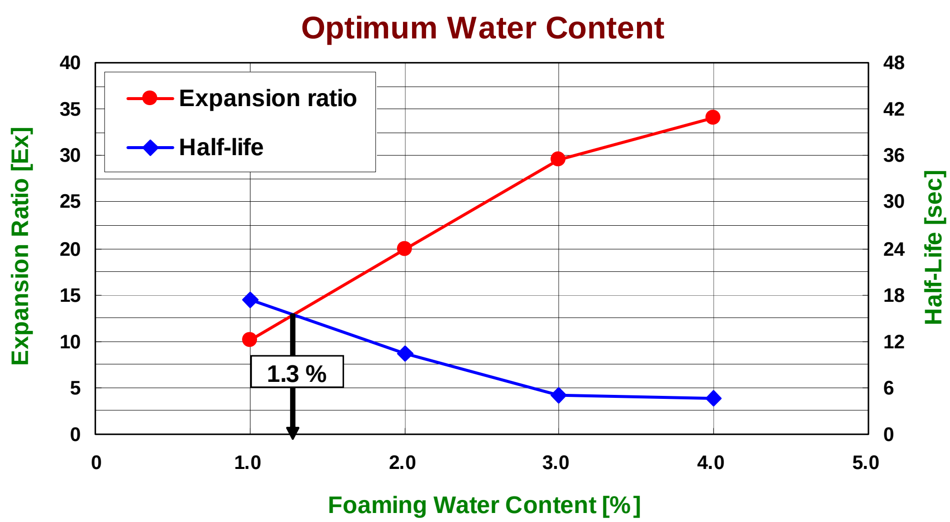


Figure 5-3. Plot of expansion ratio and half-life against water content at 170° C

Table 5-4 presents test results of foaming characteristics at an asphalt temperature of 180°C. Figure 5-4 shows an optimum water content of 1.1% at an expansion ratio of 13 and a half-life of 16 seconds.

Table 5-4. Test results of foaming characteristics at 180°C

Water content (%)	Flow (l/h)	1 Measurement		2 Measurement		3 Measurement		Average	
		Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life
1.0	3.6	13.8	16	12.5	16	12.5	17	12.9	16.3
2.0	7.2	26.3	7	28.8	6	23.8	6	26.3	6.3
3.0	10.8	31.3	5	31.3	5	30.0	5	30.8	5.0
4.0	14.4	36.3	4.5	38.8	4	36.3	4.5	37.1	4.3
5.0	18.0	-	-	-	-	-	-	-	-

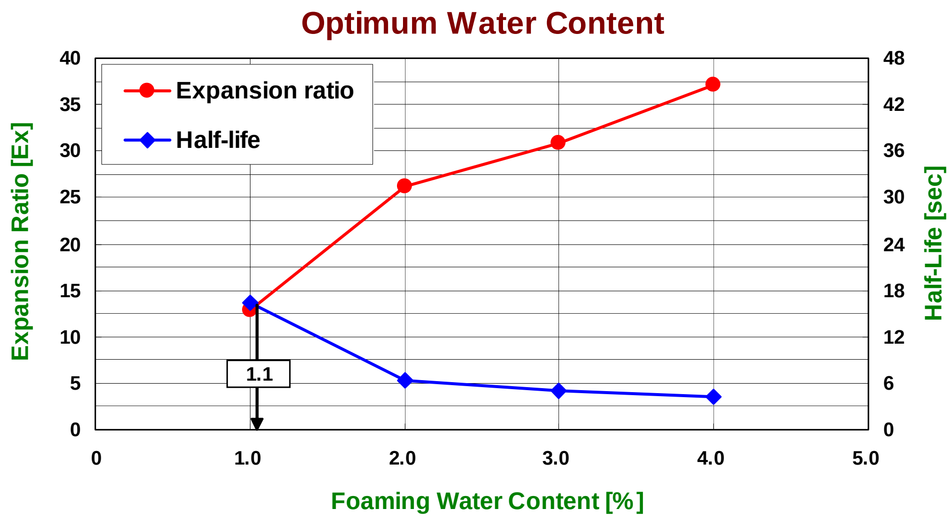


Figure 5-4. Plot of expansion ratio and half-life against water content at 180°C

Table 5-5 summarizes the foaming characteristics at an asphalt temperature of 160°C, 170°C and 180°C. As may be seen in the table, the increasing temperature led to higher expansion ratios and half-lives. However, the rate of increase was reduced significantly as temperatures were increased from 170°C to 180°C. At the higher temperature, less moisture was needed to produce optimum foaming characteristics.

Table 5-5. Final results of optimum foaming asphalt content

Temperature (°C)	Expansion ratio	Half-life (sec)	OMC (%)
160	10	12	1.5
170	12.5	15	1.3
180	13	16	1.1

Figure 5-5 illustrates the relationship between the expansion ratio and half-life measured at four different moisture contents for three different temperatures. Since the PG 52-34 asphalt binder is very soft, a relatively higher expansion ratio and half-life were achieved compared to a hard asphalt binder such as PG 58-34. As shown in Figure 5-5, at 170°C, a high half-life was achieved while an acceptable expansion ratio was maintained. Especially, at a foaming moisture content of 1%, it produced the highest half-life. As a result, for our study, we selected the foaming temperature of 170°C, with an optimum foaming water content of

1.3%. It is interesting to note, however, that the optimum water content is lower than that found in past foaming tests (2% to 2.5%) that also met the design criteria of an expansion ratio of 10 and half-life of 12 seconds (some suggested 20 seconds).

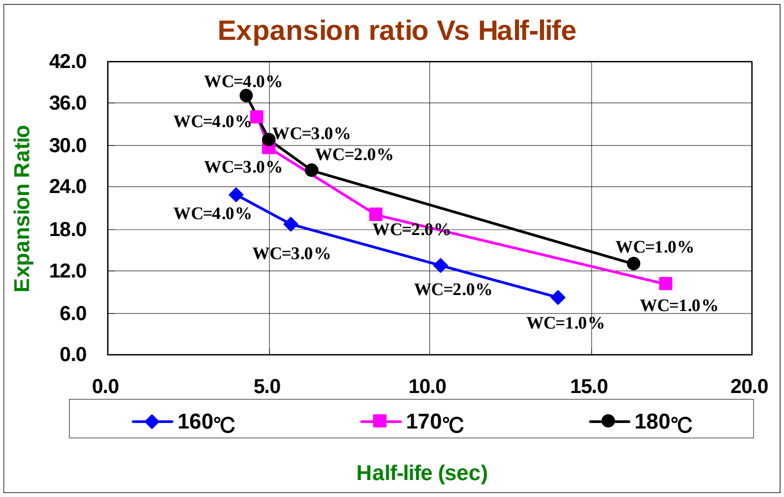


Figure 5-5. Relationship of expansion ratio vs. half-life measured at four different moisture contents for three different temperatures

5.3 RAP materials

RAP samples were collected from the westbound section of the US-20 CIR site that used foamed asphalt, which is located about four miles west of the intersection of US-20 and Highway 13 near the city of Manchester, IA. The RAP samples were dried outside for two days (32°C). Samples were spread early in the morning and collected in the late evening. The moisture content of the dried RAP samples were between 1.0% and 0.3%. Figure 5-6 shows the RAP drying process.

The Iowa DOT was provided with four bags of samples, one from Zone A (CIR- Foam mixtures) and three from Zone B (milled RAP materials). The DOT performed sieve analysis of the extracted aggregate from RAP, and Abson recovery tests of the aged asphalt. Table 5-6 shows that, as expected, the extracted aggregate gradation from RAP-Foam (Zone A) was coarser than that of the RAP materials (Zone B). As may be seen in Table 5-7, asphalt content extracted from CIR-Foam mixtures was 1.1% higher than that of the RAP materials. This was considerably below the 2.7% specified by the Iowa DOT. Based on the extracted sample analysis, foamed asphalt content of from 1.1% to 1.5% was used in this project.

Figure 5-6. Drying process of RAP samples

Table 5-6. Gradation of aggregates extracted from RAP

Location / Sieve size (mm)	Zone A	Zone B		
25.0	100	100	100	100
19.0	100	100	100	100
12.5	86	95	92	93
9.5	72	87	83	83
4.76 (No.4)	45	62	60	63
2.36 (No. 8)	34	46	45	49
1.18 (No.16)	29	37	37	40
0.6 (No.30)	24	29	29	32
0.3 (No. 50)	17	20	19	21
0.15 (No. 100)	12	13	12	14
0.075 (No. 200)	9	10	9.4	10.5

Table 5-7. Asphalt content extracted from RAP

Location	Zone A	Zone B		
Asphalt content (%)	5.72	4.75	4.42	4.69
Average	5.72	4.62		

To develop RAP with a controlled gradation and maximum size of 25 mm, RAP larger than 25 mm were discarded. The remaining RAP were then divided into four stockpiles that were retained on one of the following sieves: 12.5 mm, 9.5 mm, 4.75 mm and those that passed through the 4.75 mm sieve. Three different gradations were developed—Fine, Field, and Coarse—to determine their impact on the performance of the CIR-Foam mixture. Table 5-8 summarizes the proportions of RAP that were retained on each sieve and that passed through the 4.75 mm sieve for three different gradations. The resulting cumulative gradation and three RAP gradations are shown in Figure 5-7 and Table 5-9, respectively.

Table 5-8. The proportion of three RAP gradations for mix design

Gradation	Proportion (%)			
	25.0-12.5 mm	9.5-12.5 mm	4.75- 9.5 mm	< 4.75 mm
Fine	4	6	23	67
Field	12.5	9.5	30	48
Coarse	23	13	34	30

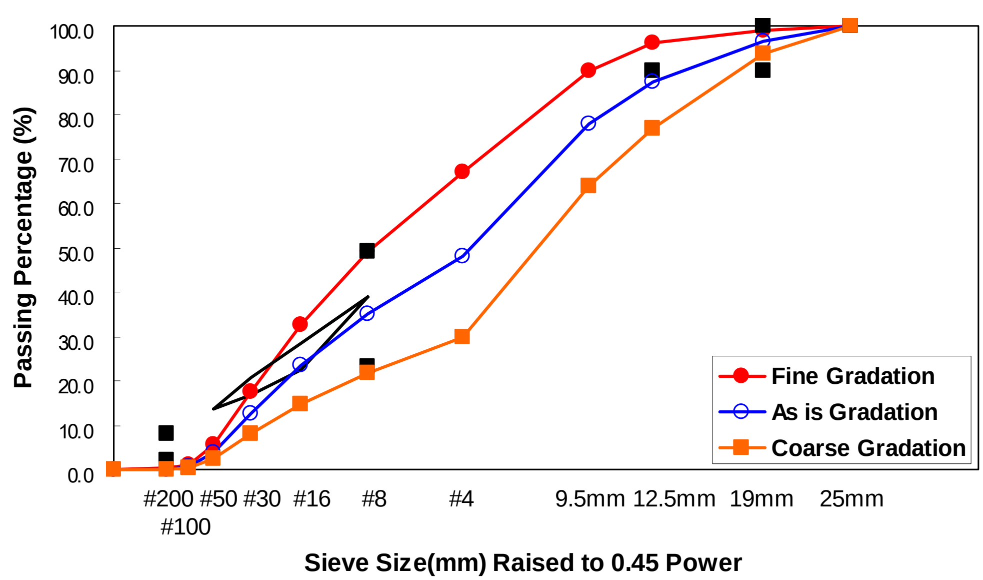


Figure 5-7. Three different gradations for CIR-Foam mixtures

Table 5-9. Detailed proportions of three RAP gradations

Sieve size (mm) \ Gradation	Fine	Field	Coarse
25.0	100.0	100.0	100.0
19.0	98.9	96.7	93.8
12.5	96.0	87.5	77.0
9.5	90.0	78.0	64.0
4.75 (No. 4)	67.0	48.0	30.0
2.36 (No. 8)	49.0	35.1	21.9
1.18 (No. 16)	32.6	23.4	14.6
0.6 (No. 30)	17.7	12.7	7.9
0.3 (No. 50)	5.6	4.0	2.5
0.15 (No. 100)	1.0	0.8	0.5
0.075 (No. 200)	0.2	0.2	0.1

5.4 Optimum moisture content

The optimum moisture content during mixing and compaction is considered to be one of the most important mix design criteria for CIR-Foam mixtures. Moisture is needed to soften and break down agglomeration in the aggregates, and to aid asphalt dispersion during mixing and field compaction. The modified proctor test was conducted in accordance with the ASTM D 1557 "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (2,700 kN-m/m^3-56,000 ft-lbf/ft^3)." Following the ASTM D 1557, Optimum Moisture Contents (OMC) were determined to be 5.1%, 5.0% and 3.9% for Fine, Field and Coarse gradations, respectively. Table 5-10 summarizes the four levels of moisture content selected for the foamed asphalt mix design: OMC, OMC-0.5%, OMC-1.0% and OMC-1.5%.

Table 5-10. Moisture contents selected for three gradations

Gradation \ Moisture content	OMC	OMC-0.5%	OMC-1.0%	OMC-1.5%
Fine	5.1 %	4.6 %	4.1 %	3.6 %
Field	5.0 %	4.5 %	4.0 %	3.5 %
Coarse	3.9 %	3.4 %	2.9 %	2.4 %

5.5 Experimental design

Table 5-11 shows 13 combinations of asphalt and moisture contents, which were used to create test samples using the three different aggregate gradations. Each mixture was measured for bulk specific gravity (estimate), Marshall stability, and indirect tensile strength (dry and wet). Selected mix design parameters for the laboratory experiment are summarized in Figure 5-8. Please note that the specimens in the figure were air cured for an additional 29 days because Marshall testing equipment was not available during that period.

Table 5-11. Test plan for laboratory mix design (first round)

Moisture content \ Asphalt content	1.5	2.0	2.5	3.0	3.5
OMC					
OMC-0.5 %					
OMC-1.0 %					
OMC-1.5 %					

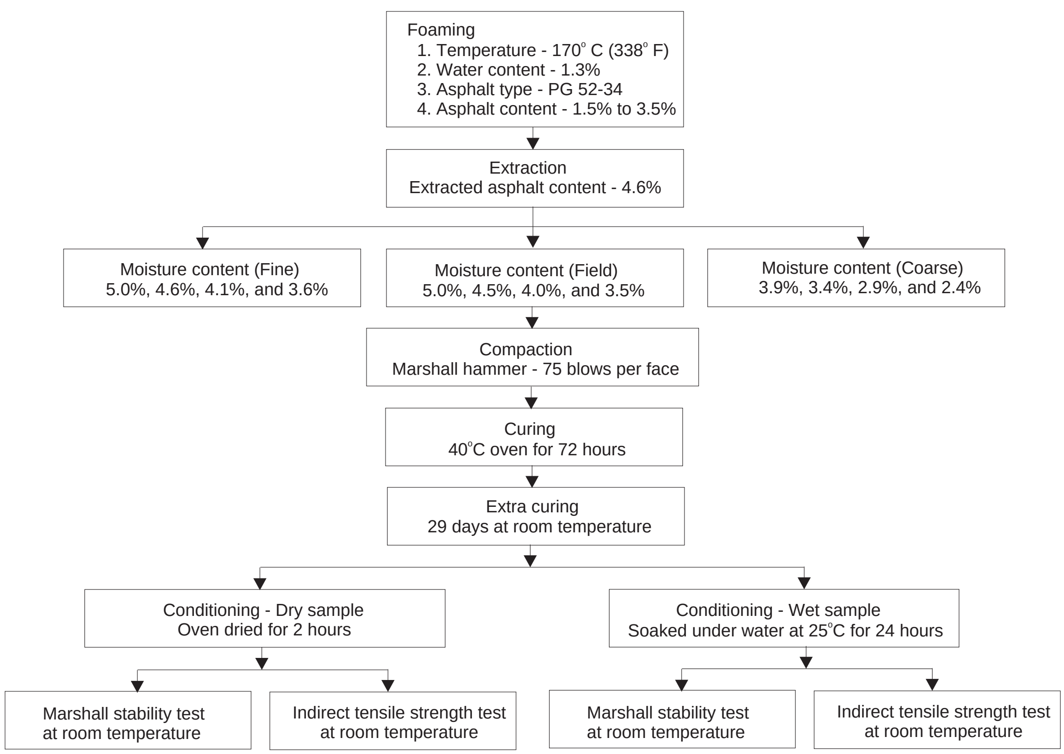


Figure 5-8. Laboratory mix design procedure (first round)

5.5.1 Sample preparation

- **Fine gradation**

Water content (WC) of 5.1% (OMC) clearly exhibited an excessive amount of moisture for all foamed asphalt contents (FACs) except 1.5%. Based on our visual observations during the compaction process, WCs of 4.6% and 4.1% seemed optimal for all FACs. For WC of 3.6%, we had difficulty compacting and molding the samples due to the lack of moisture, except FAC 3.5%.

- **Field gradation**

WC of 5.0% (OMC) clearly exhibited an excessive amount of moisture for all FACs. Based on visual observations during the compaction process, WC of 4.5% seemed optimal for all FACs except 2.0%, and WC of 4.0% was optimum for most FACs. For WC of 3.5%, we had difficulty compacting and molding the samples due to the lack of moisture, except FAC 3.5%.

- **Coarse gradation**

WC of 3.9% (OMC) clearly exhibited an excessive amount of moisture for all FACs. Based on visual observations during the compaction process, WC of 3.4% seemed optimum for all FACs and WC of 2.9 was optimum for FAC 3.0% and 3.5%. For WC of 2.4%, we had difficulty compacting and molding the samples due to the lack of moisture, except 3.5%.

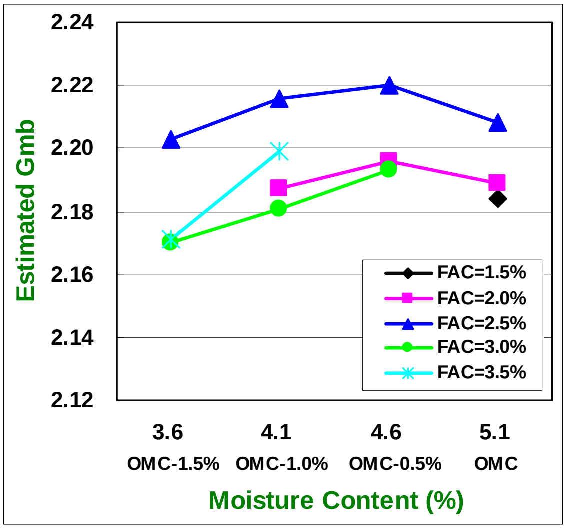
5.5.2 Density measurement

The bulk specific gravities (Gmb) of the CIR-Foam mixtures were estimated by measuring the volume of Marshall specimens using a caliper. Table 5-12 summarizes bulk specific gravities of Marshall specimens for three different gradations at four different moisture contents and five foamed asphalt contents.

