AAPTP
Airport Asphalt Pavement Technology Program

Validation of Gyration Level for Superpave Gyratory Compactor (SGC) for Mix Design and Control of Airport Asphalt Mixtures

Final Report

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Airport Asphalt Pavement Technology Program

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The Airport Asphalt Pavement Technology Program (AAPTP) is a cooperative agreement effort between the **National Asphalt Pavement Association** (NAPA) and the **Federal Aviation Administration** (FAA) to advance asphalt pavements and pavement materials. The AAPTP advances solutions for asphalt pavement design, construction, and materials deemed important to airfield reliability, efficiency, and safety. The program leverages NAPA's unique technology implementation capabilities with assistance from the FAA and industry to advance deployment and adoption of innovative asphalt material technologies.

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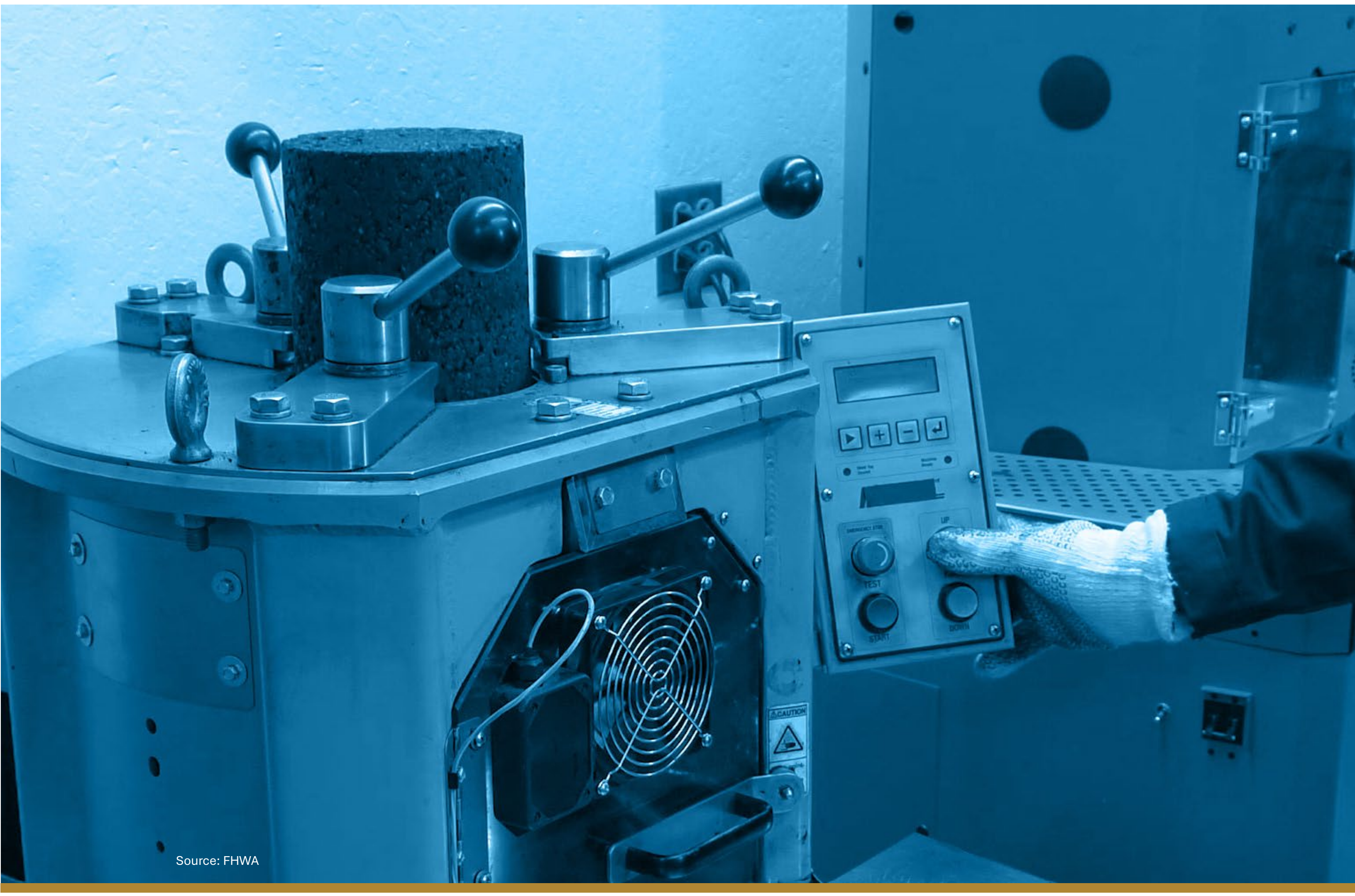

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1s	One standard deviation
d2s	Difference two-sigma limit, a value used in precision statements to define the acceptable range of two test results.
AAPTP	Airport Asphalt Pavement Technology Program
AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of variance
APA	Asphalt Pavement Analyzer
ASTM	ASTM International
AV	Air voids
CDF	Cumulative distribution function
DOT	Department of Transportation
ERDC	U.S. Army Engineer Research and Development Center
FAA	Federal Aviation Administration
F&E	Flat and elongated
G_{mb}	Bulk specific gravity of the compacted asphalt mixture
G_{mm}	Maximum specific gravity of the asphalt mixture
HMA	Hot mix asphalt
ILP	Illinois locking point
JMF	Job mix formula
LMLC	Laboratory-mixed, laboratory-compacted
MH	Marshall hammer
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
N_{design}	Design number of gyrations
N_{EQ}	Number of equivalent SGC design gyrations
NMAS	Nominal maximum aggregate size
PCSI	Primary control sieve index
PMLC	Plant-mixed, laboratory-compacted
PSP	Proficiency Sample Program
QA	Quality assurance
QC	Quality control
SMA	Stone matrix asphalt
SGC	Superpave gyratory compactor
SHRP	Strategic Highway Research Program
SSD	Saturated surface-dry
TDOT	Tennessee Department of Transportation
UFGS	Unified Facilities Guide Specification

UNR	University of Nevada, Reno
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregate
WMA	Warm mix asphalt

1. Introduction

This report documents the research conducted for the “Validation of Gyration Level for Superpave Gyratory Compactor (SGC) for Mix Design and Control of Airport Asphalt Mixtures” project conducted under the Airport Asphalt Pavement Technology Program (AAPTP). The objective of this project was to recommend SGC compactive efforts that provide asphalt mixture volumetric properties equivalent to 50 and 75 blows with a Marshall hammer. The report is organized into five chapters. Chapter 1 presents background information and research objectives. Chapter 2 includes a literature review. Chapters 3 and 4 present the experimental plan and the laboratory testing and data analysis. Chapter 5 summarizes the findings, conclusions, and recommendations of the study.

1.1 Background

The Marshall method was originally conceptualized and developed by Bruce G. Marshall of the Mississippi Highway Department in 1939 (White, 1985). Marshall aimed to create a reliable method for selecting the optimal asphalt content to achieve the desired density, stability, and flow values in asphalt paving mixtures. The Marshall method compaction hammer was based on the Proctor hammer used for soils, followed by a 5,000-lb static leveling load applied for 2 min. The compactive effort was modified through laboratory experiments and field tests at the U.S. Army Corps of Engineers Waterways Experiment Station in the 1940s, which eventually led to the standard 10-lb manual hammer, dropped 18 inches to 1 foot, with a diameter of 3 7/8 inches—slightly smaller than the mold, which had an inside diameter of 4 inches (White, 1985). The 50-blow compactive effort with the “Marshall hammer” was established based on those field tests. Good field construction was considered to be that which achieved 98 percent of the 50-blow compactive effort (White, 1985).

The widespread adoption of the Marshall method and its associated hammer can be attributed to its simplicity, cost-effectiveness, and extensive use by the U.S. military during and after World War II. It remains one of the most widely used mix design methods worldwide.

Today, the SGC is one of the most common devices used for mix design and quality assurance testing of asphalt paving mixtures. The SGC was developed through the Strategic Highway Research Program (SHRP) in the early 1990s to address the limitations of existing compaction methods by providing a more consistent and realistic simulation of field compaction conditions (Harman et al., 2001). The SHRP gyratory compaction method was adapted from concepts borrowed from other gyratory compactors used by the Texas Highway Department, the U.S. Army Corps of Engineers, and the Laboratoire Central des

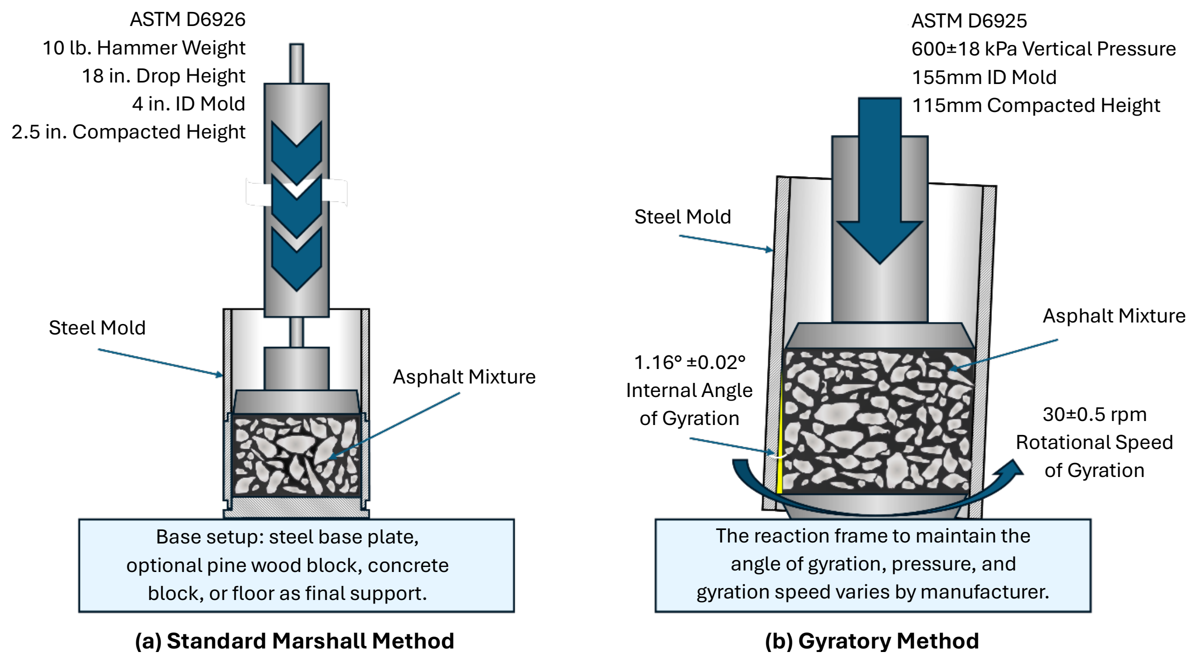
Ponts et Chaussées (LCPC) in France. The LCPC gyratory compactor, which utilized a constant angle, was particularly influential.

Initially, the SGC was designed to increase the compaction energy beyond what the Marshall hammer could achieve to better simulate the compaction of in-service highway pavements. Over time, several refinements were made to the SGC compaction procedure, and new parameters have been developed to assess mixture compactability from the device. Gyration levels were simplified and lowered in response to stronger aggregate structures and polymer-modified asphalts, which resisted compaction during construction and further densification under traffic (Prowell & Brown, 2007).

Significant differences exist between compaction with a Marshall hammer and an SGC, as presented in Table 1 and illustrated in Figure 1. As noted in Table1, one of the key differences is the type of energy applied to the mixture during compaction. The Marshall hammer compacts mixtures using impact energy from a falling weight, whereas the SGC compacts using a combination of continuous shear and compression forces. At mixture compaction temperatures, asphalt binders are a viscous fluid coating that reacts to the rate of applied energy. A quick burst of energy, such as with the Marshall hammer, will resist flow more than the slower and consistently applied force of a gyratory compactor. Another key difference is specimen size. The volumes of SGC specimens are nearly 4.5 times greater than those of Marshall specimens. For a given mixture, the larger volume provides more freedom for aggregate movements without the constraints of the cylindrical mold and top and bottom plates during compaction.

Table 1. Comparison of Key Aspects of Marshall Hammer and SGC Compaction Methods

Feature	Marshall Hammer	Superpave Gyratory Compactor
ASTM Standard	ASTM D6926	ASTM D6925
Types of Energy	Impact energy from a manually or mechanically operated hammer, applied to both sides of the specimen	Shear and compressive energy with a constant angle of gyration and vertical pressure
Type of Load	Repeated stress	Constant strain
Dimensions of Asphalt Specimens	4-inch (101.6 mm) diameter × 2.5 inch (63.5 mm) high	5.91-inch (150 mm) diameter × 4.53 inch (115 mm) high
Equipment Cost	Around $7,600	Around $60,000



ID = inner diameter.

Source: National Center for Asphalt Technology

Figure 1. Illustrations of Asphalt Mixture Compaction with a Marshall Hammer (a) and an SGC (b)

Precision data from the American Association of State Highway and Transportation Officials' (AASHTO) **re:source** Proficiency Sample Program (PSP) for the bulk specific gravity of compacted mixtures (G_{mb}) over the last 10 years is summarized in Table 2. The table lists, by year, the number of laboratories participating in the PSP and the within-laboratory and between-laboratory standard deviations of G_{mb} for both compaction methods. The variability statistics change from year to year as the mix design used in the PSP changes. The results show that within-laboratory (repeatability) standard deviations are much smaller than between-laboratory (reproducibility) standard deviations for both methods. Comparing the within-laboratory G_{mb} standard deviations of the two methods reveals that they are generally similar in magnitude. Over the last 10 years, the Marshall within-laboratory standard deviations were lower than the SGC within-laboratory standard deviations in 7 years. However, the between-laboratory standard deviations for Marshall compaction were higher than those for SGC in all 10 years. This indicates that the SGC method provides more consistent results across laboratories compared to the Marshall method.

Table 2. Comparison of Within-laboratory and Between-laboratory Standard Deviations of Mixture Bulk Specific Gravity (SSD Method) for Marshall and SGC Compaction Methods

Year	Marshall			SGC		
	No. of Labs	Within-Lab Std. Dev.	Between-Lab Std. Dev.	No. of Labs	Within-Lab Std. Dev.	Between-Lab Std. Dev.
2024	587	0.0082	0.0230	875	0.0102	0.0196
2023	638	0.0084	0.0245	872	0.0079	0.0190
2022	614	0.0042	0.0126	880	0.0039	0.0113
2021	612	0.0089	0.0255	858	0.0090	0.0176
2020	632	0.0071	0.0259	867	0.0088	0.0208
2019	644	0.0064	0.0212	832	0.0072	0.0150
2018	657	0.0078	0.0253	781	0.0097	0.0189
2017	667	0.0084	0.0268	795	0.0077	0.0232
2016	627	0.0076	0.0214	728	0.0084	0.0144
2015	637	0.0075	0.0212	713	0.0111	0.0192

SSD = saturated surface-dry.

1.2 Current P-401 Specifications

The Federal Aviation Administration's (FAA) current advisory circular (AC) 150/5370-10H, *Standard Specifications for Construction of Airports* (dated Dec. 21, 2018), allows the engineer to select compaction by either the Marshall hammer or SGC (FAA, 2018). The specifications require a compaction level of 50 blows (Marshall hammer) or 50 gyrations (SGC) for asphalt mixtures for airfield pavements serving aircraft of 60,000 lb or less, and 75 blows or 75 gyrations for mixtures supporting aircraft weighing more than 60,000 lb. The Marshall hammer compaction method was used for many decades prior to the development of the SGC and is generally considered to result in mixtures with satisfactory performance. However, since the introduction of the SGC as an option in FAA AC 150/5370-10G in 2014, the SGC has gradually become the method of choice for most FAA projects, particularly in the eastern United States. Some concern remains among many airfield asphalt pavement engineers that specimen densities from Marshall and SGC compaction are not equivalent, and the differences result in airfield asphalt mixtures that may perform differently in service.

2. Literature Review

Forty-one publications were reviewed and compiled into the following six subsections:

- Comparison of SGC and Marshall Compaction on Airfield Mixture Designs.
- Highway Mixture Design Comparison of SGC Gyrations to Marshall Blows.
- Influence of Reheating on Asphalt Mixture Volumetric Properties.
- Effect of Aggregate Properties on Volumetrics and Compactability.
- Locking Point of Asphalt Mixtures Designed Utilizing SGC and Marshall Compactors.
- Summary of Literature Review and Findings.

A comparison of the design number of gyrations (N_{design}) to Marshall hammer blows for airfield mixture designs is directly related to this research project objective and deliverables. Comparison of N_{design} gyrations to Marshall hammer blows for State department of transportation (DOT) mixture designs is included because most State DOTs transitioned from Marshall compaction to SGC with the introduction of the Superpave mixture design method in the 1990s. Findings from highway research may supplement the past research comparing N_{design} gyrations to Marshall hammer blows for airfield mixture design.

When assessing this information, it is important to recognize that the FAA AC 150/5370-10H (2018) specifications are generally more rigorous than most State DOT specification requirements with respect to gradation limits, design air voids (AV), voids in mineral aggregate (VMA) criteria, and limits on reclaimed asphalt pavement. Another reason for considering the highway-related information is that the FAA AC 150/5370-10H (2018) specifications include the following two statements:

> "This specification contains job mix formula options for both Marshall and Gyratory Mix Design Methods. The Engineer shall select the method to be used for the project, considering the prevalent method in use in the local project area. The specifications must be edited to follow one methodology or the other. The bid documents can not include both design methodologies."

> "For airfield pavement projects at non primary airports, serving aircraft less than 60,000 pounds (27216 kg), state highway specifications may be used in states where the state has requested and received FAA approval to use state highway specifications."

A review of the literature on the impacts of reheating plant-produced asphalt mixtures on volumetric mixture properties is included because the research plan relied on the use of reheated plant-mixed, laboratory-compacted P-401 and P-403 mixtures. Thus, understanding the impact of reheating on both SGC- and Marshall-compacted specimens is an important consideration when comparing bulk specific gravities and densities. Binder stiffness due to reheating may have a greater impact on Marshall hammer versus SGC compaction because the Marshall hammer applies a constant stress, while the SGC is a constant strain type of compaction. Thus, the research team conducted a limited laboratory experiment to assess the effect of reheating on SGC- and Marshall-compacted bulk specific gravities, which is presented later in this report.

The effect of aggregate properties on mixture volumetrics and compactability is included because P-401 and P-403 mixtures were obtained from airfield projects across the country. These mixtures included various aggregate types, minerology, and compositions from across the United States, with a wide range of physical and mechanical properties. It is well known that higher-density aggregates, such as basalt, typically possess greater strength and toughness than lower-density aggregates, such as soft limestones. This raises the question of whether aggregate properties affect mixture volumetrics and compactability.

Locking point is a term used to describe when the height of a specimen in an SGC does not change with the application of a series of two or more gyrations. It is observed when the aggregate skeleton no longer moves under the applied shear stress in the compactor or is at a “locking point.” Different agencies use different definitions for locking point, and the locking point can be observed multiple times during the compaction of an SGC sample. Conversely, it may not be observed at all during the compaction process. When locking point occurs, especially when it occurs repeatedly, the number of gyrations required to achieve a given density level will increase.

2.1 Comparison of SGC and Marshall Compaction on Airfield Mixture Designs

The basic purpose of this research was to answer the question of what N_{design} gyrations are needed to produce compacted specimen densities equal to those observed for FAA P-401 and P-403 mixtures compacted to 50 and 75 Marshall hammer blows. Although several previous studies have examined this topic and provided recommendations that form the basis of the current FAA P-401 and P-403 specifications, the question has yet to be convincingly answered.

In AAPTP Project 04-03, Cooley et al. (2009) investigated the implementation of Superpave mixtures for airfields. The study examined the number of equivalent SGC design gyrations (N_{EQ}) to Marshall hammer compactive efforts and the gyration levels needed to achieve adequate rutting resistance for the intended airfield application. Field cores and raw materials were collected from 10 airfields across the United States to (1) determine the volumetric properties, in-place density, asphalt binder content, and gradation and (2) replicate those asphalt mixtures using Marshall and SGC compactive efforts.

The study determined N_{EQ} using three approaches. The first approach examined the ultimate in-place densities achieved during service and the compactive effort used to design the mixtures. The authors noted that mix design densities using the SGC were too high, suggesting that higher binder contents would have been appropriate. The second approach compared the compacted specimen densities for Marshall and SGC compactive efforts. The results showed that the N_{EQ} for 75-blow Marshall compaction ranged from 43 to 55 gyrations at a 95 percent confidence interval, and the N_{EQ} for 50-blow Marshall compaction ranged from 32 to 40 gyrations. The third approach evaluated the number of gyrations needed to achieve the highest asphalt content that would pass the flow number test. Each mix design was compacted to two to four gyration levels.