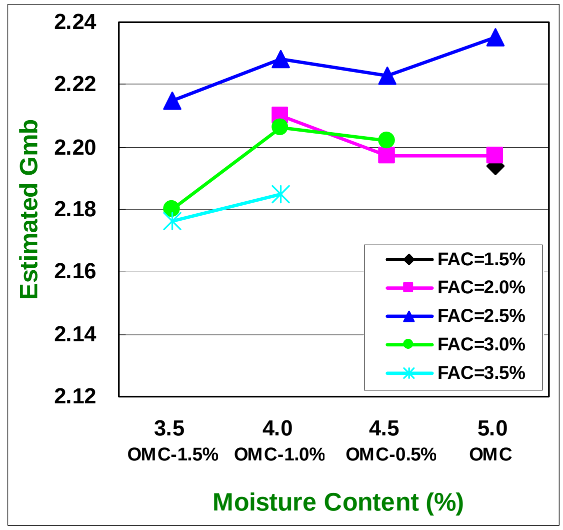
Estimated bulk specific gravities of Fine, Field, and Coarse gradations are plotted against four different moisture contents and five foamed asphalt contents (FAC) in Figures 5-9. These plots clearly indicate that maximum density was achieved at 2.5% FAC and OMC-0.5% (or OMC).

Table 5-12. Estimated Gmb values of CIR-Foam mixtures for three different gradations

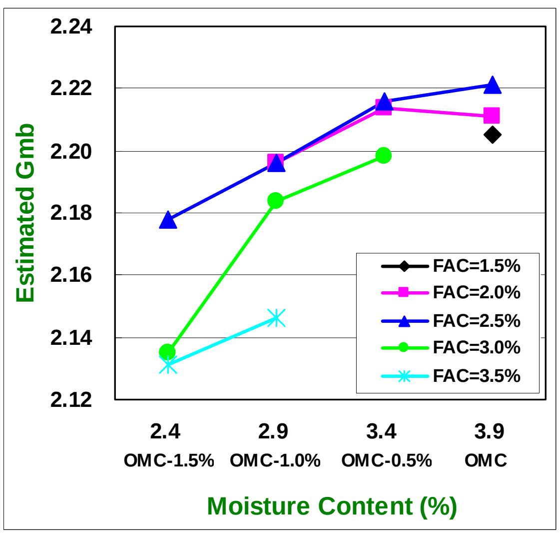
Moisture content /gradation \ Asphalt content		1.5	2.0	2.5	3.0	3.5
OMC	Fine gradation (5.1%)	2.184	2.189	2.208		
	Field gradation (5.0%)	2.194	2.197	2.235		
	Coarse gradation (3.9%)	2.205	2.211	2.221		
OMC-0.5%	Fine gradation (4.6%)		2.196	2.220	2.193	
	Field gradation (4.5%)		2.197	2.223	2.202	
	Coarse gradation (3.4%)		2.214	2.216	2.198	
OMC-1.0%	Fine gradation (4.1%)		2.187	2.216	2.181	2.199
	Field gradation (4.0%)		2.210	2.228	2.206	2.185
	Coarse gradation (2.9%)		2.196	2.196	2.184	2.146
OMC-1.5%	Fine gradation (3.6%)			2.203	2.170	2.171
	Field gradation (3.5%)			2.215	2.180	2.176
	Coarse gradation (2.4%)			2.178	2.135	2.131



(a) Fine Gradation



(b) Field Gradation



(c) Coarse Gradation

Figure 5-9. Estimated Gmb vs. moisture content

5.5.3 Marshall stability test

CIR-Foam mixtures were compacted at room temperature (24°C) and cured in the oven at 40°C for three days, then air-cured for 29 days. Dry samples were cured in the oven at 25°C for one more day with the wet samples cured under water at 25°C for one more day. The Marshall stability ratio of the CIR-Foam mixtures were computed as follows:

$$\text{Marshall Stability Ratio (MSR)} = \frac{MS_{Wet}}{MS_{Dry}} \times 100$$

Where:

MS_{Wet} = Marshall stability under wet condition
MS_{Dry} = Marshall stability under dry condition

As shown in Figure 5-10, Marshall stability tests were performed at room temperature.

Figure 5-10. Marshall stability test

Table 5-13 summarizes Marshall stability values for dry and wet samples made at each combination of four different moisture contents and five foamed asphalt contents for three different gradations.

- **Fine gradation**

For dry samples of Fine gradation, as shown in Figure 5-11, the highest Marshall stability value was obtained at 2.5% FAC and OMC-1.0%. However, for wet samples of Fine gradation, as shown in Figure 5-11, all four FAC contents from 1.5% to 3.0% achieved the highest values at OMC and OMC-0.5%.

- **Field gradation**

For both dry and wet samples of Field gradation, as shown in Figures 5-12 the highest Marshall stability value was obtained again at 2.5 % FAC and OMC-0.5 % and OMC-1.0 %, respectively.

- **Coarse gradation**

For dry samples of Coarse gradation, as shown in Figure 5-13, the highest Marshall stability value was obtained at 2.0 % FAC and OMC-0.5 %. However, for wet samples of Coarse gradation, as shown in Figure 5-13, all three FAC contents from 1.5 % to 2.5 % achieved the highest values at OMC and OMC-0.5 %.

Table 5-13. Marshall stability values of CIR-Foam mixture for three different gradations

Moisture content/gradation \ Asphalt content			1.5	2.0	2.5	3.0	3.5
OMC	Fine (5.1%)	Dry	3356	3378	3731		
		Wet	3571	3037	3418		
	Field (5.0%)	Dry	3552	3177	3280		
		Wet	3069	2929	3068		
	Coarse (3.9%)	Dry	3499	3466	3418		
		Wet	3052	2862	3169		
OMC-0.5%	Fine (4.6%)	Dry		3445	3625	3354	
		Wet		3447	3343	3198	
	Field (4.5%)	Dry		3466	3683	3083	
		Wet		3068	3450	2825	
	Coarse (3.4%)	Dry		3735	3445	3328	
		Wet		2899	2939	2686	
OMC-1.0%	Fine (4.1%)	Dry		3461	3865	3409	3409
		Wet		3263	3165	3222	2763
	Field (4.0%)	Dry		3342	3491	3360	3537
		Wet		3294	3786	2814	2611
	Coarse (2.9%)	Dry		3587	3577	3419	2936
		Wet		2982	2889	2567	1971
OMC-1.5%	Fine (3.6%)	Dry			3665	3252	3381
		Wet			3563	2546	2732
	Field (3.5%)	Dry			3698	2913	2921
		Wet			3281	2912	2408
	Coarse (2.4%)	Dry			3428	2967	3232
		Wet			2374	2262	1787

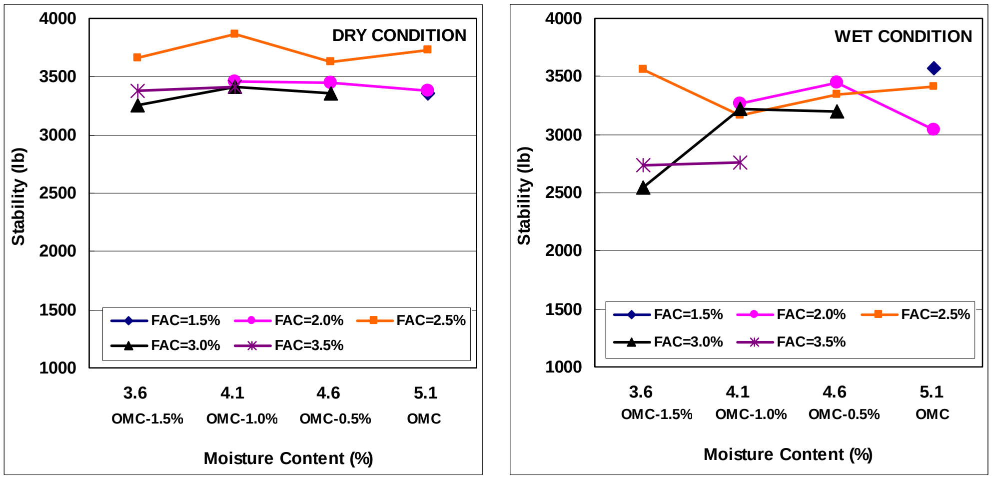


Figure 5-11. Stability vs. moisture content for dry and wet samples (Fine gradation)

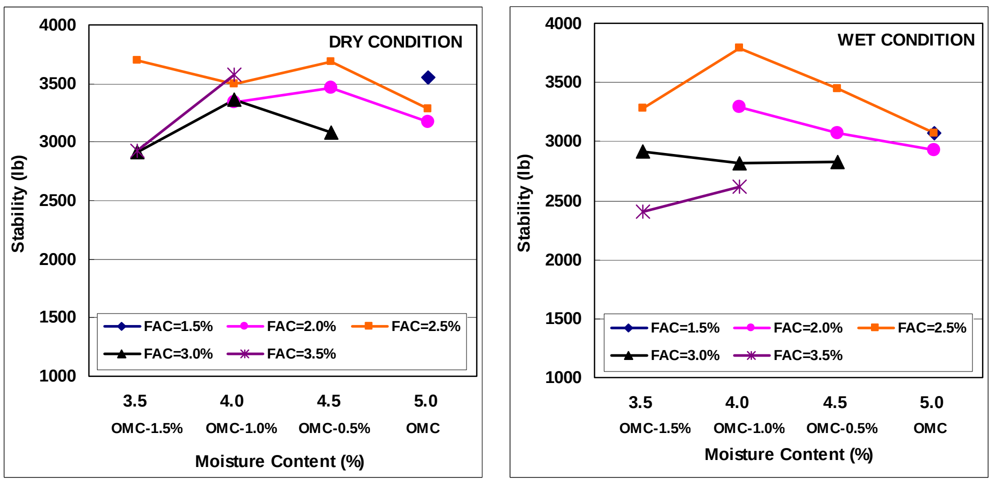


Figure 5-12. Stability vs. moisture content at dry and wet samples (Field gradation)

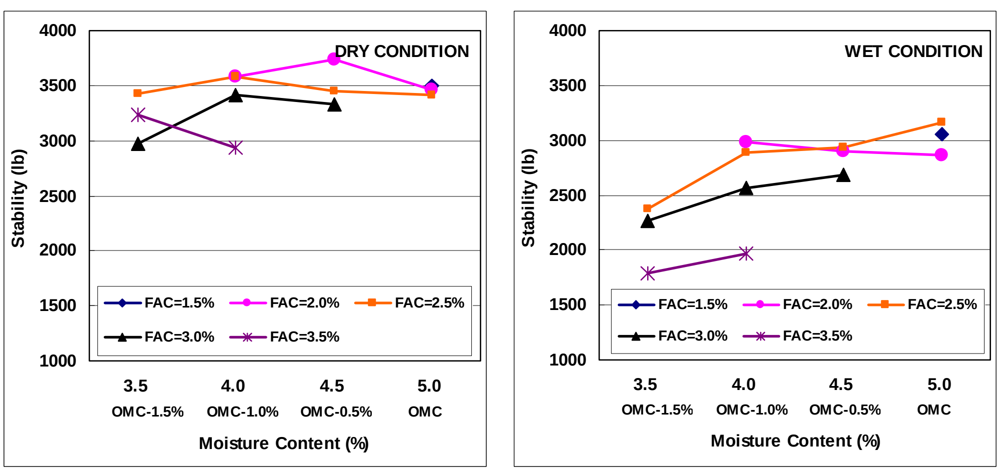


Figure 5-13. Stability vs. moisture content at dry and wet samples (Coarse gradation)

5.5.4 Indirect tensile test

The indirect tensile tests were performed using the Marshall machine and the100 mm diameter indirect tensile breaking head. The indirect tensile strength and the tensile strength ratio of the CIR-Foam mixtures were computed as follows:

Indirect tensile strength (ITS) = $\dfrac{2 \times P_{\max}}{\pi \times D \times t}$

Tensile strength ratio (TSR) = $\dfrac{ITS_{Wet}}{ITS_{Dry}} \times 100$

Where:

P_{max} = maximum load, lbs
D = specimen height before tensile test, inches
t = specimen diameter, inches
ITS_{Wet} = indirect tensile strength at wet condition
ITS_{Dry} = indirect tensile strength at dry condition

CIR-Foam mixtures were cured in the oven at 40°C for three days and cured in the air for 29 days. Dry samples were cured in the oven at 25°C for one more day, while the wet samples were cured under water at 25°C for one more day. As shown in Figure 5-14, the indirect tensile tests were performed at room temperature.

Figure 5-14. Indirect tensile test

Table 5-14 summarizes indirect tensile strength values for dry and wet samples made at each combination of four different moisture contents and five foamed asphalt contents for three different gradations.

- **Fine gradation**

For both dry and wet samples of the Fine gradation, as shown in Figure 5-15, the highest indirect tensile strength value was obtained at 2.5% FAC and OMC-1.0%.

- **Field gradation**

For both dry and wet samples of Field gradation, as shown in Figure 5-16, the highest indirect tensile strength value was obtained again at 2.5% FAC and at OMC-0.5% or OMC-1.0%. However, for both dry and wet samples, FAC 2.0% achieved the highest value at OMC-1.0%. For dry samples, FAC 2.0% also achieved the highest value at OMC.

- **Coarse gradation**

For dry samples of Coarse gradation, as shown in Figure 5-17, the highest indirect tensile strength value was obtained at both 2.0% and 2.5% FAC and OMC-0.5%. However, for wet samples of Coarse gradation, as shown in Figure 5-17, both 2.0% and 2.5% FAC achieved the highest values at OMC.

Table 5-14. Indirect tensile strength values of CIR-Foam mixture for three different gradations

Moisture content/gradation \ Asphalt content			1.5	2.0	2.5	3.0	3.5
OMC	Fine (5.1%)	Dry	66.2	55.7	71.6		
		Wet	43.3	50.7	78.6		
	Field (5.0%)	Dry	50.1	45.0	70.6		
		Wet	42.5	43.8	46.2		
	Coarse (3.9%)	Dry	51.4	53.3	55.3		
		Wet	35.3	38.8	39.2		
OMC-0.5%	Fine (4.6%)	Dry		69.0	79.0	47.6	
		Wet		52.4	85.9	49.6	
	Field (4.5%)	Dry		51.3	73.0	43.9	
		Wet		38.7	50.7	39.9	
	Coarse (3.4%)	Dry		56. 9	60.5	49.6	
		Wet		35.3	32.7	32.3	
OMC-1.0%	Fine (4.1%)	Dry		65.6	85.8	58.8	52.1
		Wet		49.4	89.3	49.2	35.1
	Field (4.0%)	Dry		68.5	72.9	43.9	40.2
		Wet		51.2	53.0	33.6	29.6
	Coarse (2.9%)	Dry		51.3	48.1	44.8	34.6
		Wet		27.4	31.2	25.7	27.0
OMC-1.5%	Fine (3.6%)	Dry			79.6	47.6	53.0
		Wet			70.0	38.8	36.6
	Field (3.5%)	Dry			62.1	40.6	40.7
		Wet			40.9	27.8	27.8
	Coarse (2.4%)	Dry			52.1	31.5	33.5
		Wet			35.1	18.7	19.9

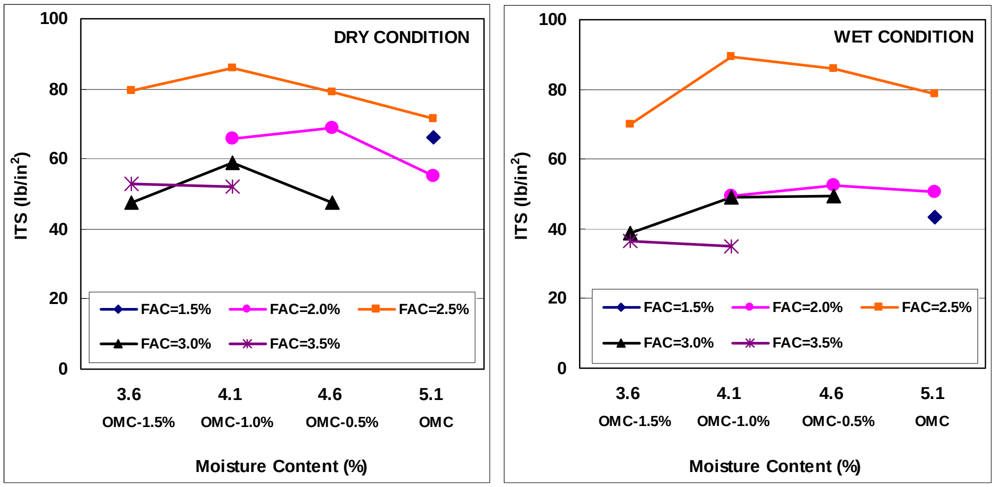


Figure 5-15. ITS vs. moisture content at dry and wet samples (Fine gradation)

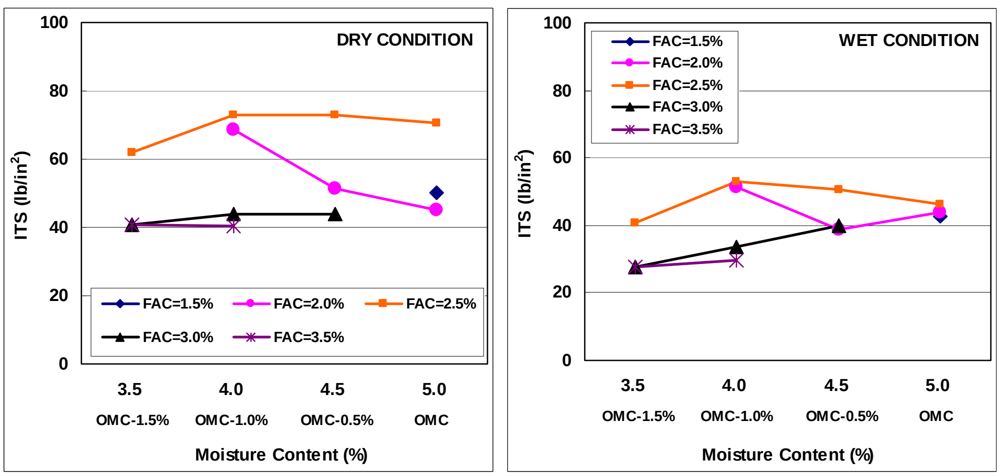


Figure 5-16. ITS vs. moisture content at dry and wet samples (Field gradation)

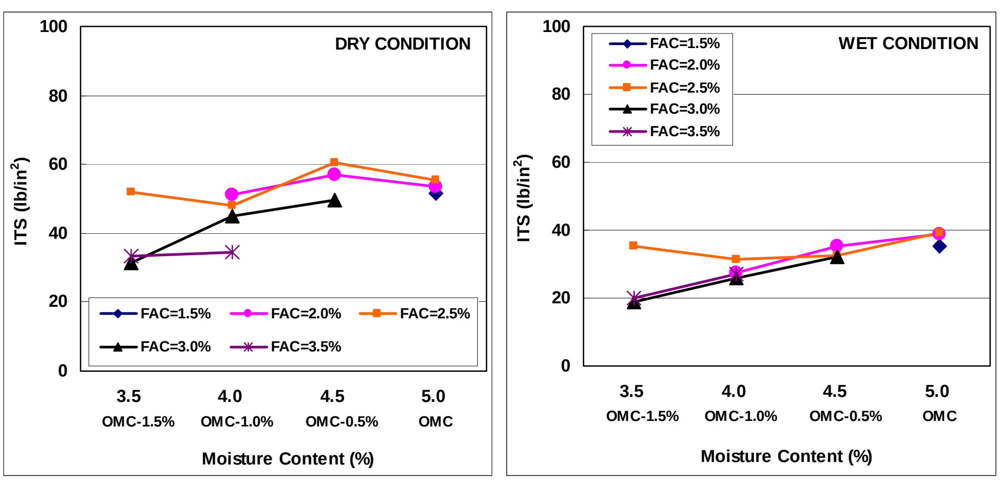


Figure 5-17. ITS vs. moisture content at dry samples (Coarse gradation)

5.6 Summary of first round test results

All laboratory test results of CIR-Foam mixtures for Fine, Field, and Coarse gradations are summarized in Tables 5-15, 5-16, and 5-17, and plotted in Figures 5-18, 5-19, 5-20, respectively. Based on these plots, the following conclusions were drawn.