Table 3 summarizes the N_{EQ} for the airfield mixes determined using the performance testing results. N_{EQ} values ranged from 35 to 75 gyrations and varied with tire pressure, generally indicating that a higher tire pressure necessitated a higher N_{EQ}. Table 4 shows the N_{EQ} values by tire pressure based on flow number test results and the final recommended N_{EQ} values, which were simply increased by 10 gyrations based on the analysis. This adjustment was made because the researchers concluded that the calculated N_{EQ} results were significantly lower than the N_{EQ} values used for highway and airfield pavement design.

Table 3. Estimated N_{EQ} Based on Flow Number Testing (Cooley et al., 2009)

Airfield	Max. Gross Weight (lb)	Max. Gross Weight per Tire (lb)	Tire Pressure (psi)	Estimated N_{EQ}
Jacqueline Cochran Regional Airport (TRM)	20,000	10,000	75	50
Mineral County Memorial Airport (C24)	12,500	6,250	90	50
Oxford-Henderson Airport (HNZ)	30,000	15,000	75	35
Little Rock Air Force Base (LRF)	155,000	38,750	105	50
Naval Air Station Oceana (NTU)	66,000	33,000	240	75
Volk Field (VOK)	42,500	21,250	215	75
Jackson-Medgar Wiley Evers International Airport (JAN)	890,000	55,625	200	35
Newark Liberty International Airport (EWR)	873,000	54,563	200	35
Palm Springs International Airport (PSP)	800,000	52,500	200	N/A
Spokane International Airport (GEG)	400,000	100,000	200	N/A

N/A = insufficient data available to estimate N_{design}.

Table 4. N_{design} Values Based on Research and Actual Recommended N_{design} (Cooley et al., 2009)

Tire Pressure (psi)	N_{EQ} (Based on Research Results)	N_{EQ} (Recommended)
<100	40	50
100–200	55	65
>200	70	80

Two case study projects were then evaluated to compare volumetric properties during production. For the first project, 50-blow Marshall compaction was compared to 50 gyrations. The data showed that the SGC-compacted mixture bulk specific gravity (G_{mb}) results were consistently higher than Marshall G_{mb} results. For the second project, 75-blow Marshall compaction was compared with 65 gyrations, and the SGC G_{mb} results were close to the Marshall compaction G_{mb} for most of the samples.

Possible limitations of this study include:

- The study included only six mixtures with 75-blow Marshall mix designs and four Superpave mixtures with design gyrations ranging from 75 to 139. The limited data and the wide range of N_{EQ} results made it challenging to develop recommendations.
- It is unclear whether the researchers used a manual or automatic Marshall hammer.
- The criteria used for the flow number test have not been validated for airfield pavements.

Christensen et al. (2010) investigated the relationship between 75-blow Marshall and SGC compaction using eight FAA mix designs with good field performance. To evaluate the effect of binder grade and type on N_{EQ}, three binders (PG 64-22, PG 76-22 SBS-modified, and PG 76-22 Novophalt-modified) were used for some of the mixtures. To determine the number of gyrations equivalent to 75-blow Marshall compaction, the researchers first verified the original mix designs and then prepared SGC specimens using 75, 100, and either 50 or 125 gyrations, depending on the results of the compaction with 75 and 100 gyrations. In the final step, AV as a function of gyrations were plotted to estimate N-equivalent to yield the same AV content as the verified Marshall design.

Two laboratories independently determined the N_{EQ} for the 75-blow Marshall mix designs. The study found that the average equivalent number of SGC gyrations was 62 for a 75-blow Marshall mixture, with a range of 35 to 100 gyrations. Since AAPTP Project 04-03, described above, was more comprehensive and the recommended number of gyrations for N_{EQ} differed by less than 10 gyrations (62 versus 69), the researchers recommended an SGC compaction effort of 70 gyrations to yield volumetric properties similar to those of 75-blow Marshall mix designs. The researchers acknowledged that the equivalent gyratory compactive effort varied considerably among the mixes and that this difference was largely due to differences in the asphalt contents of the verified Marshall designs.

Possible limitations of this study include:

- The materials used were not exactly the same as those used in the original mixtures, and the asphalt contents of the original mix designs were adjusted. The N_{EQ} experiments used different binders and grades (PG 64-22, PG 76-22 Novophalt-modified, and PG 76-22 SBS-modified) than the original mix designs.
- The study did not include evaluation of N_{EQ} for 50-blow Marshall mix designs.

The U.S. Army Engineer Research and Development Center (ERDC) evaluated the number of gyrations required to provide a density equal to 75-blow Marshall designs (Rushing, 2011). The evaluation included 32 aggregate combinations with different maximum aggregate sizes, aggregate types, gradations, and percentages of mortar sand, as well as two binder grades. For each combination, the aggregate gradation and design binder content with 75 blows of a manual Marshall hammer and 3.5 percent AV were based on FAA AC 150/5370-10D (2008) criteria. The results were presented as a histogram with N_{EQ} ranging from 21 to 125 gyrations, with a mean value of 69 gyrations and a standard deviation of 25. For simplicity, the author suggested an N_{EQ} of 70 gyrations for designing airfield mixtures for aircraft greater than 60,000 lb. The study discussed how the Marshall hammer and the SGC are fundamentally different in compaction method and how no direct correlation between Marshall and SGC could be ascertained. The researchers indicated that nominal maximum aggregate size (NMAS) and binder type were contributing factors to the variability of the number of gyrations. Further research and field validation were recommended prior to implementation. Interestingly, the analysis of the SGC data found that only 36 percent of the asphalt mixtures passed both Superpave criteria for $N_{initial}$ and $N_{maximum}$. In general, the mixtures containing chert gravel aggregates or 10 percent mortar sand did not meet these criteria, highlighting the impact of aggregate texture and angularity during compaction.

A potential limitation of this study:

- The study was limited to obtaining the equivalent number of gyrations for 75-blow Marshall only.

Rushing et al. (2012) conducted further analysis to evaluate the impact of N_{EQ} on the mixture binder content using mixtures from their previous study (Rushing, 2011). Each mixture was evaluated to determine the AV content at 70 gyrations and then at 10 and 20 gyrations above and below 70 gyrations. Figure 2 presents the average change in AV with change in gyrations. The results showed a decrease in AV content with increasing gyrations; typically, a 0.5 percent change in AV results in a 10-gyration change. Since the binder content of the mixes has to be adjusted to achieve a target AV of 3.5 percent, a change in the N_{EQ} would result in a change in the selected binder content. Since only 36 percent of the mixes in their 2009 study met both $N_{initial}$ and N_{max} criteria, the researchers recommended that $N_{initial}$ and N_{max} criteria be eliminated as design criteria for airfield Superpave mixtures.

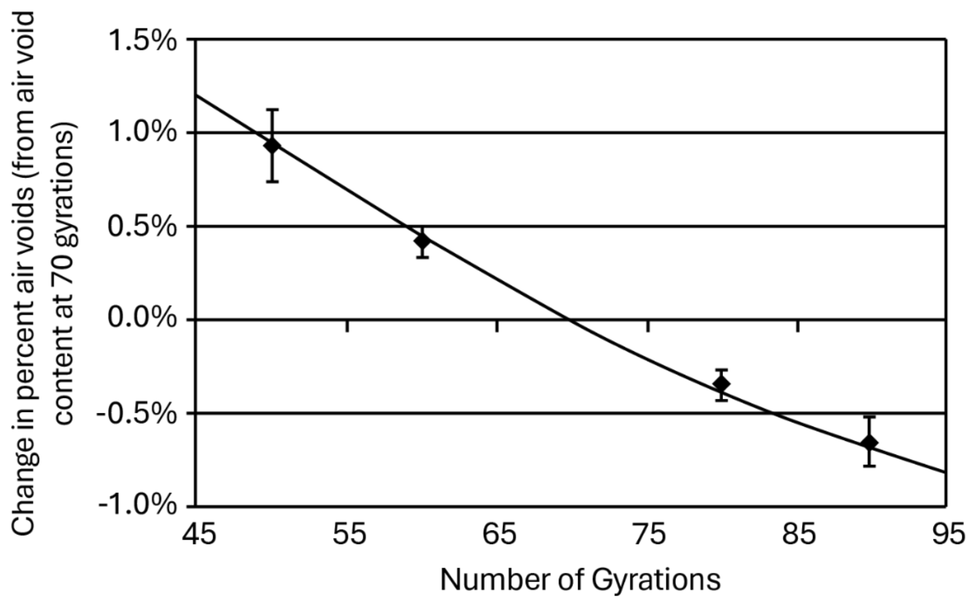


Figure 2. Influence of Number of Gyrations on AV (Rushing et al., 2012)

Note: From "Criteria for Using the Superpave Gyratory Compactor to Design Airport HMA Mixtures," by J. F. Rushing, T. D. White, E. R. Brown, & N. Garg in *International Journal of Pavement Engineering, 13*(2), 2012, 126–136. Used with permission.

Christensen (2013) published a report providing a thorough review of three of the studies described above (Cooley et al., 2009; Christensen et al., 2010; and Rushing, 2011) and their recommendations. As presented previously, Rushing (2011) and Christensen et al. (2010) recommended using 70 gyrations when designing airfield asphalt mixes. Despite the wide ranges reported for equivalent SGC compaction for airfield mixtures, Christensen concluded that, on average, similar volumetric properties are expected between mixtures compacted to 75 blows and 70 gyrations. Although Cooley et al. (2009) recommended considering aircraft tire pressure when setting the number of gyrations, Christensen (2013) suggested that additional research was needed to correlate the gyration levels with tire pressure, since the performance test used to develop N_{EQ} by aircraft tire pressure had not been calibrated or correlated to actual field performance.

Potential limitations of this study:

- The author was a lead researcher in the FAA/SRA/AAT study, which may have influenced recommendations to follow the findings and conclusions of that project.
- The study did not present additional research.

Rushing, McCaffrey, and Warnock (2014) evaluated the SGC option in the Unified Facilities Guide Specification (UFGS) 32-12-15.13 by comparing the density of six plant-produced mixtures compacted using 75 blows with a Marshall hammer versus 75 gyrations in an SGC. Among the six mixtures, three mixtures had higher AV with the SGC, two mixtures had similar AV contents, and one mixture exhibited lower AV with the SGC. The author noted that mixtures with higher AV contents would require an increase in asphalt content to meet the UFGS mix design target of 3.5 percent AV, which would increase the rutting susceptibility of those mixtures. Conversely, the durability of the mixture could be improved by adding more asphalt.