Foaming process

The foaming process of the Wirtgen foaming equipment was validated by varying the amount of water and the asphalt content. A water content of 1.3% was used to create the optimum foaming characteristics at 170°C under air pressure of 4 bars and water pressure of 5 bars. The foamed asphalt injection pressure was measured constant at 1.5 bars regardless of air and water pressures. A 2.5 mm nozzle was used, which may be too large to create the best formed asphalt.

FAC content

Based on the preliminary data, maximum stability (both dry and wet), bulk density, and indirect tensile strength (both dry and wet) were obtained at 2.5% FAC at OMC-0.5% or OMC-1.0%. There was a significant drop in these values (except bulk density) at FAC contents above 2.5%.

Gradation

Based on the preliminary data for all FAC contents, the Fine gradation produced the highest stability and indirect tensile strengths. For given optimum FAC of 2.5%, the Coarse gradation produced a lower stability and indirect tensile strength than the Field gradation.

Water content

Based on the preliminary data, water content did not affect the test results significantly. The highest test values, however, were obtained at OMC-1.0% for Fine gradation, OMC-0.5% and OMC-1.0% for Field gradation, and OMC-0.5% for Coarse gradation.

Dry vs. wet

Based on our preliminary observations of the data, most wet specimens seemed to exhibit relatively high retained strength. This prompted us to change the wet process from soaking to vacuum moisture conditioning in the second round.

Table 5-15. Summary of laboratory test results of CIR-Foam mixtures at Fine gradation

Water content \ Asphalt content		1.5	2.0	2.5	3.0	3.5
OMC (5.1%)	Moisture	Optimum	Too much	Too much		
	Estimated Gmb	2.184	2.189	2.208		
	Stability (Dry/Wet)	3356 / 3571	3378 / 3037	3731 / 3418		
	ITS (Dry/Wet)	66.2 / 43.3	55.7 / 50.7	71.6 / 78.6		
OMC-0.5% (4.6%)	Moisture		Optimum	Optimum	Optimum	
	Estimated Gmb		2.196	2.220	2.193	
	Stability (Dry/Wet)		3445 / 3447	3625 / 3343	3354 / 3198	
	ITS (Dry/Wet)		69.0 / 52.4	79.0 / 85.9	47.6 / 49.6	
OMC-1.0% (4.1%)	Moisture		Optimum	Optimum	Optimum	Optimum
	Estimated Gmb		2.187	2.216	2.181	2.199
	Stability (Dry/Wet)		3461 / 3263	3865 / 3165	3409 / 3222	3409 / 2763
	ITS (Dry/Wet)		65.6 / 49.4	85.8 / 89.3	58.8 / 49.2	52.1 / 35.1
OMC-1.5% (3.6%)	Moisture			Too little	Too little	Optimum
	Estimated Gmb			2.203	2.170	2.171
	Stability (Dry/Wet)			3665 / 3563	3252 / 2546	3381 / 2732
	ITS (Dry/Wet)			79.6 / 70.0	47.6 / 38.8	53.0 / 36.6

Table 5-16. Summary of laboratory test results of CIR-Foam mixtures at Field gradation

Water content \ Asphalt content		1.5	2.0	2.5	3.0	3.5
OMC (5.0%)	Moisture	Too much	Too much	Too much		
	Estimated Gmb	2.194	2.197	2.235		
	Stability (Dry/Wet)	3552 / 3069	3177 / 2929	3280 / 3068		
	ITS (Dry/Wet)	50.1 / 42.5	45.0 / 43.8	70.6 / 46.2		
OMC-0.5% (4.5%)	Moisture		Too much	Optimum	Optimum	
	Estimated Gmb		2.197	2.223	2.202	
	Stability (Dry/Wet)		3466 / 3068	3683 / 3450	3083 / 2825	
	ITS (Dry/Wet)		51.3 / 38.7	73.0 / 50.7	43.9 / 39.9	
OMC-1.0% (4.0%)	Moisture		Optimum	Optimum	Too little	Optimum
	Estimated Gmb		2.210	2.228	2.206	2.185
	Stability (Dry/Wet)		3342 / 3294	3491 / 3786	3360 / 2814	3537 / 2611
	ITS (Dry/Wet)		68.5 / 51.2	72.9 / 53.0	43.9 / 33.6	40.2 / 29.6
OMC-1.5% (3.5%)	Moisture			Too little	Too little	Optimum
	Estimated Gmb			2.215	2.180	2.176
	Stability (Dry/Wet)			3698 / 3281	2913 / 2912	2921 / 2408
	ITS (Dry/Wet)			62.1 / 40.9	40.6 / 27.8	40.7 / 27.8

Table 5-17. Summary of laboratory test results of CIR-Foam mixtures at Coarse gradation

Water content \ Asphalt content		1.5	2.0	2.5	3.0	3.5
OMC (3.9%)	Moisture	Too much	Too much	Too much		
	Estimated Gmb	2.205	2.211	2.221		
	Stability (Dry/Wet)	3499 / 3052	3466 / 2862	3418 / 3169		
	ITS (Dry/Wet)	51.4 / 35.3	53.3 / 38.8	55.3 / 39.2		
OMC-0.5% (3.4%)	Moisture		Optimum	Optimum	Optimum	
	Estimated Gmb		2.214	2.216	2.198	
	Stability (Dry/Wet)		3735 / 2899	3445 / 2939	3328 / 2686	
	ITS (Dry/Wet)		56. 9 / 35.3	60.5 / 32.7	49.6 / 32.3	
OMC-1.0% (2.9%)	Moisture		Too little	Too little	Optimum	Optimum
	Estimated Gmb		2.196	2.196	2.184	2.146
	Stability (Dry/Wet)		3587 / 2982	3577 / 2889	3419 / 2567	2936 / 1971
	ITS (Dry/Wet)		51.3 / 27.4	48.1 / 31.2	44.8 / 25.7	34.6 / 27.0
OMC-1.5% (2.4%)	Moisture			Too little	Too little	Optimum
	Estimated Gmb			2.178	2.135	2.131
	Stability (Dry/Wet)			3428 / 2374	2967 / 2262	3232 / 1787
	ITS (Dry/Wet)			52.1 / 35.1	31.5 / 18.7	33.5 / 19.9

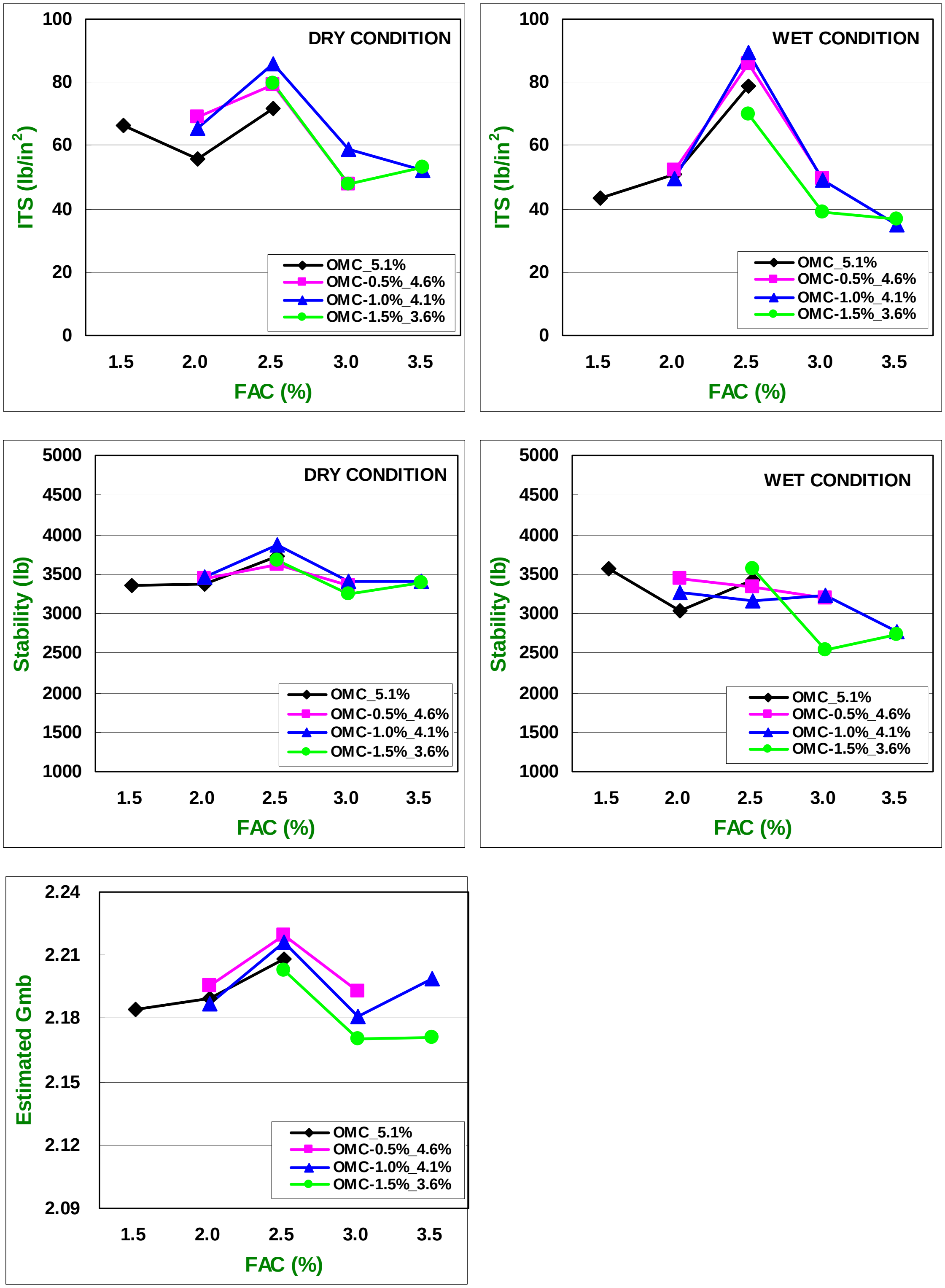


Figure 5-18. Plots of ITS, Stability, and Gmb vs. FAC for Fine gradation

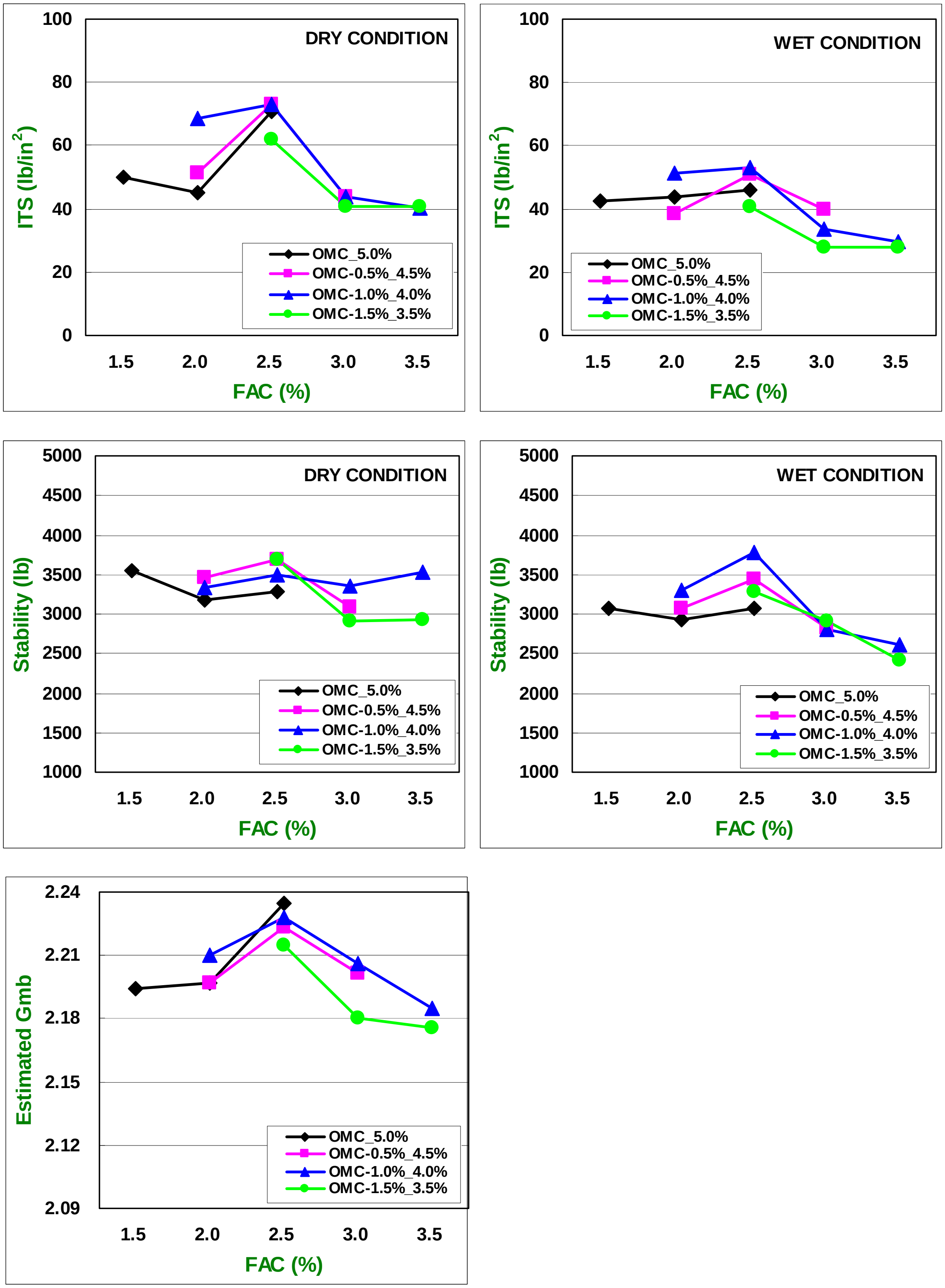


Figure 5-19. Plots of ITS, Stability, and Gmb vs. FAC for Field gradation

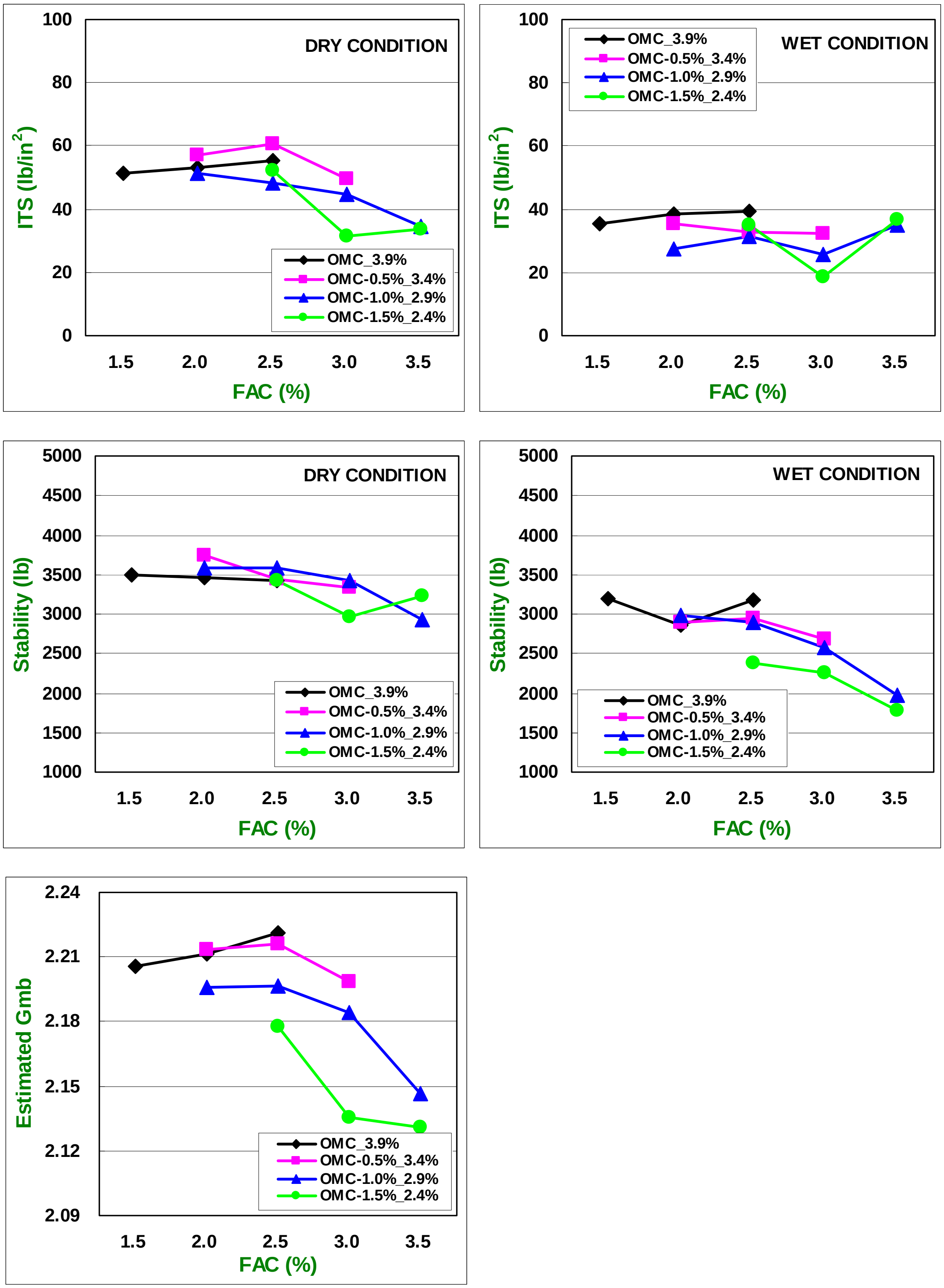


Figure 5-20. Plots of ITS, Stability, and Gmb vs. FAC for Coarse gradation

6. DETERMINATION OF MIX DESIGN PARAMETERS FOR CIR WITH FOAMED ASPHALT: SECOND ROUND

6.1 Introduction

With experience gained from the first round of tests we were able to improve the experimental design and laboratory testing procedures for the second round. Two major changes were made in the second round test procedure: (1) the wet condition procedure was changed from soaking to vacuum saturation, and (2) the same set of moisture contents were used for different gradations without performing the Modified Proctor test. Details of these changes are summarized in Table 6-1.

Table 6-1. Differences between first and second mix design

Items	First round	Second round
Asphalt binder	PG 52-34	PG 46-34
Number of samples	2 samples per set	3 samples per set
Water content of RAP	Fine gradation (5.1, 4.6%, 4.1%, and 3.9%) Field gradation (5.0%, 4.5%, 4.0%, and 3.5%) Coarse gradation (3.9%, 3.4%, 2.9%, and 2.4%)	Fine gradation (5.0 %, 4.5 %, 4.0 %, and 3.5%) Field gradations (4.5 %, 4.0 %, 3.5 %, and 3.0%) Coarse gradations (4.5 %, 4.0 %, 3.5 %, and 3.0%)
Dry curing condition	72 hours in 40° C oven	68 hours in 40° C oven
Wet curing condition	Soaking for 24 hours	20min soaking, 50 min Vacuum Saturation, and 10 min soaking
Extra curing condition	29 days at room temperature	None
Paper disk	Used	Not used

6.2 Determination of optimum foaming water content

Due to the limited availability of asphalt binders in the middle of the winder of 2002, the performance grade asphalt binder PG 46-34 was used instead of PG 52-34. PG 46-34 is nearly identical to PG 52-34; it barely missed the criteria at 52°C and met them at 51°C. The foamed asphalt test was conducted to determine the optimum foaming water content under the following conditions.

- Asphalt: PG 46-34
- Air pressure: 4 bars

- Water pressure: 5 bars
- Asphalt binder pressure: 1.5 bars
- Temperature of asphalt binder: 160°C to 180°C, at 10°C increments
- Water content: 1% to 5%, at 1% increments

Both expansion ratio and half-life were measured at water contents varying from 1% to 5%, at 1% increments. Two measurements were made for each level of water content. Table 6-2 shows test results of foaming characteristics at an asphalt temperature of 160°C. Figure 6-1 illustrates the optimum water content of 1.4% at an expansion ratio of 10 and a half-life of 12 seconds.

Table 6-2. Test results of foaming characteristics at 160°C

Water content (%)	Flow (l/h)	1 Measurement		2 Measurement		3 Measurement		Average	
		Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life
1.0	3.6	6.7	16	7.8	15			7.2	15.5
2.0	7.2	15.6	8	15.6	8			15.6	8.0
3.0	10.8	18.9	7	18.9	7			18.9	7.0
4.0	14.4	23.3	4	22.2	5			22.8	4.5
5.0	18.0	25.6	3	25.6	5			25.6	4.0

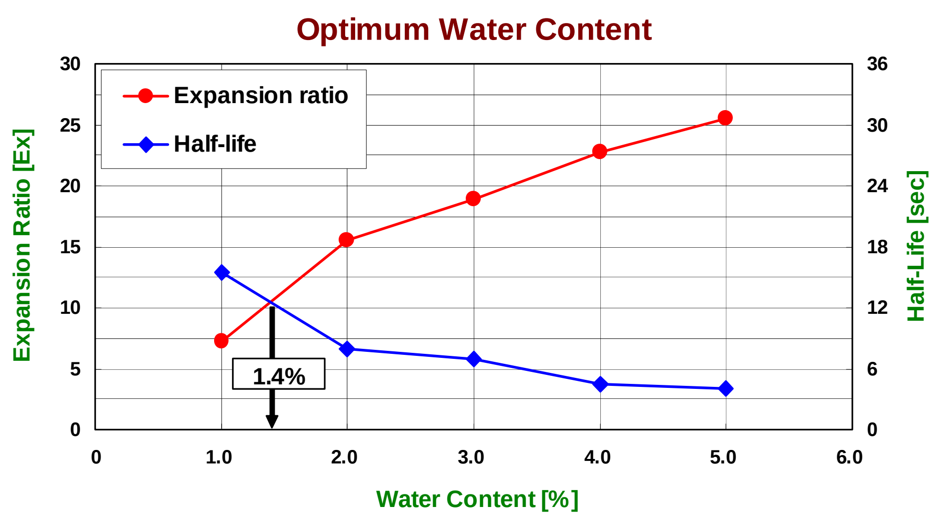


Figure 6-1. Plot of expansion ratio and half-life against water content at 160°C

Table 6-3 shows test results of foaming characteristics at an asphalt temperature of 170°C. Figure 6-2 illustrates the optimum water content of 1.3% at an expansion ratio of 10 and a half-life of 12 seconds.

Table 6-3. Test results of foaming characteristics at 170°C

Water content (%)	Flow (l/h)	1		2		3		Average	
		Measurement		Measurement		Measurement			
		Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life
1.0	3.6	10.0	13	7.8	14			8.9	13.5
2.0	7.2	13.3	6	15.6	7			14.4	6.5
3.0	10.8	20.0	6	18.9	5			19.4	5.5
4.0	14.4	22.2	4	22.2	5			22.2	4.5
5.0	18.0	25.6	4	24.4	3			25.0	3.5

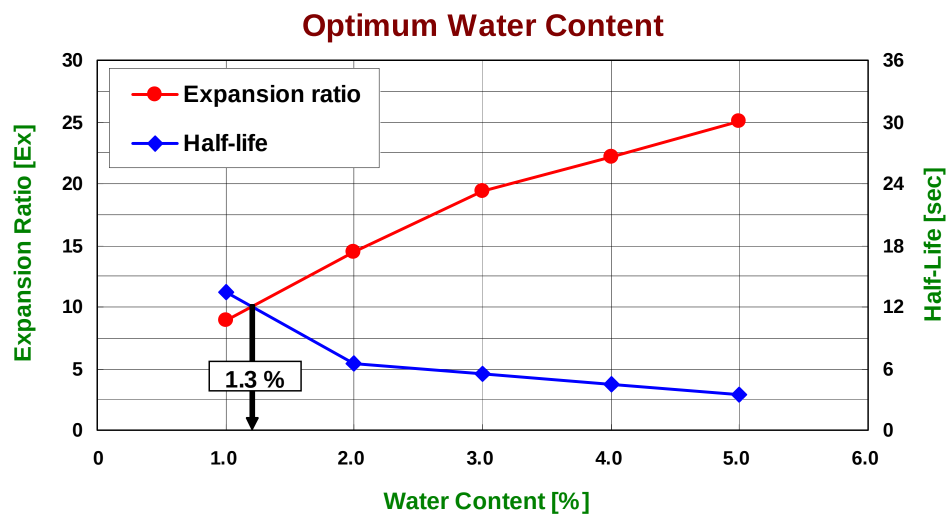


Figure 6-2. Plot of expansion ratio and half-life against water content at 170°C

Table 6-4 shows test results of foaming characteristics at an asphalt temperature of 180°C. Figure 6-3 illustrates the optimum water content of 1.1% at an expansion ratio of 11 and a half-life of 13 seconds.

Table 6-4. Test results of foaming characteristics at 180°C

Water content (%)	Flow (l/h)	1 Measurement		2 Measurement		3 Measurement		Average	
		Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life	Ex-ratio	Half-life
1.0	3.6	10.0	12	11.3	14			10.6	13.0
2.0	7.2	17.5	5	18.8	5			18.1	5.0
3.0	10.8	21.3	4	21.3	5			21.3	4.5
4.0	14.4	26.3	4	27.5	5			26.9	4.5
5.0	18.0	28.8	3	30.0	6			29.4	4.0

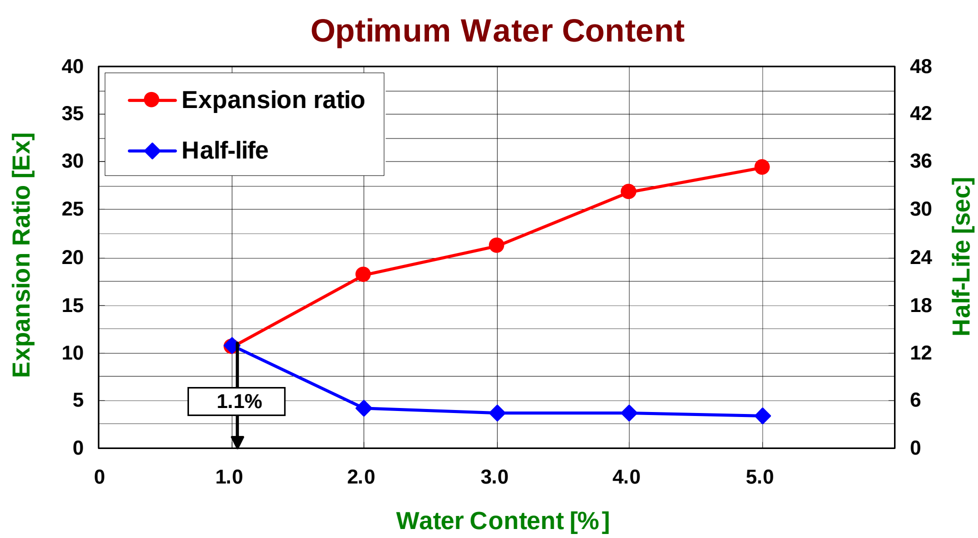


Figure 6-3. Plot of expansion ratio and half-life against water content at 180°C

Table 6-5 summarizes the foaming characteristics at an asphalt temperature of 160°C, 170°C and 180°C. The table shows, as expected, that increasing temperatures led to a higher expansion ratio and half-life. As an optimum, we selected the foaming temperature of 170°C with an optimum foaming water content of 1.3%.

Table 6-5. Final results of optimum foaming asphalt content

Temperature (°C)	**Expansion ratio**	**Half-life (sec)**	**OMC (%)**
160	10	12	1.4
170	10	12	1.3
180	11	13	1.1

6.3 Experimental design

Table 6-6 shows twenty combinations of asphalt and water contents, which were selected to create test samples for each of the three different aggregate gradations. The same RAP gradations used for the first round experiment were also used for this experiment. We measured bulk specific gravity (estimate), Marshall stability (wet and dry), and indirect tensile strength (wet and dry) for each mixture. Selected mix design parameters for the laboratory experiment are summarized in the flowchart shown in Figure 6-4.

Table 6-6. Mix design matrix for three gradations (second round)

Asphalt content / Moisture content		1.5	2.0	2.5	3.0	3.5	4.0
Fine gradation	5.0%						
	4.5%						
	4.0%						
	3.5%						
Field Gradation	4.5%						
	4.0%						
	3.5%						
	3.0%						
Coarse Gradation	4.5%						
	4.0%						
	3.5%						
	3.0%						

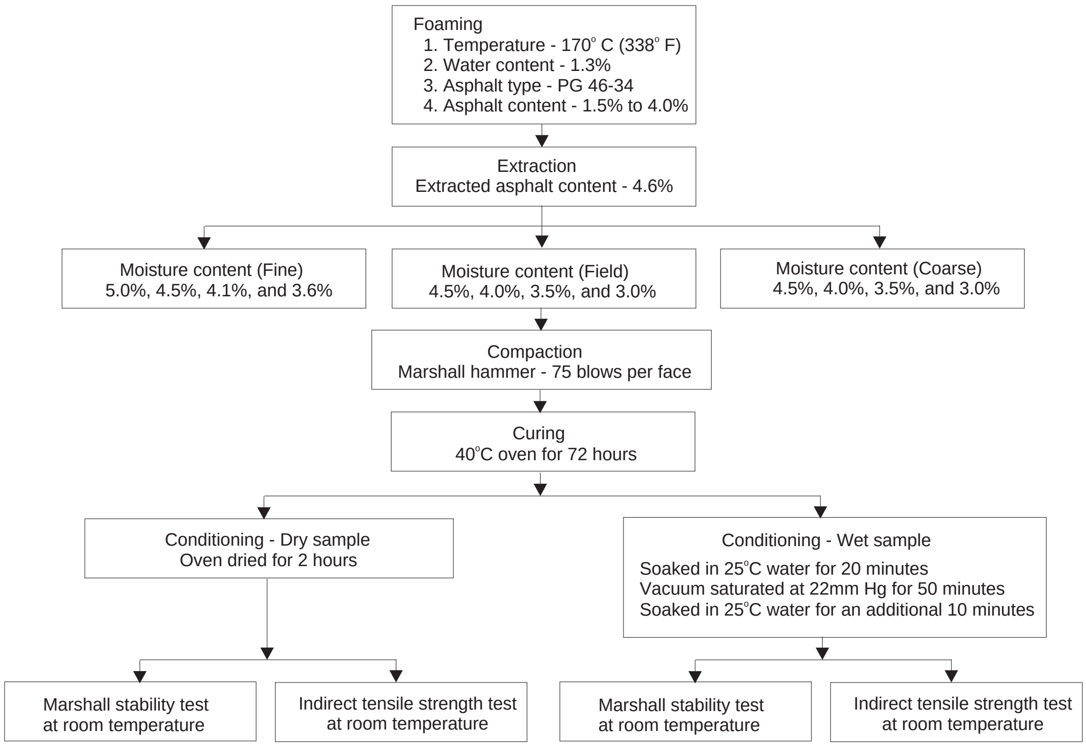


Figure 6-4. Laboratory mix design procedure (second round)

6.3.1 Sample preparation

- **Fine gradation**

Water Content (WC) of 5.0% clearly exhibited an excessive amount of moisture for all Foamed Asphalt Contents (FAC). Based on our visual observations during the compaction process, WC of 4.5% seemed optimum for FACs of 1.5%, 2.0%, and 2.5%, while WCs of 4.0% were optimum for FACs of 2.5%, 3.0% and 3.5%. For a WC of 3.5%, we had difficulty compacting and molding the samples due to lack of moisture.

- **Field gradation**

For field gradations, the same observations were made on the impact of WCs and FACs on mixture compactability.

- **Coarse gradation**

WC of 4.5% clearly exhibited an excessive amount of moisture for all Foamed Asphalt Contents (FAC). Visual observations during the compaction process indicated that WC of

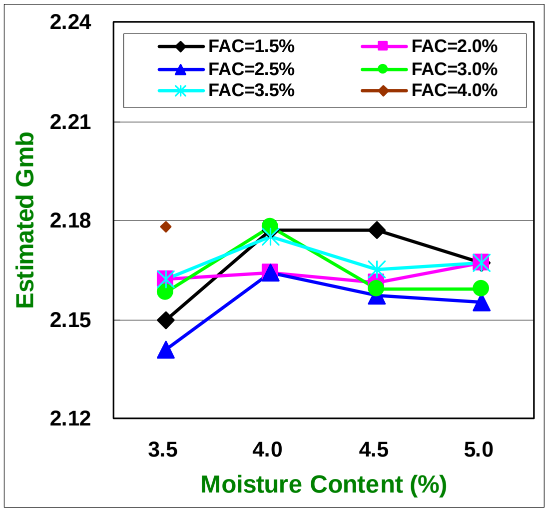
4.0% seemed optimum for FAC of 2.0%, and a WC of 3.5% was optimum for all FACs. For WC of 3.0%, we had difficulty compacting and molding the samples due to lack of moisture.