To reduce the potential of designing mixtures with rutting susceptibility, a performance test such as the Asphalt Pavement Analyzer (APA) could be added to the specification. In this research, the APA was found to be an effective tool for screening the rutting susceptibility of UFGS mixtures during mix design. Finally, the within-laboratory standard deviation of AV for SGC-compacted samples was less than half of that for Marshall-compacted specimens. The author stated that contractor payment would not be affected when preparing quality control/quality assurance (QC/QA) samples with the SGC.

Potential limitations of this study:

- The assumption that a mix designer will increase the asphalt content to achieve a target AV content may not be correct, especially if the mixture's VMA is above the minimum criteria. More likely, mix designers will adjust the gradation and achieve a lower AV content and a minimum satisfactory VMA.
- The finding that the single-operator variability with the SGC is less than half of that with the Marshall hammer is not consistent with the current precision statements of ASTM D6925 and ASTM D6926.
- The study did not include an evaluation of N_{EQ} for 50-blow Marshall mix designs.

James et al. (2015) summarized the N_{EQ} results from the previous studies by Cooley et al. (2009), Rushing (2011), and Rushing et al. (2014) and provided the summary statistics shown in Table 5. The average N_{EQ} for 50-blow Marshall compaction was 55 gyrations, and the average N_{EQ} for 75-blow Marshall compaction was 61 gyrations, a difference of only six gyrations. Both datasets had large standard deviations. However, simply averaging the results of the previous studies may be misleading.

Table 5. Summary Statistics of N_{EQ} from Previous Studies (adapted from James et al., 2015)

Statistic	50 Blows	75 Blows
Observations	12	62
N_{EQ} Average	55	61
N_{EQ} Range	30–80	36–86
N_{EQ} Standard Deviation	24.6	24.3

2.2 Highway Mixture Design Comparison of SGC Gyrations to Marshall Blows

A majority of highway mixture designs in the United States are designed according to the Superpave mixture design method. When the Superpave mixture design method was released in the early 1990s, several local, State, and national agencies made efforts to convert Marshall mixture designs to Superpave, including determining equivalent N_{design} gyrations. A key difference between highway mixture design versus airfield mixture design is the variety of specifications that exist for highway mixture designs. Each State DOT may have 10 or more different mixture types with varying volumetric property specifications, while the FAA AC 150/5370-10H (2018) has much more stringent and uniform mixture design requirements.

Two studies were conducted to assist a group of city and county agencies in Nevada with transitioning from Marshall mixture design to Superpave. One study investigated the correlation between the number of blows with a manual Marshall hammer and the number of gyrations with an SGC (Montenegro, 2018). As shown in Table 6, eight mix designs used in the study were evaluated and compared to the FAA P-401 gradation and VMA criteria. It should be noted that some of these mixtures were below the FAA P-401 minimum VMA requirement and therefore required higher asphalt contents to meet the specification. Nonetheless, Mixes C, F, and H were further analyzed since they were reasonably close to the FAA P-401 Gradation 1 range and met the minimum VMA requirement.

A follow-up study by Elias (2020) expanded on the work of Montenegro (2018) using the locking point concept. Six mixes were tested, and as in the previous study, they were close but nonetheless did not meet FAA P-401 specifications. Elias (2020) reported that the range of gyrations to meet local agency specifications was between 25 and 36 gyrations. Other agencies have also found similar results, but most agencies use 50 gyrations as a minimum. It is important to note that the locking point was not reached when samples were compacted to 50 gyrations.

An Alabama study by Watson, Brown, and Moore (2005) had the objectives of comparing the performance of SGC and Marshall mixes and determining if the SGC N_{design} should be adjusted. Twenty-five paired Marshall and SGC projects were evaluated. The researchers found that the asphalt contents of Superpave mixtures could be increased without affecting rutting resistance. No conclusion was made regarding reducing N_{design} gyrations.

Table 6. Rapid Takeover Concrete (RTC) Mixture Designs vs. FAA P-401 Specifications (adapted from Montenegro, 2018)

FAA Gradation Bands	Percentage by Weight Passing Sieves			UNR 2018 RTC Mix Gradations							
Sieve Size	Gradation 1	Gradation 2	Gradation 3	Mix A	Mix B	Mix C	Mix D	Mix E	Mix F	Mix G	Mix H
1 inch (25.0 mm)	100	—	—	—	—	—	—	—	—	—	—
3/4 inch (19.0 mm)	90–100	100	—	100	100	96	100	100	96	100	100
1/2 inch (12.5 mm)	68–88	90–100	100	90	90	86	100	100	86	88	100
3/8 inch (9.5 mm)	60–82	72–88	90–100	76	79	76	90	90	75	77	93
No. 4 (4.75 mm)	45–67	53–73	58–78	49	53	55	56	56	53	57	57
No. 8 (2.36 mm)	32–54	38–60	40–60								
No. 16 (1.18 mm)	22–44	26–48	28–48								
No. 30 (600 µm)	15–35	18–38	18–38								
No. 50 (300 µm)	9–25	11–27	11–27								
No. 100 (150 µm)	6–18	6–18	6–18	8	9	10	9	9	10	8	8
No. 200 (75 µm)	3–6	3–6	3–6	5.8	6.0	7.2	6.2	6.2	6.8	6.0	6.1
Minimum VMA	14.0	15.0	16.0	13.3	13.4	14.6	14.1	14.0	14.4	13.0	14.3

UNR = University of Nevada, Reno.

The National Cooperative Highway Research Program (NCHRP) Report 573 covered the subject of SGC gyration levels (Prowell & Brown, 2007). The study reported that reducing N_{design} would allow contractors to design mixtures that could better meet field compaction criteria. As shown in Table 7, the study also presented the effects of increasing or decreasing N_{design} on various mixture properties, including VMA and voids filled with asphalt (VFA). The researchers recommended reducing the N_{design} levels in the AASHTO Superpave method, as shown in Table 8. Although the AASHTO N_{design} requirements have not been revised, more than half of the State DOTs have reduced their compactive efforts since the study was published.

Table 7. Effect of Design Compaction on Mixture Properties(Prowell & Brown, 2007)

Property	Increased N_{design}	Decreased N_{design}
Coarse Aggregate Angularity	Increased demand for crushed aggregate	Reduced demand for crushed aggregate or no change
Fine Aggregate Angularity	Reduced natural sand	Reduced need for manufactured sand or no change
Gradation	Changed to increase VMA	Changed to reduce VMA or no change
AV	No effect	No effect
VMA	No effect after mix adjustment	No effect after mix adjustment
VFA	Little or no change	Little or no change
Construction Compaction	More difficult	Less difficult
Mixture Stiffness	Increased stiffness	Decreased stiffness

Table 8. Recommended N_{design} Gyrations from NCHRP Report 573 (Prowell & Brown, 2007)

20-Year Design ESAL	AASHTO R 35 N_{design}	NCHRP 573 N_{design}
<300,000	50	50
300,000 to 3,000,000	75	65
3,000,000 to 10,000,000	100	80
10,000,000 to 30,000,000	100	80
>30,000,000	125	100

ESAL = equivalent single axle load.

Research has been conducted on stone matrix asphalt (SMA) and equivalent N_{design} gyrations for Marshall mixtures in Alabama and Georgia. A study conducted by West and James (2005) using Alabama SMA mixes determined the equivalent SGC gyrations to match a 50-blow Marshall mix design. The study found that, on average, 63 gyrations was equivalent to a 50-blow automatic Marshall hammer. Another study, by West et al. (2007), conducted using Georgia SMA mixtures compared the 50-blow Marshall to SGC compaction. The study found that 35 gyrations was equivalent to 50 blows with an automatic Marshall hammer for the Georgia SMA mixtures. The researchers noted that this result was substantially lower than for the Alabama SMA study and provided evidence of the impact of aggregate toughness on the compaction behavior of stone-on-stone mixtures.

A study for the Tennessee DOT (TDOT) conducted by Huang, Polaczyk, and Hu (2020) investigated converting TDOT Marshall mixtures to SGC mixtures. Based on this study with plant-produced mixtures, the N_{EQ} ranged from 38 to 77 to match 50-blow Marshall mixtures. The study was then replicated with laboratory-produced mixtures, where the N_{design} ranged from 64 to 72 gyrations, averaging 68 gyrations to match 50-blow Marshall mixtures. It is worth noting that TDOT still requires Marshall compaction for all of its highway mix designs.

In summary, studies to compare 50- and 75-blow Marshall mixtures with SGC compactive efforts for highway mix designs have reported a wide range of results. Several studies suggest that the equivalent N_{design} depends on other mixture factors such as the blend gradation, binder type, and aggregate properties. Overall, the transition to Superpave by most State DOTs has largely eliminated rutting as a primary distress for asphalt pavements. There is also a general consensus among asphalt technologists that the SGC compactive efforts have resulted in lower asphalt content mixtures than previously used with Marshall compaction.

2.3 Influence of Reheating on Asphalt Mixture Volumetric Properties

The research plan for this study relied exclusively on the use of plant-produced mixtures sampled from ongoing airport projects nationwide and shipped to the National Center for Asphalt Technology (NCAT) or University of Nevada, Reno (UNR) laboratories. Thus, a literature review was conducted to better understand the potential impacts of sample containers and mixture reheating procedures on Marshall-and SGC-compacted mixture volumetrics. The objective was to determine a standard protocol for acquiring loose hot-mix asphalt (HMA) field samples collected onsite, cooling and shipping them to a laboratory, and reheating them for compaction. Several papers in the literature focused on the influence of reheating on mixture performance properties, but they did not contain mixture volumetrics data.

Two types of sample containers were identified in the literature: metal buckets and cardboard boxes. Five-gallon metal buckets were used to collect loose HMA directly from batch and continuous mixture asphalt plants for transportation, storage, and reheating (Kidd, Stephenson, & White, 2019). Similarly, cardboard boxes were used to collect plant-produced mixtures and transport them to laboratories for reheating and testing (Lemke et al., 2018).

Kidd et al. (2019) investigated two methods of mixture reheating. The first method involved emptying the 5-gal metal bucket onto a steel tray and placing the mixture into the oven. The second method involved sealing the 5-gal metal bucket and drilling a small hole into the container to permit ventilation of gases and allow a temperature probe to be inserted, as shown in Figure 3. The temperature of the loose mixture was recorded every 10 min. The open container method was reported to be much more consistent in both time to reach compaction temperature and uniformity of temperature within the container.

Figure 3. Reheating Method (Kidd et al., 2019)

Note: From "Implications of Reheating of Asphalt Mixes on Performance Testing," by A. Kidd, G. Stephenson, & G. White, 2019, August, *Proceedings of the 18th AAPA International Flexible Pavements Conference 2019*, Australian Asphalt Pavement Association. Used with permission.