6.3.2 Density measurement

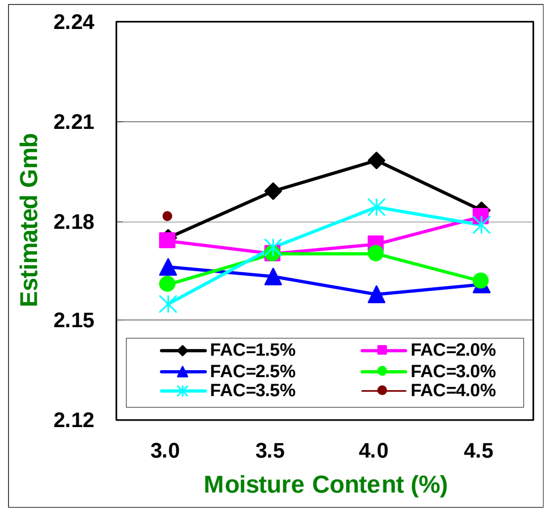
The bulk specific gravities (Gmb) of the CIR-Foam mixtures were estimated by measuring the volume of Marshall specimens using a caliper. Table 6-7 summarizes bulk specific gravities of Marshall specimens for three different gradations, four different moisture contents and five foamed asphalt contents. Please note that the densities are lower than the ones measured during the first round, which might have resulted from the recalibration of Marshall hammer. Estimated bulk specific gravities of Fine, Field, and Coarse gradations are plotted against four different moisture contents and five foamed asphalt contents (FAC) in Figure 6-5.

Table 6-7. Estimated Gmb values of CIR-Foam mixtures for three different gradations

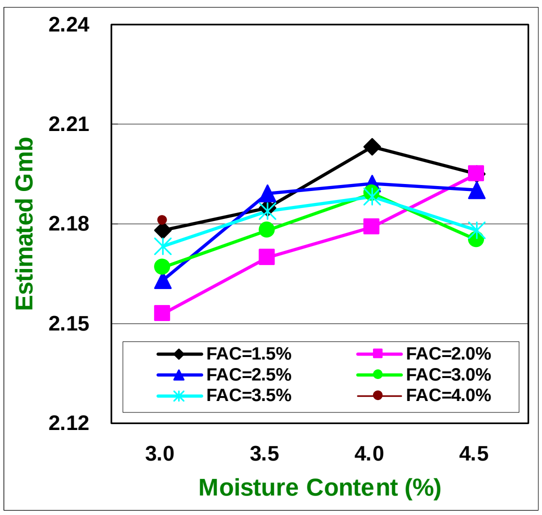
Gradation (moisture content) \ Asphalt Content (%)	1.5	2.0	2.5	3.0	3.5	4.0
Fine gradation (5.0 %)	2.167	2.167	2.155	2.159	2.167	
Field gradation (4.5 %)	2.183	2.181	2.161	2.162	2.179	
Coarse gradation (4.5 %)	2.192	2.195	2.19	2.175	2.178	
Fine gradation (4.5 %)	2.177	2.161	2.157	2.159	2.165	
Field gradation (4.0 %)	2.198	2.173	2.158	2.17	2.184	
Coarse gradation (4.0 %)	2.203	2.179	2.192	2.189	2.188	
Fine gradation (4.0 %)	2.177	2.164	2.164	2.178	2.175	
Field gradation (3.5 %)	2.189	2.170	2.163	2.17	2.172	
Coarse gradation (3.5 %)	2.185	2.17	2.189	2.178	2.184	
Fine gradation (3.5 %)	2.150	2.162	2.141	2.158	2.162	2.178
Field gradation (3.0%)	2.175	2.174	2.166	2.161	2.155	2.181
Coarse gradation (3.0%)	2.178	2.153	2.163	2.167	2.173	2.181



(a) Fine gradation



(b) Field gradation



(c) Coarse gradation

Figure 6-5. Estimated Gmb vs. moisture content

6.3.3 Marshall stability test

CIR-Foam mixtures were compacted at room temperature (23°C) and cured in the oven at 40°C for 68 hours. After oven curing, the samples were allowed to cool to room temperature. This normally took about 2 hours, but was reduced to 15 minutes when a fan was used (Figure 6-6).

Figure 6-6. Cooling the cured samples

Dry samples for Marshall testing were cured in the oven at 25°C for two hours. Wet samples were placed in 25°C water for 20 minutes and vacuumed saturated at 20 mm Hg for 50 minutes (see Figure 6-7). The wet samples were left under water for additional 10 minutes.

Figure 6-7. Vacuum saturation for making wet samples

Table 6-8 summarizes Marshall stability values for dry and wet samples made at each combination of four different moisture contents and six foamed asphalt contents for three different gradations.

- **Fine gradation**

As shown in Figure 6-8, the high Marshall stability values for dry samples were obtained at 1.5% FAC for all WCs, whereas for wet samples, the highest Marshall stability values were obtained at 1.5% FAC and 4.5% and 5.0% WCs.

- **Field gradation**

Figure 6-9 shows that the results obtained for the Field gradation were nearly identical to those produced by the Fine gradation. For wet samples, however, the Field gradation resulted in higher stability values than the Fine gradation.

- **Coarse gradation**

Figure 6-10 indicates that for the Coarse gradation, high Marshall stability values for dry sample were obtained at 2.0% FAC and all WCs whereas, for wet samples the highest Marshall stability values were obtained at 2.5% FAC and 4.0% and 4.5% WC.

Table 6-8. Marshall stability values of CIR-Foam mixture for three different gradations

Gradation (moisture content) \ Asphalt content		1.5	2.0	2.5	3.0	3.5	4.0
Fine (5.0 %)	Dry	3594.2	3405.2	3269.5	3224.8	3083.3	
	Wet	2350.0	1873.3	1861.0	1943.0	1833.3	
Field (4.5 %)	Dry	3437.8	3384.6	3012.9	3278.4	3214.0	
	Wet	2713.3	2345.0	2353.3	2346.7	2096.7	
Coarse (4.5 %)	Dry	3419.5	3418.5	3365.7	3405.6	3252.3	
	Wet	2730.3	2381.7	2764.7	2321.7	2090.0	
Fine (4.5 %)	Dry	3519.3	3307.0	3443.6	3485.1	3109.0	
	Wet	2384.1	2216.7	1996.7	1978.3	1746.7	
Field (4.0 %)	Dry	3551.8	3414.0	3028.3	3366.6	3158.3	
	Wet	2640.0	2450.0	2316.7	2241.7	2306.7	
Coarse (4.0 %)	Dry	3549.6	3451.0	3288.2	3431.1	3186.7	
	Wet	2340.0	2458.3	2605.0	2268.3	2235.0	
Fine (4.0 %)	Dry	3533.4	3455.0	3360.8	3426.3	3406.7	
	Wet	2123.3	2127.3	2326.0	2028.3	1943.3	
Field (3.5 %)	Dry	3557.7	3401.4	3291.3	3208.5	2818.0	
	Wet	2553.3	2380.0	2613.3	2085.0	2240.0	
Coarse (3.5 %)	Dry	3674.2	3469.8	3386.2	3309.4	3157.0	
	Wet	2460.0	2313.3	2401.7	2403.3	2196.7	
Fine (3.5 %)	Dry	3689.4	3441.5	3483.5	3117.7	3236.7	3261.0
	Wet	2230.0	2240.0	2243.3	1976.7	2223.3	1943.3
Field (3.0 %)	Dry	3588.8	3215.2	3327.4	3233.3	2931.0	3249.1
	Wet	2633.3	2456.7	2476.7	2005.0	2430.0	2223.3
Coarse (3.0 %)	Dry	3488.1	3387.5	3279.5	3200.7	3023.0	3185.9
	Wet	2500.0	2486.7	2440.0	2326.7	2486.7	1926.7

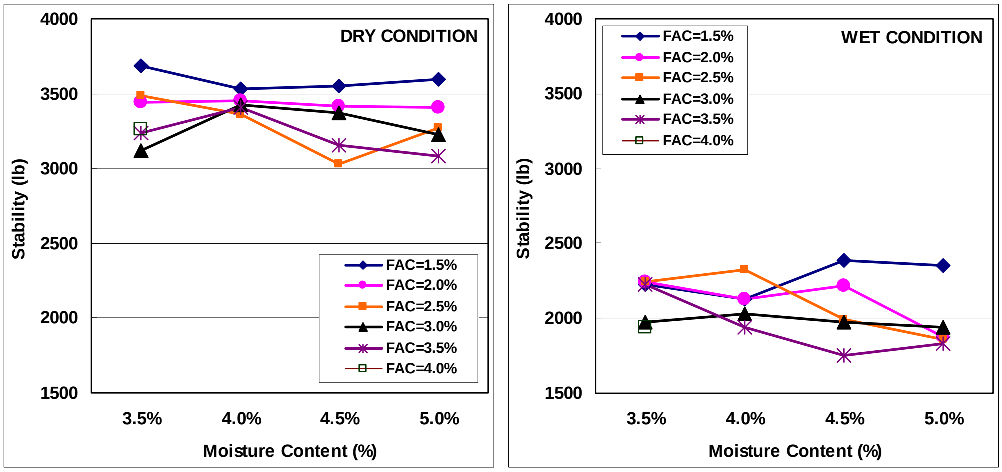


Figure 6-8. Stability vs. moisture content for dry and wet samples (Fine gradation)

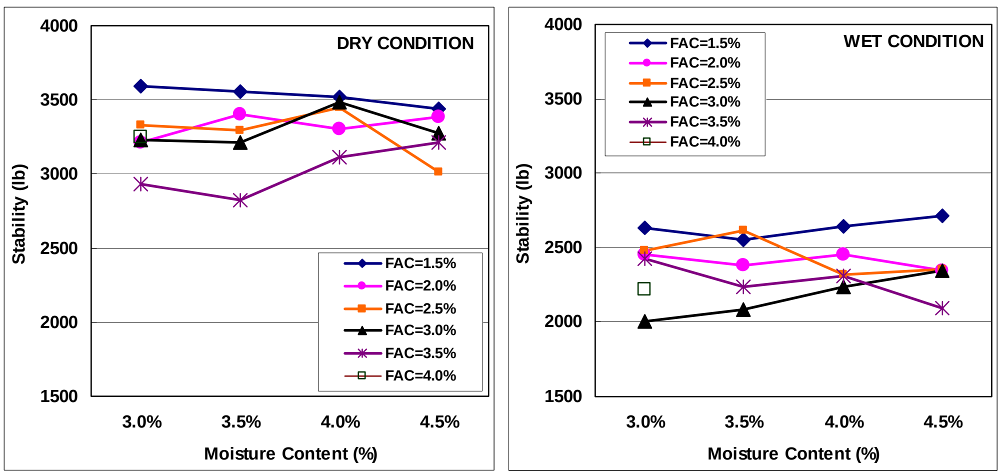


Figure 6-9. Stability vs. moisture content for dry and wet samples (Field gradation)

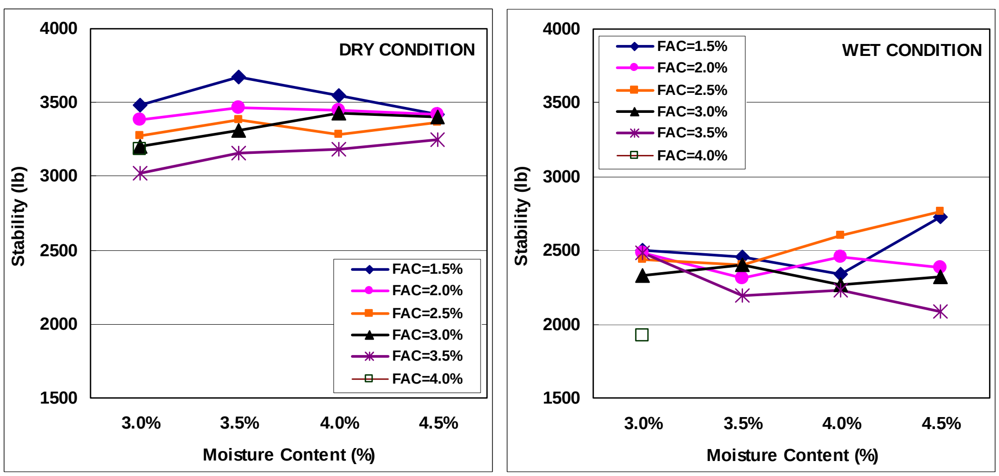


Figure 6-10. Stability vs. moisture content for dry and wet samples (Coarse gradation)

6.3.4 Indirect tensile test

For the indirect tensile test, the sample condition process was identical to that used for the Marshall test. Table 6-9 summarizes the indirect tensile strength values for dry and wet samples made at each combination of four different moisture contents and six foamed asphalt contents for three different gradations. It is interesting to note that the trend in indirect tensile tests results is very similar to the trend found in the Marshall stability test.

- **Fine gradation**

As shown in Figure 6-11, the high indirect tensile strengths for dry samples were obtained at 1.5% and 2.0% FAC for WCs of 3.5%, 4.0% and 4.5%. For wet samples the highest indirect tensile strengths were obtained at 2.5% FAC and WCs of 3.5%, 4.0%, and 4.5%. These values dropped significantly when WC was 5.0%.

- **Field gradation**

The Field gradation results were nearly identical to those obtained for the Fine gradation, as may be seen in Figure 6-12. For wet samples, however, Field gradation produced higher strengths than Fine gradation.

- **Coarse gradation**

Figure 6-13 shows that with the Coarse gradation, high indirect tensile strengths for the dry sample were obtained at 2.0% FAC and 4.0% WC, whereas for wet samples the highest indirect tensile strengths were obtained at 2.5% FAC and 4.0% and 4.5% WC.

Table 6-9. Indirect tensile strength values of CIR-Foam mixture for three different gradations

Gradation (moisture content) \ Asphalt content		1.5	2.0	2.5	3.0	3.5	4.0
Fine (5.0 %)	Dry	42.0	42.0	40.2	45.3	34.6	
	Wet	19.5	14.8	14.4	19.2	13.9	
Field (4.5 %)	Dry	45.3	44.3	38.1	39.8	32.6	
	Wet	21.7	21.4	26.7	22.1	20.4	
Coarse (4.5 %)	Dry	40.0	39.9	44.1	42.8	31.4	
	Wet	21.6	22.4	31.9	18.0	23.0	
Fine (4.5 %)	Dry	57.3	51.9	51.4	38.6	36.2	
	Wet	19.5	17.6	20.5	17.1	16.8	
Field (4.0 %)	Dry	49.7	47.2	35.5	36.4	39.2	
	Wet	24.2	23.9	22.9	24.1	22.8	
Coarse (4.0 %)	Dry	49.8	51.9	47.8	37.7	32.0	
	Wet	20.8	19.2	26.7	19.8	22.6	
Fine (4.0 %)	Dry	51.9	51.1	41.6	39.4	34.1	
	Wet	16.8	18.4	21.4	15.7	17.0	
Field (3.5 %)	Dry	49.9	45.8	41.6	35.2	34.8	
	Wet	22.3	25.9	29.3	20.3	19.5	
Coarse (3.5 %)	Dry	46.2	41.5	39.4	35.2	31.7	
	Wet	20.4	23.3	22.5	20.1	21.3	
Fine (3.5 %)	Dry	53.6	53.3	35.8	39.7	38.7	37.9
	Wet	19.3	18.4	21.5	15.1	22.3	18.2
Field (3.0 %)	Dry	51.6	44.6	43.2	38.2	35.3	32.9
	Wet	23.8	23.3	29.1	20.8	21.3	23.6
Coarse (3.0 %)	Dry	46.4	42.7	41.2	35.6	35.4	34.4
	Wet	19.6	20.1	23.0	18.5	21.9	22.3

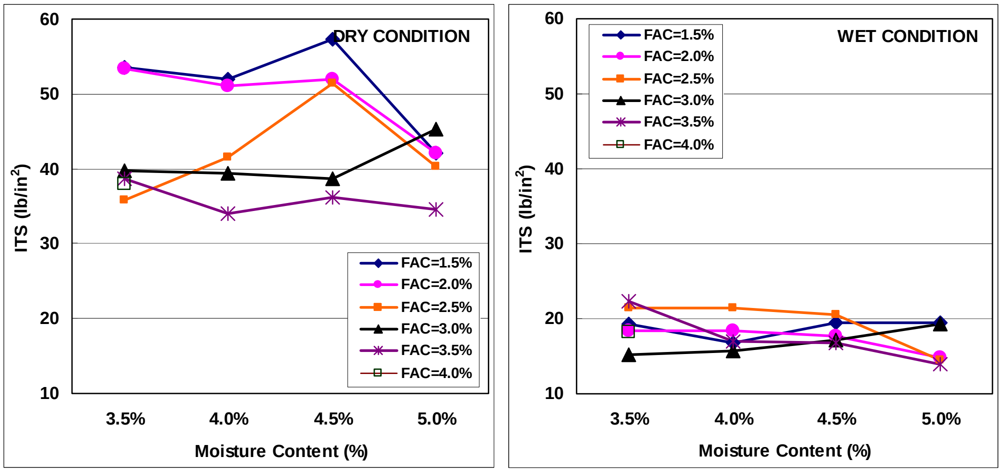


Figure 6-11. ITS vs. moisture content at dry and wet samples (Fine gradation)

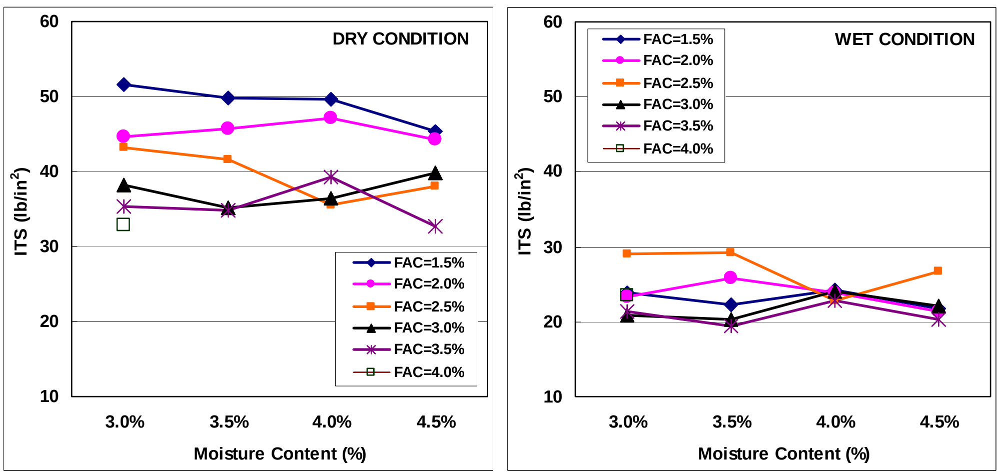


Figure 6-12. ITS vs. moisture content at dry and wet samples (Field gradation)

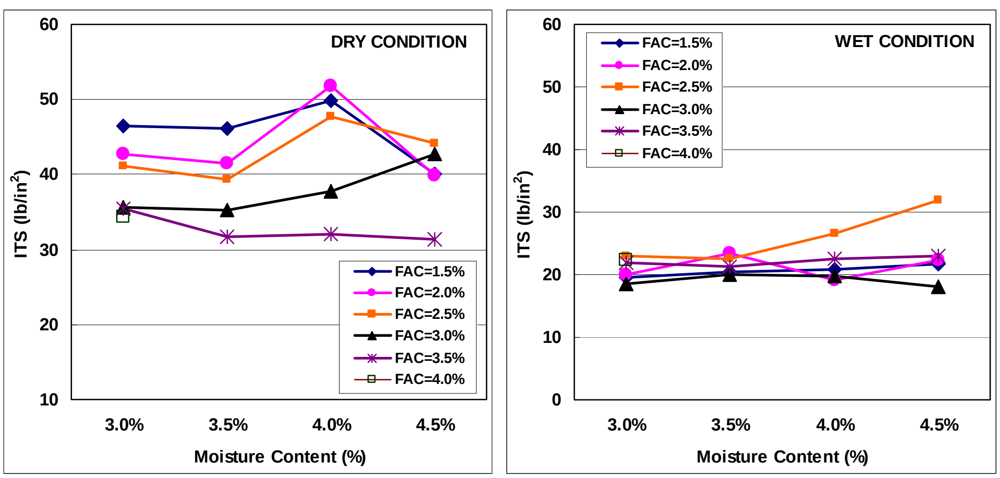


Figure 6-13. ITS vs. moisture content at dry and wet samples (Coarse gradation)

6.4 Summary of second round test results

All laboratory test results of CIR-Foam mixtures for Fine, Field, and Coarse gradations are summarized in Tables 6-10, 6-11, and 6-12, and plotted in Figures 6-14, 6-15, 6-16, respectively. Based on these plots, the following conclusions may be drawn.