Lemke et al. (2018) also investigated two methods of reheating HMA samples that were obtained and put in cardboard boxes. The first method involved opening the cardboard box and placing the loose mixture into a metal tray. The second method involved keeping the mixture in the cardboard box. Temperature probes were inserted into both boxes. Removing the mixture from the cardboard box and placing it in a metal tray decreased the time for the mixture to reach compaction temperature. The study also investigated whether placing aluminum foil over the tray would affect reheating. Reheating time was reduced by 25 percent when the pan was uncovered versus covered with aluminum foil.

The difference in volumetric and mechanical properties of field-compacted HMA samples versus reheated-compacted HMA samples was investigated by Anderson, Bukowski, and Turner (1999) using several HMA samples from interstate highway mixtures. Loose mixture was obtained and compacted and the frequency sweep test was performed at 26 °C and 41 °C as per the AASHTO TP 7 procedure. Mechanical properties of the mixtures were evaluated in terms of complex shear modulus (G*) and maximum shear strain at various temperatures. The study indicated that reheating samples did not affect these mechanical properties.

A study conducted by Diefenderfer and Hearon (2008) compared the volumetric properties of HMA and warm mix asphalt (WMA) compacted in the field versus reheated samples compacted in the laboratory. All mixtures were compacted with an SGC at 65 gyrations. Two mixtures were sampled at an asphalt plant. Both mixtures were compacted in the field, and a second portion of the loose mixtures was allowed to cool and then reheated to compaction temperature in the laboratory. The volumetrics of the hot-compacted and reheated mixtures were compared. The reheated HMA samples exhibited acceptable differences in maximum specific gravity (G_{mm}), AV, and VFA. However, VMA was 1.0 percent higher and the G_{mb} was 0.09 percent lower on average for the reheated mixture compared to the hot-compacted mixtures. For WMA samples, AV differed by 1.8 percent for one of the mixtures but was similar for the other.

Huner and Brown (2001) also studied the impact of mixture reheating on volumetric properties. The study included several mixtures with fine and coarse gradations and two binders. The mixtures were compacted with an SGC at 0, 3, and 20 hr of storage time, and volumetric properties were compared. The zero-storage samples were compacted immediately, while the 3- and 20-hr aged samples required reheating prior to compaction.

Six of the eight mixtures showed significant differences in AV between 0 and 3 hr or 0 and 20 hr. However, these statistically significant differences did not indicate a practical difference. The researchers stated, “For instance, the LOW-64-F mixture had voids in total mix (VTM) means of 4.8, 4.7, and 4.6 at 0, 3, and 20 hours, respectively. These were determined to be statistically different, but there is no practical difference.” When all eight mixtures were analyzed, no significant difference was evident for either storage time comparison. The same differences were noted for VMA and, subsequently, VFA. The study further concluded that “Re-heating the mix before compaction has no effect on volumetrics.”

Bocci et al. (2020) investigated the influence of asphalt mixture conditioning time on mixture stiffness, volumetric, and mechanical properties. The study examined the influence of conditioning time on laboratory-prepared samples and on production and paving operations. The findings indicated that prolonged storage time could lead to increased mixture stiffness and mechanical test properties, but it did not significantly influence volumetric properties of laboratory-compacted specimens using the SGC.

2.4 Effect of Aggregate Properties on Volumetrics and Compactability

Aggregate properties such as gradation, strength, particle shape, and texture can influence the compactability and design volumetrics of asphalt mixtures. Several past studies evaluated the aggregate shape—whether flat and elongated, rounded, or fractured, etc.—on mixture compactability, design gradation, and volumetrics. Carlberg et al. (2003) investigated the effect of adding fractured coarse aggregates on volumetrics. Three percentages (45, 65, and 85 percent) of fractured coarse aggregates were used to prepare dense-graded mixtures. Both Superpave and Marshall compaction were conducted using 75 gyrations and 75 blows, respectively, for specimen preparation. Results showed a decreasing trend of density with the addition of higher percentages of fractured aggregates for both compaction methods. It was also shown that Marshall densities were slightly lower than the gyratory-compacted specimens, though both sets of densities were in the desirable AV range of 3–4 percent. This trend of decreasing density with higher fractured aggregates was also reflected in other volumetric properties, such as increased VMA and decreased VFA values.

Vavrik, Fries, and Carpenter (1999) examined the effect of various levels of flat and elongated (F&E) particles on gyratory compaction characteristics. Two coarse aggregates, dolomite and gravel, were used in the study. Coarse aggregates were first categorized into three groups based on their flat-and-elongation aspect ratio. All mixtures were compacted using an SGC and evaluated for volumetric properties and compaction characteristics. Additionally, specimens were extracted to assess aggregate breakdown during compaction.

Overall, the results indicated that a mixture with a higher percentage of F&E particles results in higher AV and, consequently, higher design gyrations. The breakdown of F&E particles produces more fine aggregates, increasing AV and resulting in higher gyrations to produce the target density. This, in turn, results in increased VMA and reduced VFA. The sensitivity of F&E particles was linked to the Los Angeles (LA) abrasion loss values, as reported by Aho, Vavrik, and Carpenter (2001). Use of softer (higher LA abrasion loss) F&E aggregates is more sensitive to breakdown and may cause compactability issues.

Collins et al. (1997) evaluated the effect of degradation on design gradation using two granite aggregates: one with a low LA abrasion loss of 22 percent and one with a high LA abrasion loss of 52 percent. Specimens were compacted using an SGC and an Astec vibratory compactor to prepare test specimens with a target AV of 4.0 percent. Aggregates were then extracted from the specimens using a vacuum extractor, and their gradations were analyzed. As expected, the mixtures with high LA abrasion loss degraded more than the ones with low LA abrasion loss. This degradation shifted the design gradation close to the restricted zone. Additionally, this degradation slightly increased the dust content in the design, resulting in a potential change in dust proportion, although the dust proportions were within the limit. Such changes in design gradation are sensitive to the method of compaction, as confirmed by Zhang, Yu, and Huang (2020). They showed that SGC has less impact on the gradation than the Marshall method.

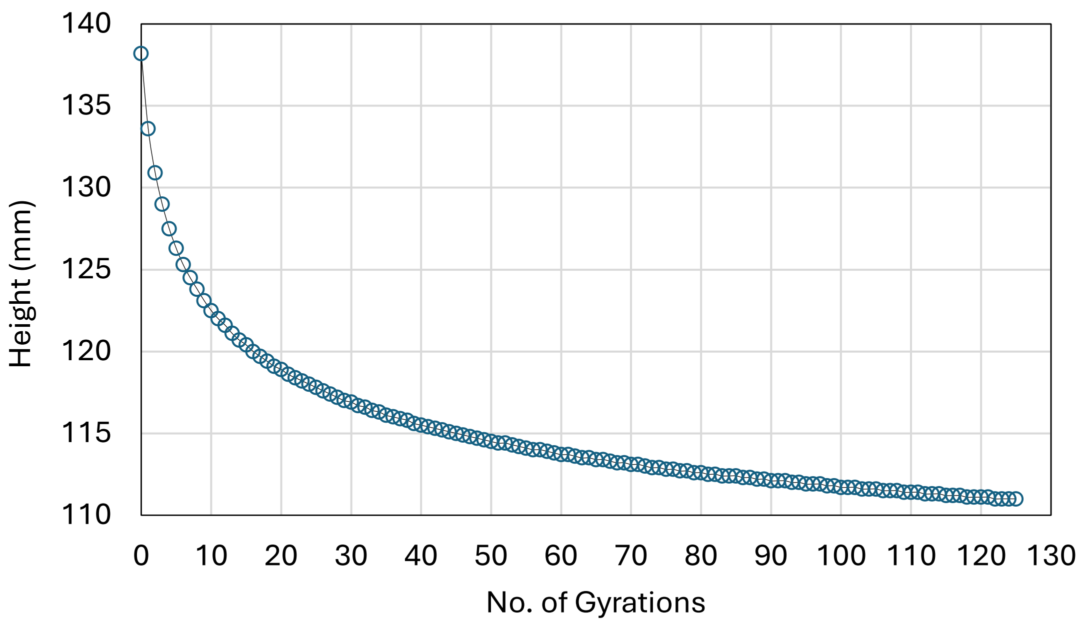
Moavenzadeh and Goetz (1963) described two primary mechanisms associated with aggregate breakdown during compaction. The first mechanism is the wearing of aggregates, which is the chipping of some sharp edges of aggregate particles. Rounded aggregates, which lack sharp edges, are less prone to this type of breakdown. The second mechanism is fracturing of aggregates, which occurs when the compactive stress exceeds aggregate strength. Thus, LA abrasion largely controls this method of breakdown. Additionally, aggregate gradation plays a significant role. Gradation that allows less density or greater contact stress is more prone to this method of breakdown. Thus, open-graded mixtures often have more aggregate breakdown than dense-graded mixtures.

2.5 Locking Point of Asphalt Mixtures Using Superpave and Marshall Compactors

The locking point concept was originally proposed by the Illinois DOT and is believed to represent the point where the aggregate skeleton "locks" together during SGC compaction. Beyond this point, application of additional gyrations results in aggregate degradation while little additional compaction occurs (Pine, 1997). It is commonly referred to as the 3-2-2 locking point, identified by analyzing the change in specimen height during SGC compaction.

The Illinois locking point (ILP) is defined as the first gyration in a series of three gyrations of equal specimen height that immediately follows two sets of two gyrations of equal specimen height. It has been suggested that the locking point is analogous to test strip refusal density during field compaction. Some State DOTs, however, have developed other locking point definitions.

An example of a mixture with 10 occurrences of ILP is shown in Figure 4. The graph shows specimen height as a function of gyrations for a 75-blow Marshall mixture with an SGC equivalent of 112 gyrations. The first occurrence of the ILP was at 83 gyrations, and between the 83rd and 122nd gyrations, the ILP was observed 10 times.



Source: National Center for Asphalt Technology

Figure 4. F-403 SGC Compaction Curve—Specimen Height vs. Gyrations

Some agencies and researchers have considered the locking point concept for selecting mix design asphalt content, rather than using a design AV level or range. Examples include Mohammad and Al Shamsi (2007) and Polaczyk et al. (2019). Use of the ILP to determine design gyrations was not considered as part of this project. However, the SGC specimen height data for each specimen compacted in this study was analyzed to determine whether a relationship between N_{EQ} and ILP existed or if it was common to observe multiple occurrences of ILP with mixtures having high N_{EQ}.

2.6 Summary of Literature Review and Findings

The literature review revealed the following key findings:

- Several studies have sought to develop correlations between Marshall hammer blows and SGC gyrations to achieve similar mixture bulk densities for airfield mixtures and highway mixtures. The range of observed N_{EQ} results for airfield mixtures has been broad, with standard deviations of 25 gyrations. Some studies recommended an N_{EQ} of 70 for 75-blow Marshall mix designs, leading the FAA to set the P-401 specification at 75 gyrations for simplicity. Fewer studies included analyses of 50-blow Marshall mixtures, and those that did also reported a wide range of N_{EQ} values, with recommendations commonly suggesting 50 gyrations to replace 50-blow Marshall compaction.
- The range of N_{EQ} gyrations observed in highway mixtures has been broader than in airfield mixtures. Airfield mixtures are all dense-graded, low-permeability mixtures with a narrower gradation band. In contrast, highway mixtures include dense-graded base, intermediate and surface mixtures, and specialty surface mixtures such as SMA, open-graded mixtures, and gap-graded crumb rubber-modified mixtures, with less focus on permeability and durability than airfield pavements.
- Several studies reported that reheating asphalt mixtures can affect mixture stiffness and influence mechanical properties. However, most studies have generally found that reheating asphalt mixtures does not significantly affect the volumetric properties of SGC-compacted mixtures.
- Aggregate characteristics such as shape, gradation, strength, and texture influence mixture volumetrics and compactability. Softer aggregates and higher percentages of F&E particles can result in significant aggregate breakdown, which can affect the resulting compacted density.
- Multiple definitions of locking point exist, although the ILP is the most common. Some researchers identified the SGC locking point as influencing mixture compactability, and some studies suggested using the locking point to determine the mix design compactive effort. In some Marshall-to-SGC correlation studies, mixtures that reach the locking point prior to N_{EQ}, especially multiple times, require more gyrations to achieve an equivalent AV content than those that do not observe a locking point.

3. Experimental Plan

3.1 Analysis Approach for Determining N_{EQ}

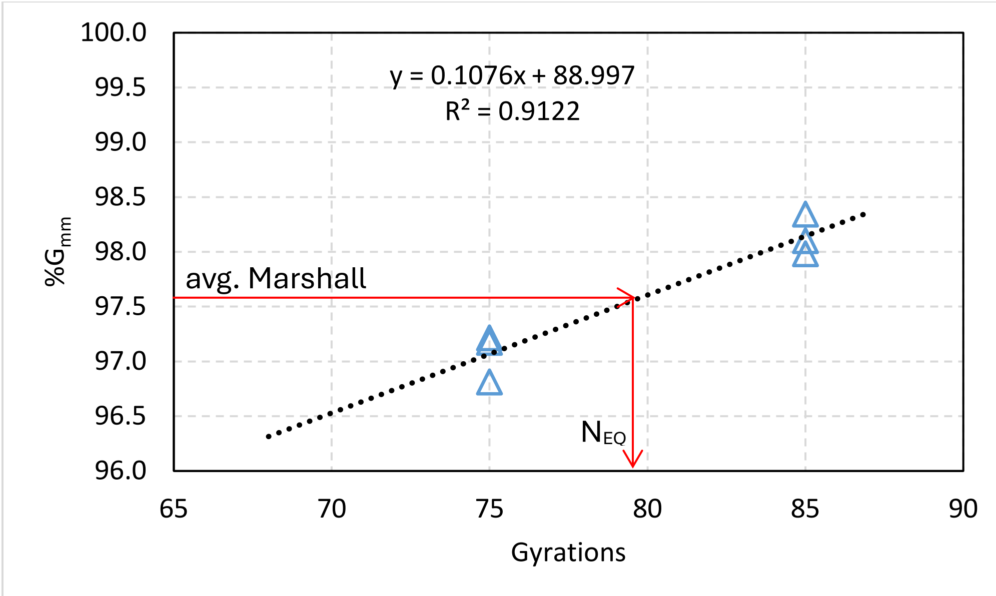
The objective of this project was to determine the number of gyrations with an SGC (N_{EQ}) needed to achieve volumetric properties equivalent to those obtained using 50 and 75 blows with a Marshall hammer. The research team used a straightforward approach to meet this objective.

Given that G_{mb} is the only mixture property affected by compactive effort, finding the number of gyrations with the SGC that yields the same G_{mb} as from the 50-blow or 75-blow Marshall hammer compaction is the most direct way to achieve equivalent volumetric properties for any mixture. To "normalize" the compaction data on a common scale, G_{mb} results for each mixture were divided by G_{mm} and expressed as percent G_{mm}. The process for determining N_{EQ} for a mixture is outlined in Table 9 and illustrated in Figure 5.

Table 9. Steps in the Process for Determining N_{EQ} for Each Mixture

Step	Description
1	Determine the mixture G_{mm}.
2	Compact three specimens with 50- or 75-blow Marshall compaction and determine the G_{mb} of the specimens.
3	Check within-laboratory d2s limits of replicate results.
4	Determine the relative density (%G_{mm}) of the Marshall specimens.
5	Compact the first set of specimens in the SGC at 50 or 75 gyrations.
6	If the average SGC %G_{mm} is greater than the average Marshall %G_{mm}, compact the second set of SGC specimens at a lower number of gyrations. If the average SGC %G_{mm} is less than the average Marshall %G_{mm}, compact the second set of SGC specimens at a higher number of gyrations.
7	Determine the linear regression equation between the number of gyrations and %G_{mm} at the two SGC compaction levels.
8	Use the linear regression equation to determine N_{EQ} at the number of gyrations corresponding to the average Marshall %G_{mm}.

d2s= difference two-sigma limit. The acceptable range of two test results.

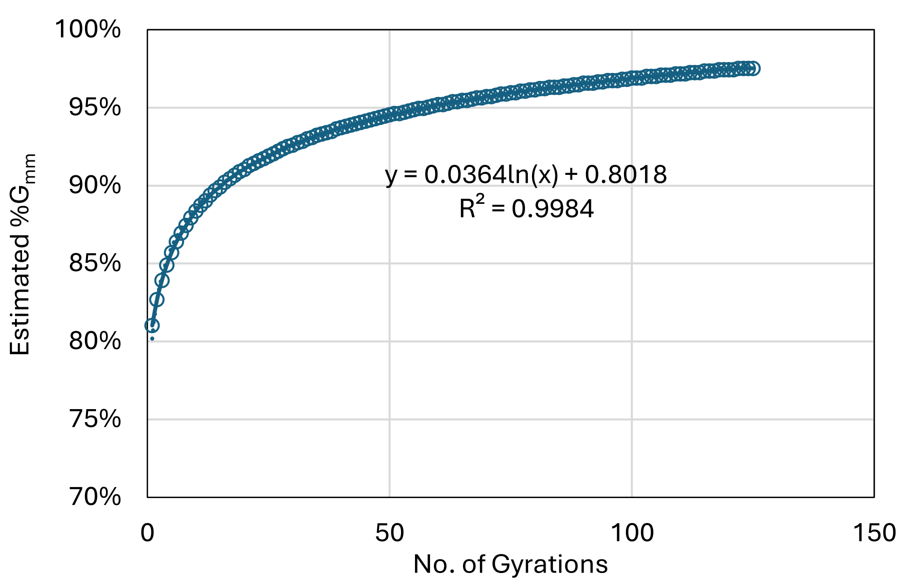


Source: National Center for Asphalt Technology

Figure 5. Graphical Illustration of Determining N_{EQ} for an Asphalt Mixture

3.1.1 Potential Error of Linear Interpolation vs. Actual Compaction Curve

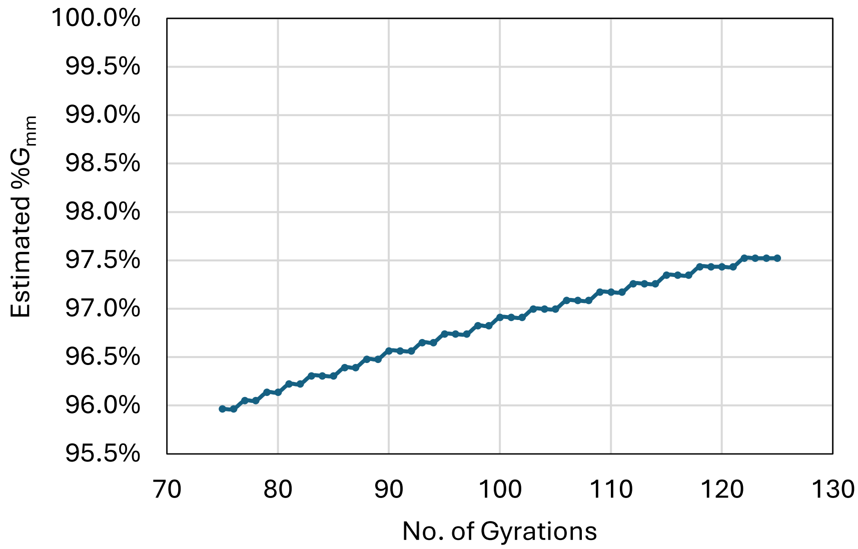
In the method described above, the change in specimen density versus gyrations is assumed to be a linear relationship ($y = m\,x + b$), where the slope m is a constant. In reality, compaction in an SGC is closely approximated as a logarithmic function, as shown in Figure 6.



Source: National Center for Asphalt Technology

Figure 6. Density Change for an Asphalt Mixture During Compaction in an SGC

However, within the range of gyrations used in the N_{EQ} determinations, the SGC compaction process is nearly linear, as shown in Figure 7, so the error from using a linear approximation is insignificant. In this figure, the stair-step appearance of the density change is due to the SGC recording of compaction heights to the nearest 0.1 mm.



Source: National Center for Asphalt Technology

Figure 7. Density Change for an Asphalt Mixture Between 75 and 125 Gyrations

On the other hand, if the two SGC compaction levels fail to bracket the density obtained with the Marshall hammer compaction, then the linear relationship must be extrapolated beyond the tested range. Extrapolations of N_{EQ} well outside the tested range could introduce significant errors.

3.2 Compaction Equipment

The key pieces of equipment required in this project were the SGC, as specified in ASTM D6925, and the Marshall hammer, as specified in ASTM D6926. ASTM D6926 allows either a Type 1 manual, hand-operated compaction hammer or a Type 2 mechanically operated compaction hammer. For this project, a decision was made at the start to use the manual hammer in both laboratories, NCAT and UNR. In addition, both laboratories used the same brand of SGC equipment for consistency.