- **FAC content**

For dry samples, low FAC of 1.5% produced the highest Marshall stability values and indirect tensile strengths for all WCs. However, for wet samples, 2.5% FAC produced the highest values for WCs of 3.5%, 4.0%, and 4.5% (for Coarse gradation only). It is interesting to note that for Field gradation, 1.5% FAC produced higher Marshall stability than 2.5% FAC.

- **Gradation**

For wet samples, Fine gradation produced the lowest stability and indirect tensile strength. For given optimum FAC of 2.5%, the Coarse aggregates produced the highest stability and indirect tensile strength.

- **Water content**

Water content did not affect the test results significantly. The highest test values, however, were obtained at 4.5% WC for Fine gradation, 4.0 % for Field gradation, and 3.5% to 4.0% for Coarse gradation.

- **Dry vs. wet**

Due to the vacuum saturation conditioning process, most wet specimens lost stability and tensile strength by up to 50%. This indicates that CIR-Foam mixtures are susceptible to water damage. Test values of dry samples were higher at low FAC of 1.5% but lost significant strength when vacuum-saturated; those at 2.5 % FAC, however, retained their wet strength reasonably well.

Table 6-10. Summary of laboratory test results of CIR-Foam mixtures at Fine gradation

Moisture content \ FAC		1.5	2.0	2.5	3.0	3.5	4.0
5.0%	Moisture	Too much	Too much	Too much	Too much	Too much	
	Estimated Gmb	2.167	2.167	2.155	2.159	2.167	
	Stability (Dry/Wet)	3594 / 2350	3405 / 1873	3270 / 1861	3225 / 1943	3083 / 1833	
	ITS (Dry/Wet)	42.0 / 19.5	42.0 / 14.8	40.2 / 14.4	45.3 / 19.2	34.6 / 13.9	
4.5%	Moisture	Optimum	Optimum	Optimum	Too much	Too much	
	Estimated Gmb	2.177	2.161	2.157	2.159	2.165	
	Stability (Dry/Wet)	3519 / 2384	3307 / 2216	3444 / 1997	3485 / 1978	3109 / 1747	
	ITS (Dry/Wet)	57.3 / 19.5	51.9 / 17.6	51.4 / 20.5	38.6 /17.1	36.2 / 16.8	
4.0%	Moisture	Too little	Too little	Optimum	Optimum	Optimum	
	Estimated Gmb	2.177	2.164	2.164	2.178	2.176	
	Stability (Dry/Wet)	3533 / 2133	3455 / 2127	3361 / 2326	3426 / 2028	3407 / 1943	
	ITS (Dry/Wet)	51.6 / 16.8	51.1 / 18.4	41.6 / 21.4	39.4 / 15.7	34.1 / 17.0	
3.5%	Moisture	Too little	Too little	Too little	Too little	Too little	Too little
	Estimated Gmb	2.150	2.162	2.141	2.158	2.162	2.178
	Stability (Dry/Wet)	3689 / 2230	3442 / 2240	3484 / 2243	3118 /1977	3237 / 2223	3261 / 1943
	ITS (Dry/Wet)	53.6 / 19.3	53.3 / 18.4	35.8 / 21.5	39.7 / 15.1	38.4 / 22.3	37.9 / 18.2

Table 6-11. Summary of laboratory test results of CIR-Foam mixtures at Field gradation

Moisture content \ Asphalt content		1.5	2.0	2.5	3.0	3.5	4.0
4.5%	Moisture	Too much	Too much	Too much	Too much	Too much	
	Estimated Gmb	2.183	2.181	2.161	2.162	2.179	
	Stability (Dry/Wet)	3438 / 2713	3385 / 2345	3013 / 2353	3278 / 2347	3214 / 2097	
	ITS (Dry/Wet)	45.3 / 21.7	44.3 / 21.4	38.1 /26.7	39.8 / 22.1	32.6 / 20.4	
4.0%	Moisture	Optimum	Optimum	Optimum	Too much	Too much	
	Estimated Gmb	2.198	2.173	2.158	2.170	2.184	
	Stability (Dry/Wet)	3552 / 2640	3414 / 2450	3028 / 2317	3367 / 2242	3158 / 2307	
	ITS (Dry/Wet)	49.7 / 24.2	47.2 / 23.9	35.5 / 22.9	36.4 / 24.1	39.2 / 22.8	
3.5%	Moisture	Too little	Too little	Optimum	Optimum	Optimum	
	Estimated Gmb	2.189	2.170	2.163	2.170	2.172	
	Stability (Dry/Wet)	3558 / 2553	3401 / 2380	3291 / 2613	3209 / 2085	2818 / 2240	
	ITS (Dry/Wet)	49.9 / 22.3	45.8 / 25.9	41.6 / 29.3	35.2 / 20.3	34.8 / 19.5	
3.0%	Moisture	Too little	Too little	Too little	Too little	Too little	Too little
	Estimated Gmb	2.175	2.174	2.166	2.161	2.155	2.181
	Stability (Dry/Wet)	3589 / 2633	3215 / 2457	3327 / 2477	3233 / 2005	2931 / 2430	3249 / 2223
	ITS (Dry/Wet)	51.6 / 23.8	44.6 / 23.3	43.2 / 29.1	38.2 / 20.8	35.5 / 21.3	32.9 / 23.6

Table 6-12. Summary of laboratory test results of CIR-Foam mixtures at Coarse gradation

Moisture content \ Asphalt content		1.5	2.0	2.5	3.0	3.5	4.0
4.5%	Moisture	Too much	Too much	Too much	Too much	Too much	
	Estimated Gmb	2.192	2.195	2.190	2.175	2.178	
	Stability (Dry/Wet)	3420 / 2730	3419 / 2382	3366 / 2765	3406 / 2322	3252 / 2090	
	ITS (Dry/Wet)	40.0 / 21.6	39.9 / 22.4	44.1 / 31.9	42.8 / 18.0	31.4 / 23.0	
4.0%	Moisture	Optimum	Optimum	Too much	Too much	Optimum	
	Estimated Gmb	2.203	2.179	2.192	2.189	2.188	
	Stability (Dry/Wet)	3550 / 2340	3451 / 2458	3288 / 2605	3431 / 2268	3187 / 2235	
	ITS (Dry/Wet)	49.8 / 20.8	51.9 / 19.2	47.8 / 26.7	37.7 / 19.8	32.0 / 22.6	
3.5%	Moisture	Too little	Optimum	Optimum	Optimum	Optimum	
	Estimated Gmb	2.185	2.170	2.189	2.178	2.184	
	Stability (Dry/Wet)	3674 / 2460	3470 / 2313	3386 / 2402	3309 / 2403	3157 / 2197	
	ITS (Dry/Wet)	46.2 / 20.4	41.5 / 23.3	39.4 /22.5	35.2 / 20.1	31.7 / 21.3	
3.0%	Moisture	Too little	Too little	Too little	Too little	Too little	Too little
	Estimated Gmb	2.178	2.153	2.163	2.167	2.173	2.181
	Stability (Dry/Wet)	3488 / 2500	3388 / 2487	3280 / 2440	3201 / 2327	3023 / 2487	3186 / 1927
	ITS (Dry/Wet)	46.4 / 19.6	42.7 / 20.1	41.2 /23.0	35.6 / 18.5	35.4 / 21.9	34.4 / 22.3

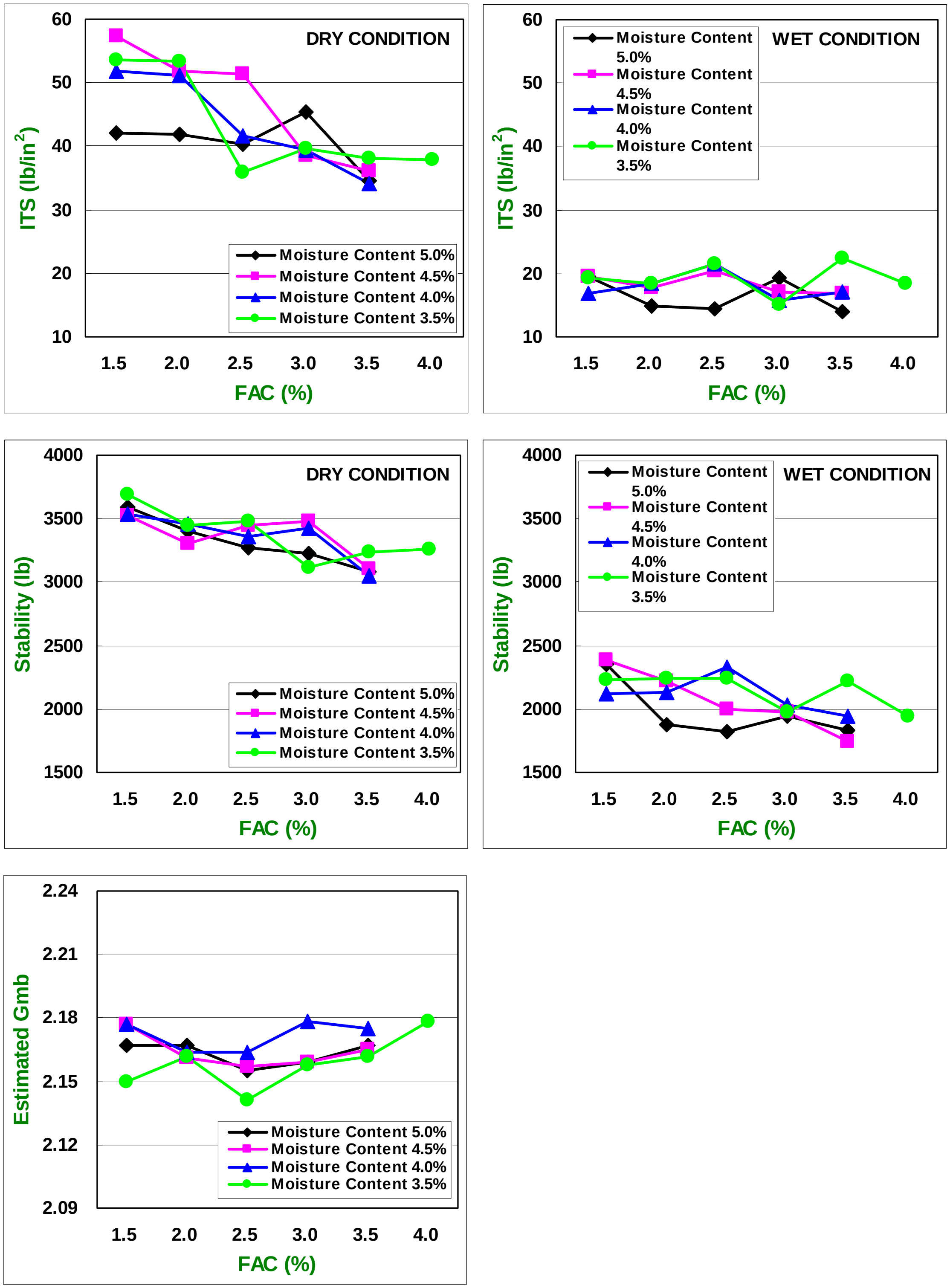


Figure 6-14. Plots of ITS, Stability, and Gmb vs. FAC for Fine gradation

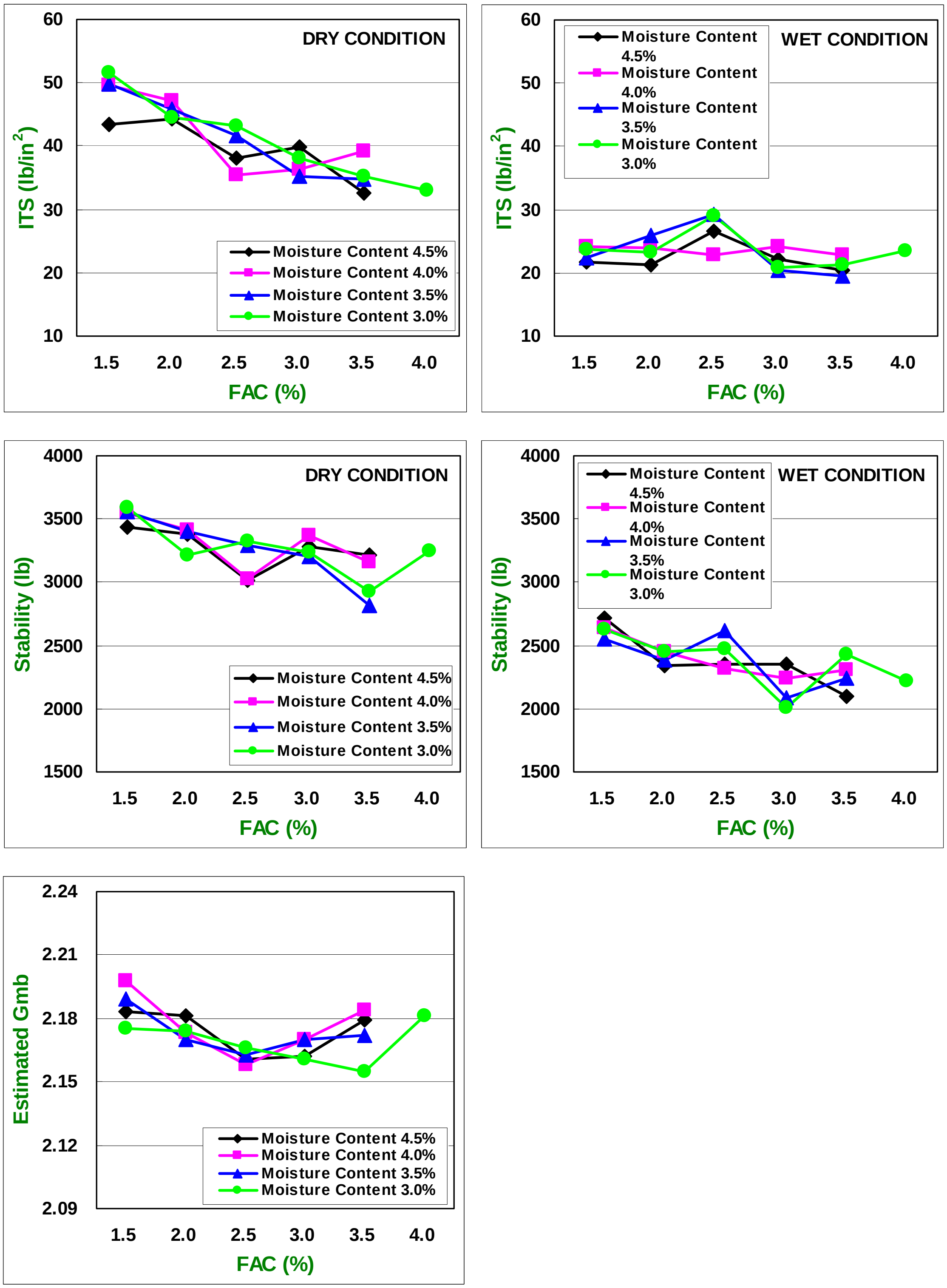


Figure 6-15. Plots of ITS, Stability, and Gmb vs. FAC for Field gradation

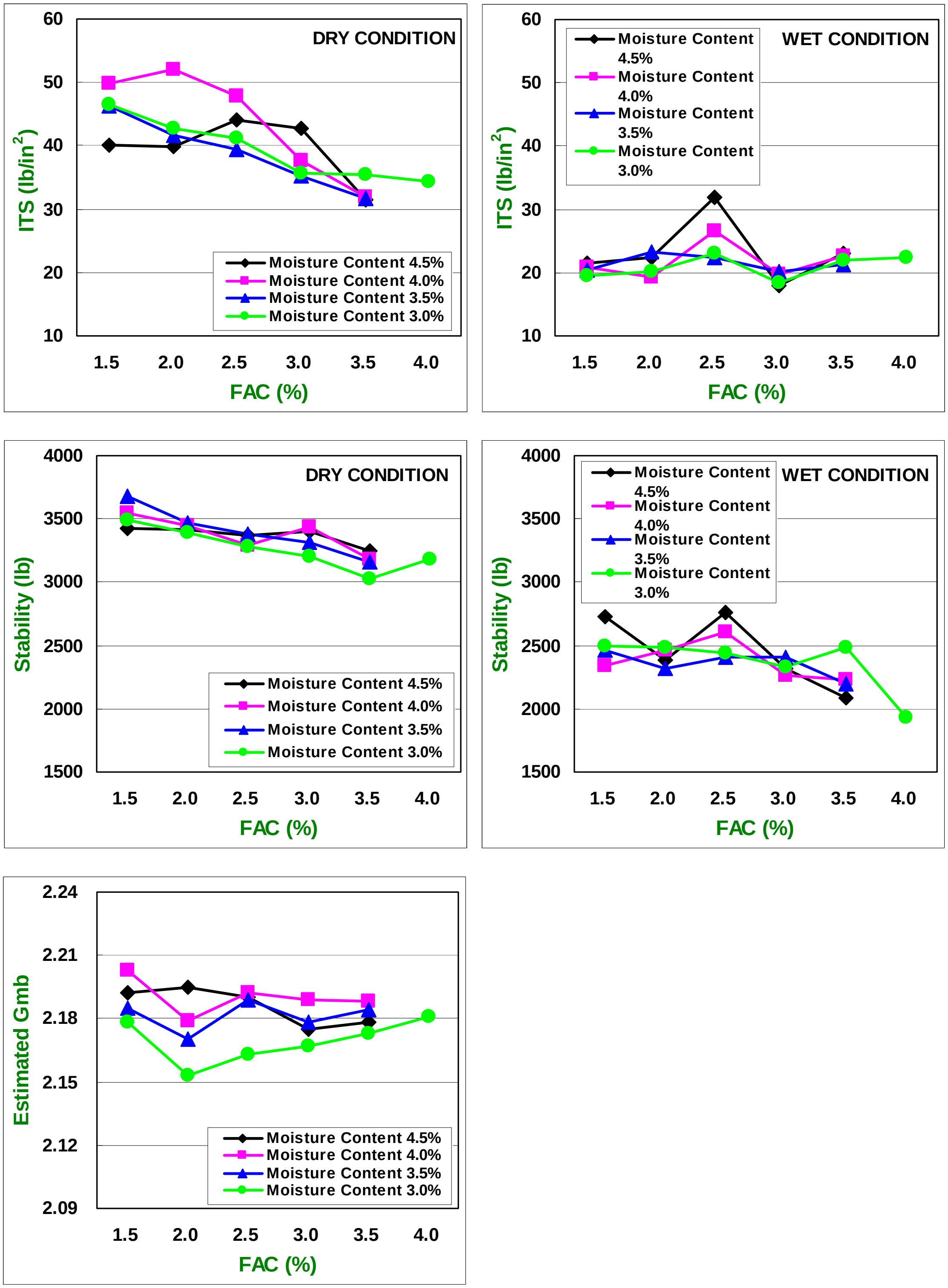


Figure 6-16. Plots of ITS, Stability, and Gmb vs. FAC for Coarse gradation

7. SUMMARY AND CONCLUSIONS

To conduct these studies, existing asphalt pavement was milled throughout the day and, to identify possible variations in RAP gradations, milled RAP samples were collected at different time periods. We concluded, based on our samples, that time of milling and temperature of pavement during the milling process does not affect gradation.

The foaming process of our laboratory equipment was validated by varying the amount water, air pressure, and water pressure. We found that the equipment produced consistent amounts of foamed asphalt under different conditions. For the first-round experiment, a foaming water content of 1.3% created the optimum foaming characteristics in terms of an expansion ratio of 12.5 and a half-life of 15 at 170°C under an air pressure of 4 bars and a water pressure of 5 bars. For the second round experiment, the same foaming water content of 1.3% created the optimum foaming characteristics in terms of an expansion ratio of 10 and half-life of 12 at 170°C under an air pressure of 4 bars and a water pressure of 5 bars. Optimum foamed asphalt content and water content for the first and second round of CIR-Foam mixtures for Fine, Field, and Coarse gradations are summarized in Table 7-1.

Table 7-1. Optimum foamed asphalt content and water content for three different gradations for the first and second rounds

Gradation	First round		Second round	
	Optimum FAC	Optimum WC	Optimum FAC	Optimum WC
Fine	2.5 %	4.1 %	2.5%	4.5 %
Field	2.5 %	4.0 % - 4.5 %	2.5%	4.0 %
Coarse	2.5 %	3.4 %	2.5%	3.5 % - 4.0 %

During the first round of tests, maximum stability (both wet and dry), bulk density, and indirect tensile strength (both dry and wet) were all obtained at a foamed asphalt content of approximately 2.5% at OMC-0.5% or OMC-1.0%. There was a significant drop in these values (except for bulk density) at foamed asphalt contents above 2.5%. The Fine gradation produced the highest stability and indirect tensile strengths. For a given optimum foamed asphalt content of 2.5%, the Coarse gradation demonstrated lower stability and indirect tensile strength than the Field gradation. Moisture content did not affect the test results significantly. The highest test values, however, were obtained at OMC-1.0% for the Fine gradation, OMC-0.5% and OMC-1.0% for the Field gradation, and OMC-0.5% for the Coarse gradation. Given the limited time they were soaked without vacuum, most wet specimens seemed to exhibit relatively high retained strength.

During the second round of tests, due to the vacuum saturation conditioning process, most wet specimens lost their test values significantly—by up to 50%. This indicates that CIR-Foam mixtures are susceptible to water damage. Although test values of dry samples were higher at low FAC of 1.5%, they lost significant strength when they were vacuum-saturated. Samples at 2.5% FAC, however, retained their wet strengths reasonably well. For wet samples, the Fine gradation produced the lowest stability and indirect tensile strength. For a given optimum FAC of 2.5%, the Coarse aggregates produced the highest stability and indirect tensile strength. Water content did not affect the test results significantly. The highest test values, however, were obtained at 4.5% WC for Fine gradation, 4.0% WC for Field gradation, and 3.5%-4.0% WC for Coarse gradation.

In conclusion, for performance grade asphalt of PG 46-34 and PG 52-34, 1.3% foaming water content is recommended for asphalt temperatures of 170°C. There were no significant differences in test results among the three different RAP gradations, and RAP may therefore be used in the field without additional virgin aggregates or fines. The optimum mix design of 2.5% FAC and 4.0% WC is recommended for CIR-foam for field gradation. These findings should be interpreted for the specific RAP source of US-20 Highway, and readers are cautioned not to extrapolate beyond the single RAP source design. Since all tests were performed using only one RAP source, it is recommended that more tests be performed using different sources of RAP materials for a broader picture of the performance of recycled pavements using foamed asphalt.

8. FUTURE STUDIES

Phase II study

The proposed mix design procedure used during the Phase I study is applicable only to the specific RAP materials obtained from Highway US-20 in Iowa. It is therefore critical that the laboratory mix design process be validated using a variety of RAP materials to determine its consistency over the wide range of such materials available throughout Iowa. In addition, to better understand the behavior of CIR mixtures using foamed asphalt, during the Phase II study, the performance of the CIR-Foam mixtures should be evaluated using the dynamic modulus test, static and dynamic creep test, and raveling test.

As shown in Figure 8-1, Phase II of this research will be performed in six tasks. Task A will entail collecting various RAP materials from six different sources. The focus of Task B will be on evaluating the various RAP materials in terms of age, asphalt content, RAP gradation, RAP elongation and flatness ratio. During the Task C, using an optimum foamed asphalt content of 2.5% and a selected moisture content of 3.5%, a significant effort will be made to determine the compaction characteristics of six different types of RAP materials using both a gyratory compactor (around 25 gyrations) and a Marshall hammer (75 blows). To validate the developed mix design process, the Task D will involve applying the procedure to six different RAP materials and three different foamed asphalt contents. For the Task E, to evaluate short- and long-term performances, we will conduct performance tests such as the dynamic modulus test, static/dynamic creep test, and raveling test. Finally, Task F will be a demonstration project constructed using the developed mix design process.

Long-term study

There is a great deal of fundamental research yet to be conducted. The current method of determining optimum foaming water content and temperature is an art involving the use of a dipstick and drum. Optimum temperature and foaming water content could rather be determined by measuring the pressure exerted inside a confined space (i.e., empty box) over time. The highest pressure imposed on the box due to expansion could be considered as a surrogate measure for the expansion ratio and the time taken for the pressure cut in half could be used instead of half-life. This new experimental procedure would not only be more consistent but also cleaner than the current dipstick and drum method. Different nozzle sizes and foaming additives should be also tested to see their effect on foaming characteristics. Foaming temperatures lower than the current 170°C should be considered. Constructability of foamed asphalt pavement is another important area of research, particularly when mix designs recommend relatively high or low foamed asphalt contents.

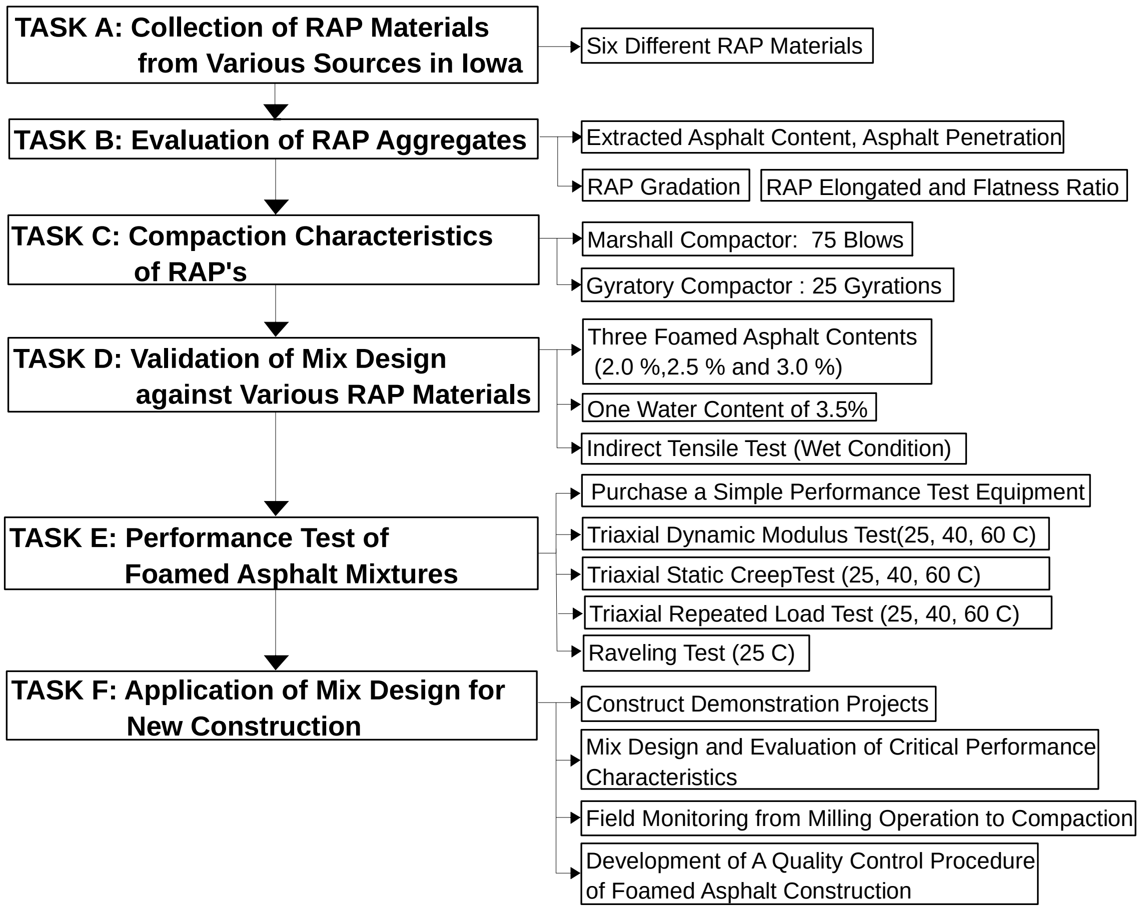


Figure 8-1. Flowchart of six tasks proposed in Phase II study

Foamed asphalt research study should be also expanded to address the needs of CIR-Emulsion laboratory mix design procedure and performance tests. Side-by-side comparison of CIR-Foam vs. CIR-emulsion using performance test equipment would be of great interest to many practitioners. Performance results from these tests would be useful as input for the new 2002 Pavement Design Guide. The structural coefficients of both CIR-Foam and CIR-Emulsion should be also determined for the Design Guide. Accurate structural coefficients would allow pavement engineers to more accurately design overlay thickness.

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Glossary of Acronyms

AASHTO: American Association of State Highway and Transportation Officials

AC: Asphalt content

AGC: Association of General Contractors of America

ARRA: Asphalt Recycling and Reclaiming Association

ARTBA: American Road and Transportation Builders Association

ASTM: American Society for Testing and Material

BC: Bitumen content

CIR: Cold in-place recycling

CIR-Foam: Cold in-place recycling-foamed asphalt

CIR-Emulsion: Cold in-place recycling-emulsified asphalt

CSS: Cationic slow-setting emulsion

FAC: Foamed asphalt content

FDR: Full depth reclamation

FDR-Foam: Full depth reclamation-foamed asphalt

HFMS: High float medium setting emulsion

ITS: Indirect tensile strength

JMF: Job mix formula

MSR: Marshall stability ratio

OFAC: Optimum foamed asphalt content

OMC: Optimum moisture content

PG: Performance grade

RAP: Reclaimed asphalt pavement

TSR: Tensile strength ratio

WC: Water content

APPENDIX: Laboratory Mix Design Procedures

I. Apparatus

The following laboratory equipment is required to carry out the design of foamed asphalt mixtures.

A. <u>Laboratory foaming asphalt equipment (Wirtgen WLB 10)</u>

Mix designs for foamed asphalt require a laboratory foamed asphalt unit capable of producing foamed asphalt at a rate of between 50g and 200g per second. The method of production should closely simulate that of a full-scale production of foamed asphalt. The equipment should have a thermostatically controlled asphalt tank capable of holding a mass of 10 kg of asphalt binder at between 150°C and 200°C, within a range of ± 5°C. In addition, a low-pressure compressed air supply of 0–500 kPa with an accuracy of ± 25 kPa should be included in the apparatus. The equipment should have a system for adding cold water to the hot asphalt, varying in percentage from 0 to 5% (by mass of asphalt binder) with an accuracy of ± 0.2%. Finally, the equipment should be designed so that the foam can be discharged directly into the mixing bowl of an electrically driven laboratory mixer with a capacity of at least 10 kg.

B. <u>Marshall compactor</u>

The Marshall compactor consists of base plate, forming mold and collar, and is 102mm in diameter and 76mm high. The Marshall hammer has a flat circular face that is 98mm in diameter and weighs 4.54 kg. Use of an automatic Marshall compactor with a rotating base is recommended. The extractor used to remove the specimen from the mold should have an ejection force of 27.7 kN generated by a hand-operated hydraulic jack.

C. <u>Specimen measurement and conditioning equipment</u>

A digital caliper is used to measure specimens up to 150mm, along with a balance able to weigh up to 10 kg with an accuracy of 0.1 g. To produce saturated wet specimens, use an aluminum volumetric container and vacuum pump with a maximum vacuum capacity of 760 mm Hg. A water bath with a temperature controller ranging from 0 to 60°C is also needed. Use a cabinet to with a steady temperature of 25° ± 1°C to condition dry specimens.

D. <u>Marshall stability equipment</u>

The Marshall stability testing machine should have a loading capacity of 5,000 lb at a rate of 50.8 mm per minute. The stability values in lbs and flows in 0.01 inches are automatically recorded in a computer database. The Marshall breaking head consists of upper and lower cylindrical segments with an inside radius curvature of 50.8mm for 102mm specimen. The indirect tensile strength breaking head has a 12.7 mm-wide upper and lower segment for 102 mm specimen.

II. Optimum foaming characteristics

The objective is to determine the optimum percentage of water needed to produce the best foam properties for a given asphalt binder. The optimum water content is determined by achieving the maximum expansion ratio and half-life of the foamed asphalt.

A. Calibration

Calibrate the asphalt binder and water flow rates. First, check the asphalt binder discharge rate, normally set at 100 g/second. If it does not discharge 100g / second, adjust the water flow rate following Eq. 1.

$$Q_{H_2O} = \frac{Q_A \times P_{H_2O} \times 3.6}{100} \qquad \text{(Eq. 1)}$$

Where:

Q_{H_2O} = Water flow-through volume (ℓ/h)

P_{H_2O} = Asphalt flow-through volume (g/s)

Q_A = Water content (%)

3.6 = Calculation factor

B. Foaming test

Step 1. Fill water tank and connect the pressured air hose to the air tank.

Step 2. Heat asphalt to the appropriate temperature, ranging from 160°C to 200°C and maintain it for at least 5 minutes before starting the foaming process.

Step 3. Set air pressure at 4 bars and water pressure at 5 bars (water pressure must be higher than air pressure by 1 bar).

Step 4. Measure expansion ration and half-life for water content from 1% to 3%, at 0.5% increments. In five 5 seconds, the foaming equipment produces foamed asphalt and discharges it into a container with a diameter of 27cm (500g of asphalt binder). To determine the expansion ratio, measure the maximum height of the foamed asphalt in this container using a graduated dipstick. Then divide the maximum expansion volume (Vmax) by the original asphalt volume (Vmin). The half-life is defined as the duration in seconds from maximum expansion to half of maximum expansion (see Figure A-1).

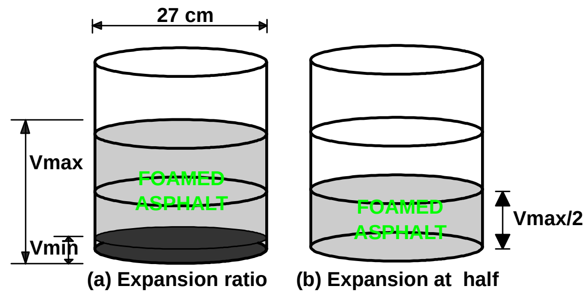

Figure A-1. Description of expansion ratio and half-life

Step 5. Plot expansion ratio and half-life against water content. For each level of water content (from 1% to 3% at 0.5% increments), three measurements of expansion ration and half-life should be made. The average of the three test results should then be plotted against water content (see Figure A-2). Optimum water content is determined at the intersection of the two graphs of expansion ratio and half-life versus water content.