3.3 Evaluation of Reheating Effects on Compacted Mixture Volumetrics

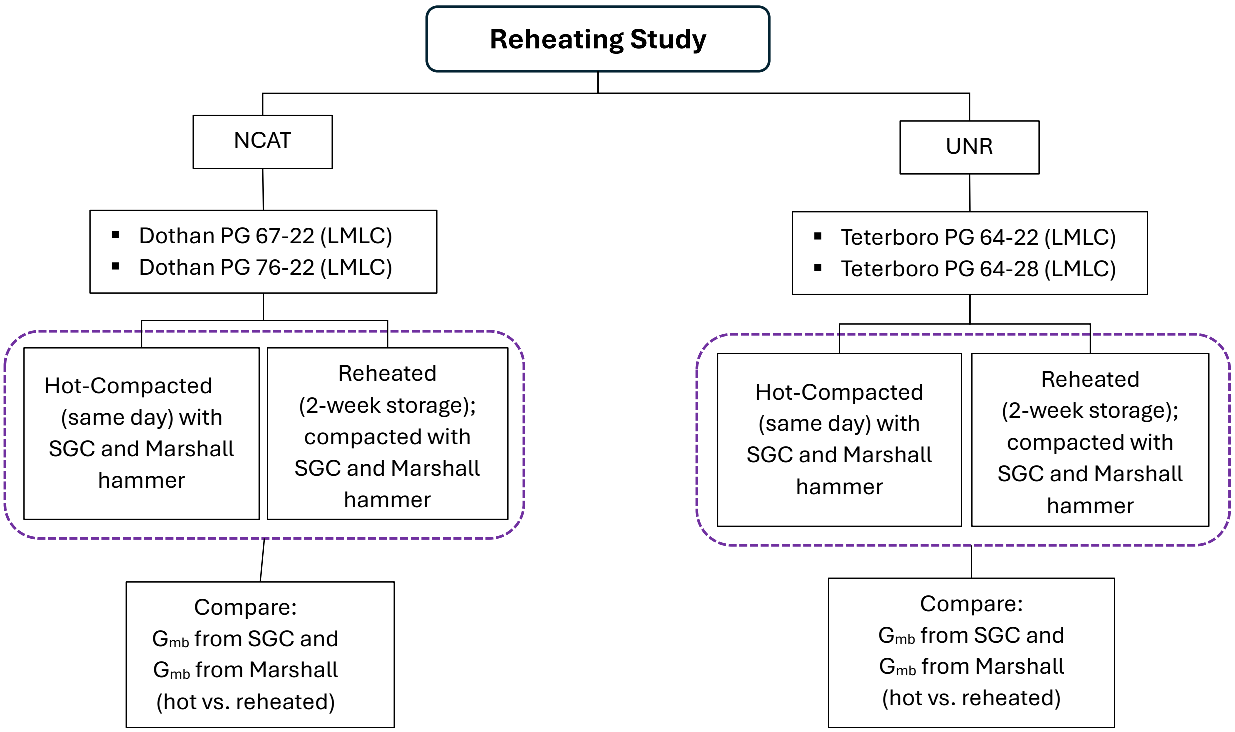
Prior to starting the N_{EQ} experiment, the research team conducted a limited study to evaluate the effect of reheating the plant-produced mixtures prior to compaction on volumetric properties. For the reheating experiment, two P-401 mixtures were identified by the research team, and raw materials were collected. One of the mixtures in this evaluation

(Teterboro mix) was also used in the reproducibility study described in the next section. Figure 8 summarizes the reheating study testing plan.

Each mix was prepared using two asphalt binders, an unmodified binder and a polymer-modified binder. The two binders used with the Dothan mix were a PG 67-22 and a PG 76-22 (original binder used in the job mix formula [JMF]). This mix was a 75-gyration design. The binders used with the Teterboro mix were a PG 64-22 (original binder used in the JMF) and a PG 64-28PM. This mix was a 75-blow Marshall design.

For each of the four mixes, four sets of specimens were compacted as follows:

1. Laboratory-prepared mixtures were short-term aged for 2 hr per ASTM D6926 (section 6.3.2) and then compacted using the Marshall hammer (hot-compacted, same day).
2. Laboratory-prepared mixtures were short-term aged for 2 hr per ASTM D6926. The mixtures were allowed to cool to the ambient laboratory temperature and stored for 2 weeks in the laboratory, then reheated to the compaction temperature and compacted with the Marshall hammer. The reheating procedure used was established for the AAPTP Balanced Mix Design Rutting and Cracking Projects (Appendix A).
3. Laboratory-prepared mixtures were short-term aged for 2 hr per ASTM D6926 and then compacted with the SGC (hot-compacted, same day).
4. Laboratory-prepared mixtures were short-term aged for 2 hr per ASTM D6926, cooled to the ambient laboratory temperature, and stored for 2 weeks in the laboratory, then reheated (as indicated in step 2) to the compaction temperature and compacted with the SGC (reheated, stored for 2 weeks).



LMLC = laboratory-mixed, laboratory compacted.

Source: National Center for Asphalt Technology

Figure 8. Reheating Study Testing Plan

Three specimens per mix were hot-compacted, and three were compacted after reheating using the SGC and Marshall hammer. Specimens were then tested to determine G_{mb}, and the results for each combination were compared. Figure 9 presents the average G_{mb} results of hot-compacted and reheated specimens for the Dothan and Teterboro mixes by compaction method and binder grade used, with error bars indicating ±1 standard deviation.

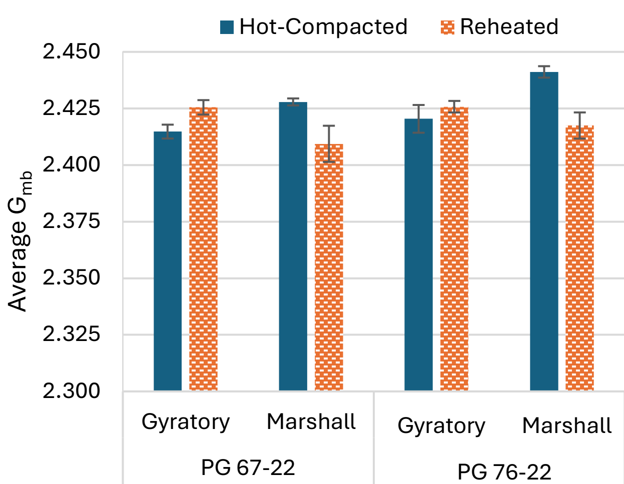
Two analyses were conducted on the results from this limited study:

- Comparison with the ASTM D2726 precision statement
  - G_{mb} results obtained from each laboratory and each subset are shown in Table 12 (16 subsets) and were compared with the single-operator one-standard deviation (1s) limit of 0.008 for the Dothan mix (12.5 mm NMAS) and 0.013 for the Teterboro mix (19.0 mm NMAS). This comparison provided an additional assessment of the repeatability of the test results for the two laboratories.
  - The differences between average G_{mb} results from hot-compacted and reheated specimens for each subset were compared with the within-laboratory difference 2-sigma (d2s) value of 0.023 for the Dothan mix and 0.037 for the Teterboro mix.

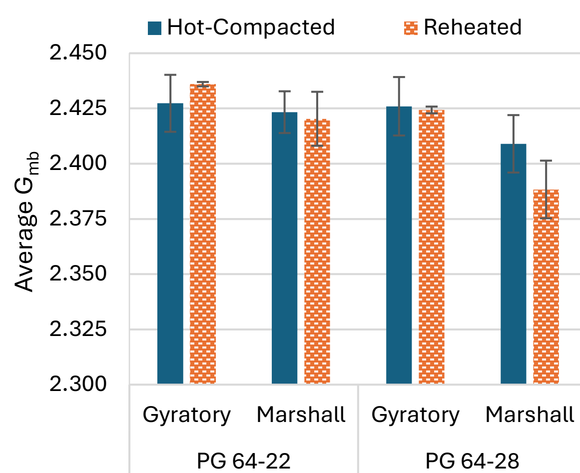
- Analysis of variance (ANOVA)
    - A one-way ANOVA at a 95 percent confidence interval was also conducted on subsets of mix type, binder grade, and compaction method to assess whether there was a significant difference between hot-compacted and reheated results. The p-values for each subset are presented in Table 10.

As shown in Table 10, all subsets had standard deviations less than the corresponding single-operator 1s limits of 0.008 and 0.013, indicating that both laboratories were able to produce repeatable data. In addition, seven of eight subsets (hot-compacted minus reheated) met the d2s within-laboratory limits of 0.023 for the Dothan mix and 0.037 for the Teterboro mix. The only subset that barely failed the d2s limit is shown in bold in Table 10. This subset corresponds to the Dothan mix with PG 76-22 binder compacted using the Marshall hammer.

Lastly, the ANOVA results show that differences between six of eight subsets (hot-compacted minus reheated) were not significantly different (p-value<0.05). The two subsets that were statistically different are shown in bold in Table 10; both subsets were for the Dothan mix. The first subset used PG 67-22 binder compacted with the SGC, and the second used the PG 76-22 binder compacted with the Marshall hammer. This second subset was the one that failed the 1s within-laboratory limit. These results indicate that reheating had minimal effect on the G_{mb} results for either Marshall or SGC compaction. In addition, there was no evidence that the binder grade affected the test results. Based on these results, it was determined that reheated samples could be used for this study with limited or no effect.