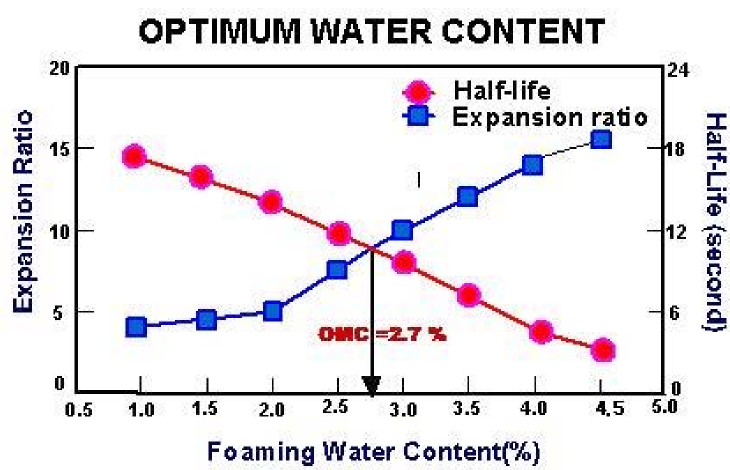

Figure A-2. Relationship between expansion ratio and half-life

III. Optimum water content for RAP aggregate

The objective is to determine the optimum moisture content for RAP aggregates. Optimum water content is determined using the Modified proctor test (ASTM D 1557 “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort [2,700 kN-m/m^3-56,000 ft-lbf/ft^3])”

Step 1. Obtain RAP samples from the field and sieve to obtain RAP that can pass through the 25mm sieve.

Step 2. Put the RAP in the bowl.

Step 3. Start the mixer before adding the water. Add water slowly (for about 5 seconds) to evenly distribute it with the RAP.

Step 4. Mix the RAP using a mechanical mixer (using speed 2 and a dough hook) for 2 minutes.

Step 5. Place RAP in the two stacked molds for compaction up to 1/3 of the height of the mold following the IM 357 procedure.

Step 6. Position the hammer and drop fifty-six blows uniformly over the RAP in the mold.

Step 7. Repeat Steps 5 and 6 three times to fill the mold with RAP.

Step 8. Remove the collar and carefully level the top.

Step 9. Weigh compacted RAP aggregates in the mold.

Step 10. Record the result as the wet density of compacted RAP after subtracting the weight of the mold.

Step 11. Remove the specimen from the mold.

Step 12. Slice vertically through the center of the specimen.

Step 13. Take samples from each cut face.

Step 14. Weigh two RAP samples from cut faces.

Step 15. Dry samples in the oven at 100°C ± 5°C for 24 hours.

Step 16. Repeat Steps 1-15, varying the moisture content of the RAP at 0.5% increments.

Step 17. Calculate the dry unit weight of RAP for a given moisture content (take the average of two samples from the cut face)

$$\gamma_t = \frac{W}{V} = \frac{M_t - M_{mold}}{V} \qquad \text{(Eq 2),}$$

$$\gamma_d = \frac{\gamma_t}{1 + \frac{\omega}{100}} \qquad \text{(Eq 3)}$$

Where:

γ_t	=	moist unit weight
M_t	=	mass of moist sample and mold
M_{mold}	=	mass of mold
V	=	volume of mold
γ_d	=	dry unit weight
a	=	water content

Step 19: Plot the dry unit weight versus the moisture content. Determine optimum moisture content to achieve maximum dry unit weight (Figure A-3).

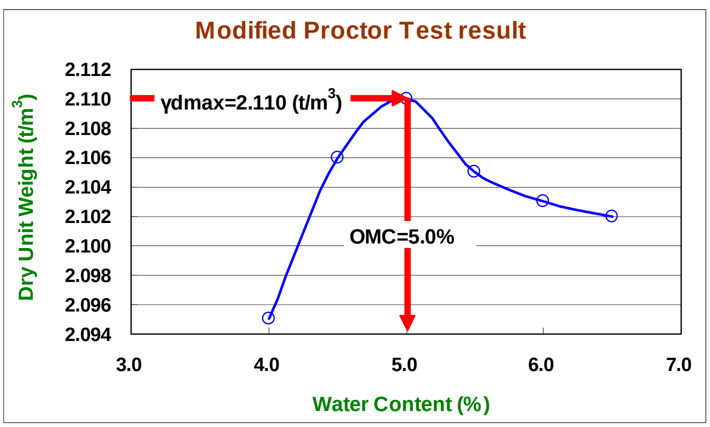

Figure A-3. Plot the dry unit weights against the moisture content

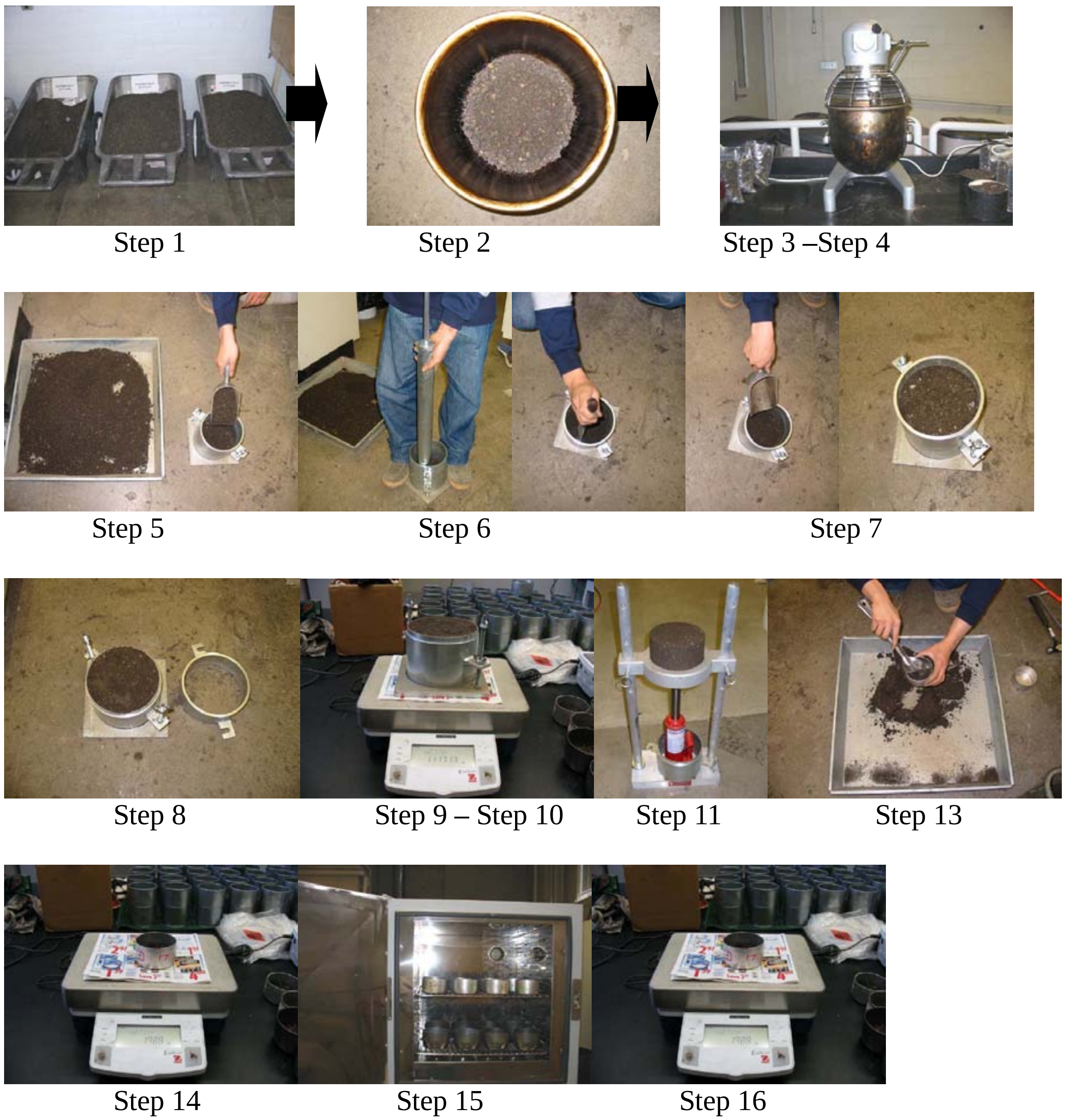

Figure A-4. Modified proctor test procedure for determining optimum water content of RAP

IV. Mix Design

A. <u>RAP aggregate preparation</u>

Step 1. Prepare cold water for mixing with RAP.

Step 2. Prepare 4500 grams of RAP for a set of three Marshall specimens.

B. <u>Mixing</u>

Step 1. Put RAP and 85% of its optimum moisture content into a bowl. Start mixer slowly (speed 2 and dough hook) and mix for approximately 60 seconds until thoroughly mixed.

Step 2. Add foamed asphalt to RAP and mix for 60 seconds.

C. <u>Compaction</u>

Step 1. Fill the mold with foamed asphalt mixture following the IM 357 procedure (about 1150g). Once the mixture is in the mold, the edges should be spaded 10-15 times and the center spaded 5-10 times. Do not use paper or release discs.

Step 2. Compact the foamed asphalt mixture by applying 75 blows of the Marshall hammer with a rotating base on both faces.

Step 3. Extrude the sample from the mold.

D. <u>Curing</u>

Step 1. Cure the mixture for three days in the oven at 40°C.

Step 2. After curing, allow specimens to cool to room temperature. This takes about two hours, but can be reduced to 15 minutes if a fan is used.

E. <u>Estimated bulk density (G_{mb})</u>

Step 1. Measure height and weight of foamed asphalt sample after curing is complete.

Step 2. Sort and separate the specimens into equal sub-lots based on density and height for Marshall and indirect tensile tests.

F. <u>Marshall stability test</u>

Step 1. Place dry specimens in 25°C oven for two hours (not 24 hours).

Step 2. Place wet specimens in 25°C water for 20 minutes, vacuum saturate at 50 mm Hg for 50 minutes, and then allow the specimens to rest in 25° water for 10 minutes.

Step 3. Perform Marshall stability test following ASTM D 1559.

Step 4. Calculate the average Marshall stability of each set of three specimens (both dry and wet specimens)

G. <u>Indirect tensile test</u>

Step 1. Place dry specimens in 25°C oven for two hours (not 24 hours).

Step 2. Place wet specimens in 25°C water for 20 minutes, vacuum saturate at 50 mm Hg for 50 minutes, then allow the specimens to rest in water for 10 minutes.

Step 3. Perform indirect tensile testing following ASTM D 4123.

Step 4. Calculate the average indirect tensile strength of each set of three specimens (both dry and wet specimens)

H. <u>Optimum foamed asphalt and water content</u>

Step 1. Plot five graphs as shown in Figure A-5.

1) Estimated Gmb vs. Foamed Asphalt Content (FAC)

2) Marshall Stability (dry condition) vs. FAC

3) Marshall Stability (wet condition) vs. FAC

4) Indirect Tensile Strength (dry condition) vs. FAC

5) Indirect Tensile Strength (wet condition) vs. FAC

Step 2. Determine the optimum FAC, which gives the maximum values in the following test results as shown in Figure A-6:

1) Marshall stability (Dry condition)

2) Marshall stability (Wet condition)

3) Indirect Tensile Strength (Dry condition)

4) Indirect Tensile Strength (Wet condition)

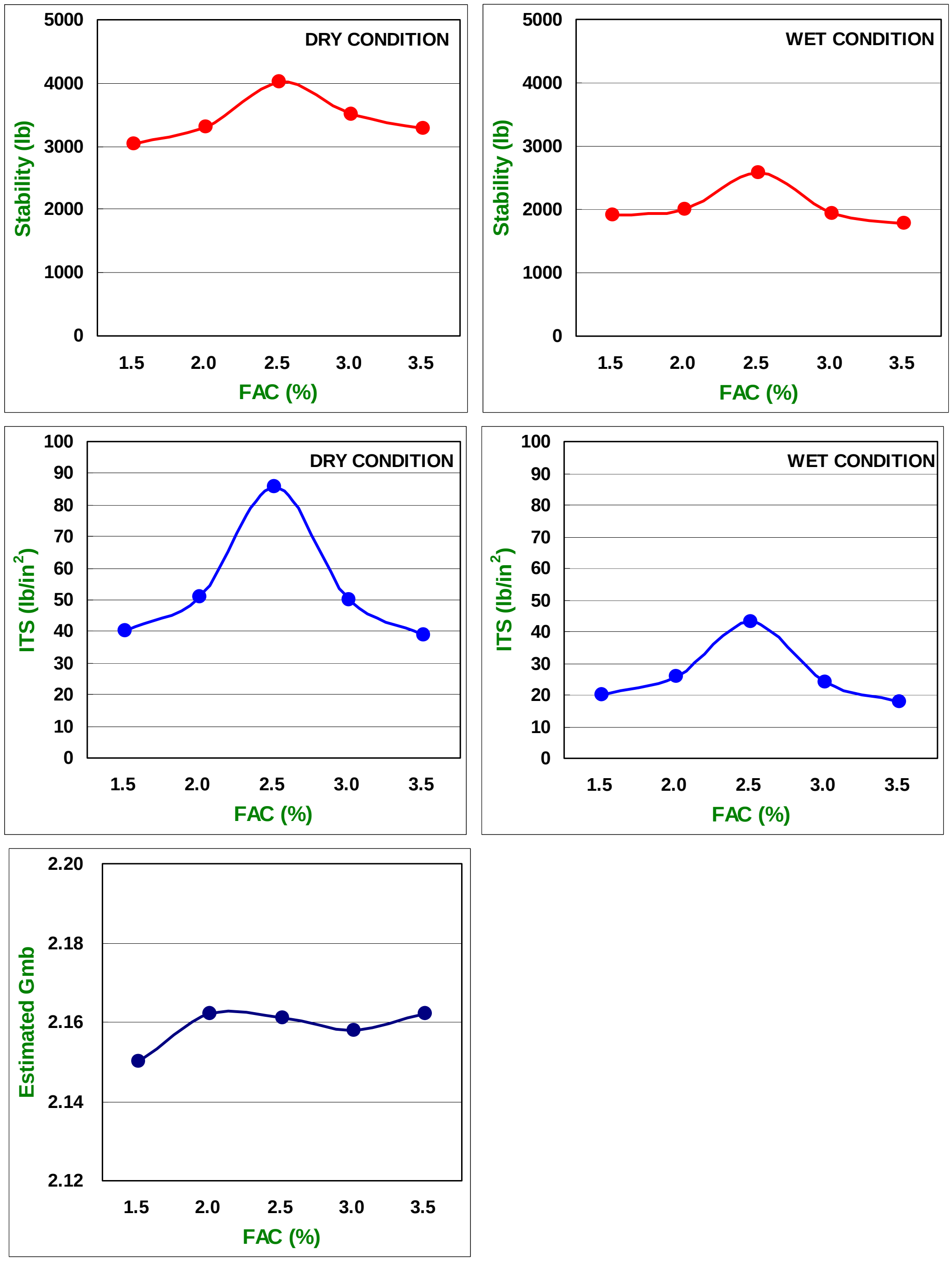

Figure A-5. Plots of stability, ITS, and Gmb vs. FAC

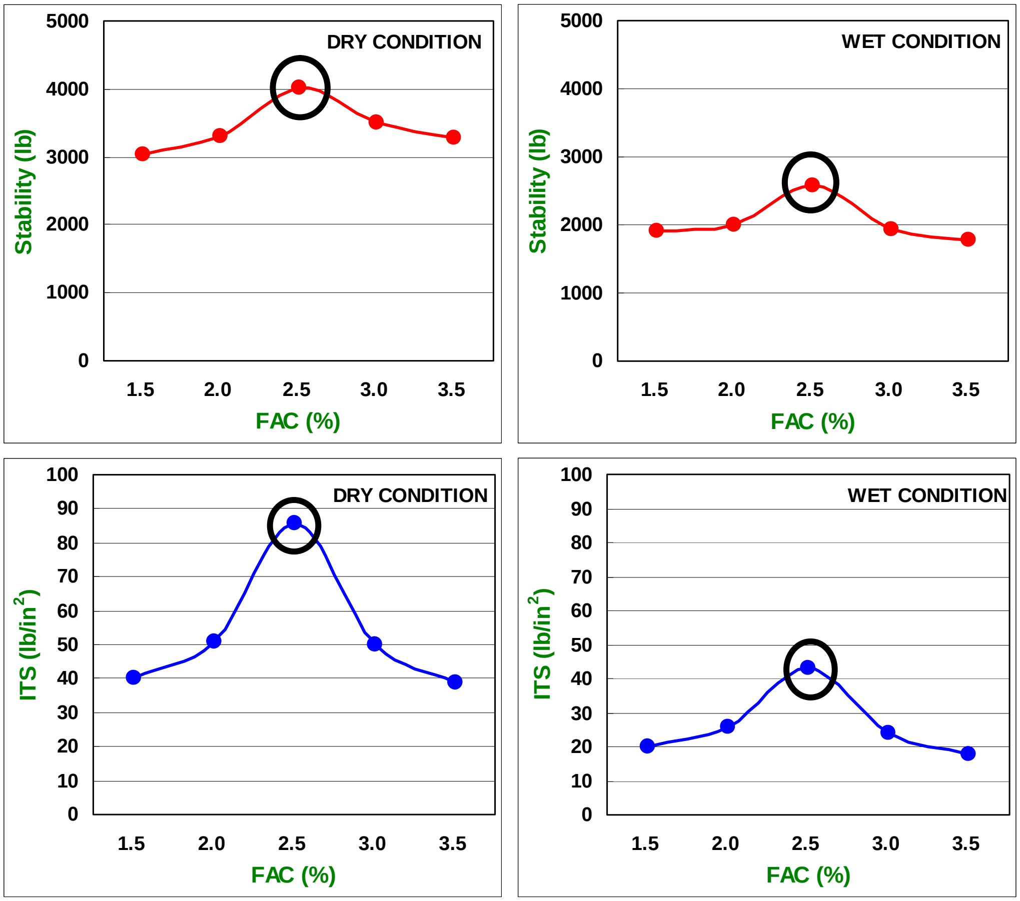

Figure A-6. Peak stability and ITS vs. FAC

A. Step 1 – Step 2 B. Step 1 B. Step 2

C. Step 1 C. Step 2 C. Step 3

D. Step 1 D. Step 2

F. Step 1, G. Step 1 F. Step 2, G. Step 2

F. Step 3 G. Step 3

Figure A-7. Laboratory mix design procedure for foamed asphalt