(a) Dothan Mix Evaluated at NCAT



(b) Teterboro Mix Evaluated at UNR

Source: National Center for Asphalt Technology

Figure 9. G_{mb} of Hot-Compacted and Reheated Specimens for Mixes in the Reheating Study: (a) Dothan Mix Evaluated at NCAT; (b) Teterboro Mix Evaluated at UNR

Table 10. Summary Results for Reheating Experiment

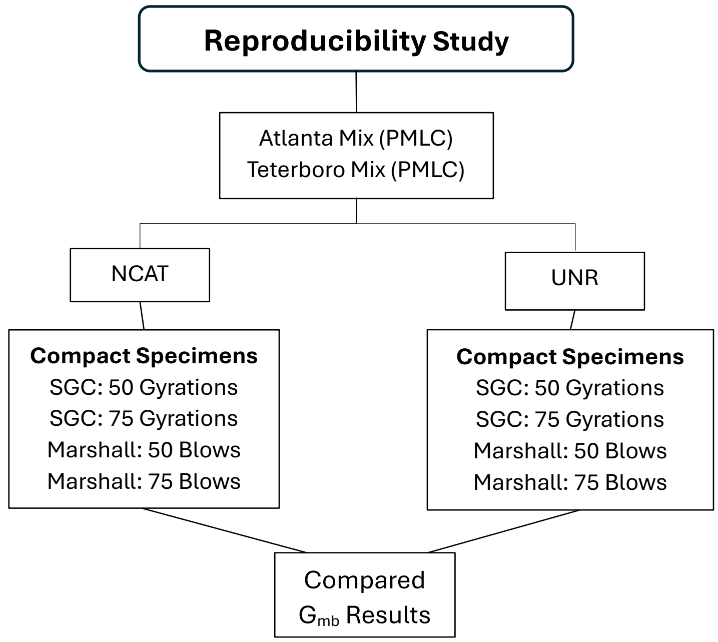
Mix	Compaction Method	Binder Grade	Reheating	Average G_{mb}	Standard Deviation	Difference Between Hot-Compacted & Reheated	p-value
Dothan	Gyratory	PG 67-22	Hot-compacted	2.415	0.003	-0.011	***0.014***[b]
			Reheated	2.426	0.003		
		PG 76-22	Hot-compacted	2.420	0.006	-0.006	0.266
			Reheated	2.426	0.003		
	Marshall	PG 67-22	Hot-compacted	2.428	0.002	0.019	0.052
			Reheated	2.409	0.008		
		PG 76-22	Hot-compacted	2.441	0.003	***0.024***[a]	***0.010***[b]
			Reheated	2.417	0.006		
Teterboro	Gyratory	PG 64-22	Hot-compacted	2.427	0.013	-0.009	0.364
			Reheated	2.436	0.001		
		PG 64-28	Hot-compacted	2.426	0.013	0.002	0.848
			Reheated	2.424	0.002		
	Marshall	PG 64-22	Hot-compacted	2.423	0.009	0.003	0.755
			Reheated	2.420	0.012		
		PG 64-28	Hot-compacted	2.409	0.013	0.011	0.124
			Reheated	2.388	0.013		

[a]This is the only result that exceeded its d2s limit.

[b]The p-value is <0.05, indicating a statistically significant difference at a 5% level of significance.

3.4 Preliminary Reproducibility Study

Two plant-produced P-401 mixtures, one with a polymer-modified binder and the other with an unmodified binder, were tested at the NCAT and UNR laboratories. The first mix is a 12.5 mm NMAS (Atlanta mix), and the second is a 19.0 mm NMAS (Teterboro mix). Both laboratories compacted three specimens each at 50 gyrations and 50 blows, and 75 gyrations and 75 blows for both mixtures. The compacted specimens were tested for G_{mb}, and the results of each combination were compared between the laboratories. The testing plan for this limited reproducibility study is summarized in Figure 10.

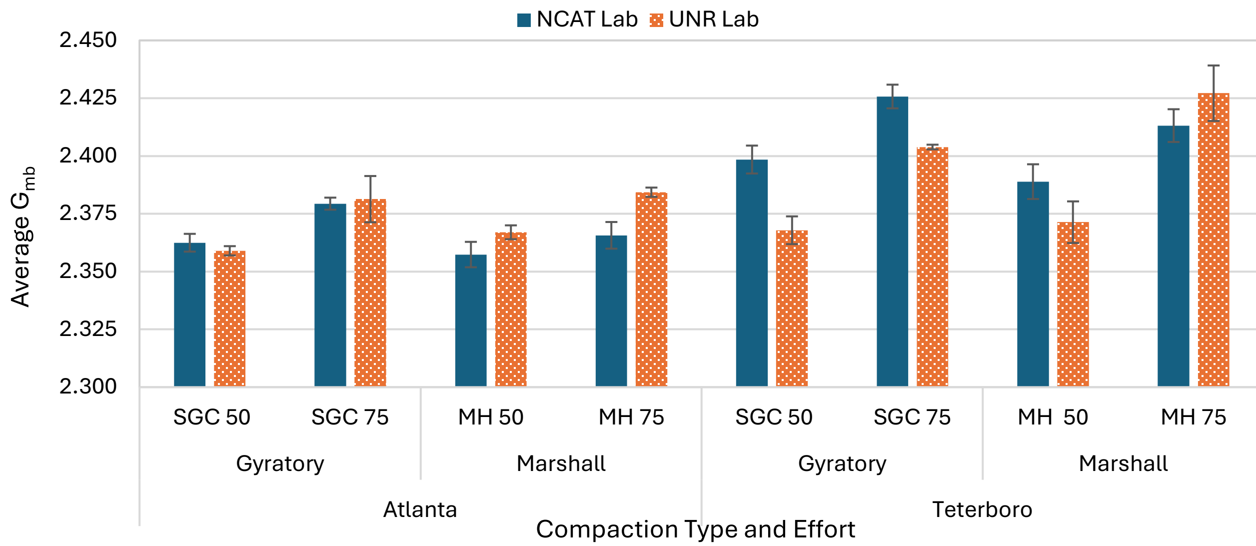


PMLC = plant-mixed, laboratory-compacted.

Source: National Center for Asphalt Technology

Figure 10. Reproducibility Testing Plan

Figure 11 presents the average G_{mb} results for each set from NCAT and UNR, with ±1 standard deviation error bars. The G_{mb} results were compared with the within-laboratory and multi-laboratory precision statement in ASTM D2726, summarized in Table 11. Table 12 summarizes the statistics for each combination and the differences between the average G_{mb} results from the two laboratories to assess reproducibility. From the table, it can be seen that all of the results were less than their corresponding single-operator 1s limits of 0.008 and 0.013 for the 12.5 mm and 19.0 mm NMAS mixtures, respectively. This indicates good repeatability for both laboratories. In addition, the differences between the laboratories' average G_{mb} for each combination are below the multi-laboratory d2s limit of 0.042. This indicates that the reproducibility between both laboratories is satisfactory.



MH = Marshall hammer.

Source: National Center for Asphalt Technology

Figure 11. G_{mb} Results of Two Plant Mixtures from NCAT and UNR Laboratories

Table 11. ASTM D2726 Precision Information Estimates

Mixture	1s Limit	d2s Limit
Single Operator		
12.5-mm NMAS	0.008	0.023
19.0-mm NMAS	0.013	0.037
Multi-Laboratory		
12.5-mm NMAS	0.015	0.042
19.0-mm NMAS	0.015	0.042

Table 12. Average G_{mb} Results and Reproducibility Validation per ASTM D2726

Mix Source	Compaction Method	Gyration / Blow	NCAT Average G_{mb}	NCAT Std. Dev. of G_{mb}	UNR Average G_{mb}	UNR Std. Dev. of G_{mb}	G_{mb} Difference Between NCAT and UNR
Atlanta (NMAS: 12.5 mm)	Gyratory	SGC 50	2.362	0.004	2.359	0.002	0.003
		SGC 75	2.379	0.003	2.381	0.010	-0.002
	Marshall	MH 50	2.357	0.005	2.367	0.003	-0.010
		MH 75	2.366	0.006	2.384	0.002	-0.019
Teterboro (NMAS: 19 mm)	Gyratory	SGC 50	2.398	0.006	2.368	0.006	0.031
		SGC 75	2.426	0.005	2.404	0.001	0.022
	Marshall	MH 50	2.389	0.008	2.371	0.009	0.018
		MH 75	2.413	0.007	2.427	0.012	-0.014

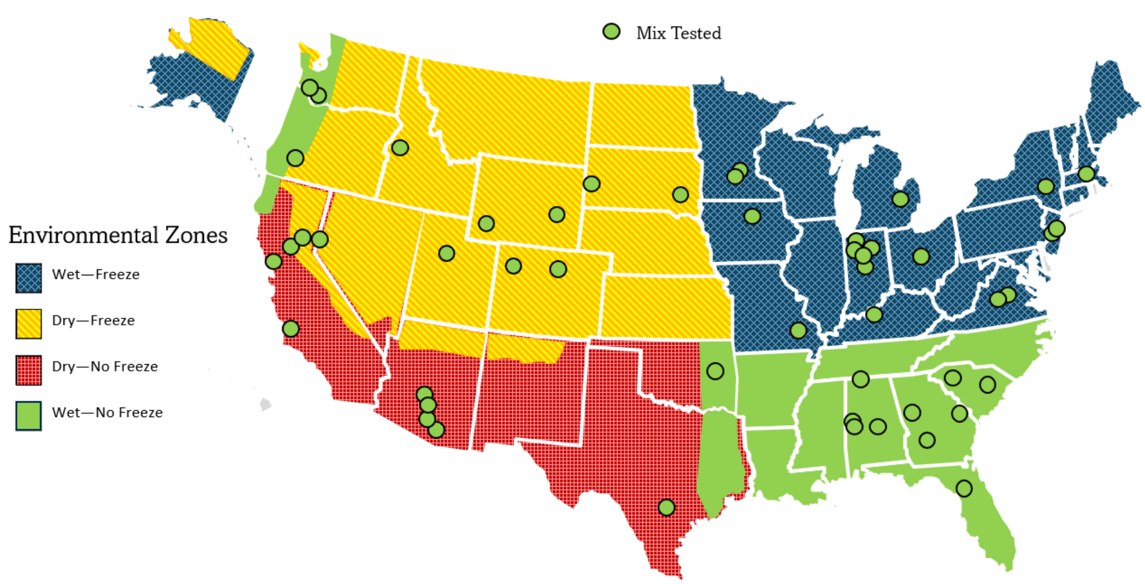
MH = Marshall hammer.

3.5 Airfield Plant Mixtures and Database Description

To accomplish the primary objective of this study, the research team contacted airport consultants and contractors across the United States to collect 51 airfield pavement mixtures (P-401/P-403) representing four climatic zones: wet-freeze, dry-freeze, dry-no-freeze, and wet-no-freeze. The mixtures were gathered from airfield paving projects constructed in 2023 and 2024. Figure 12 shows the locations of the airport projects where the mixtures were collected for this study. Forty-four of the mixtures sampled were 75-gyration/blow designs (28 Superpave and 16 Marshall), and 7 were 50-gyration/blow designs (5 Superpave and 2 Marshall). A table with the airport location and description of the mixtures is presented in Appendix B.

In addition to collecting the mixture samples, the research team compiled mix design information, aggregate types and properties, binder types, QC results, and mix production temperature information in a database for further analysis.

The mixtures gathered were split between the NCAT and UNR laboratories by location, with mixtures in the western part of the country tested at UNR and most of the mixtures in the eastern part of the country tested at NCAT. Both laboratories followed the same specimen fabrication, compaction, and testing protocols. The reheating method used was established for the AAPTP Balanced Mix Design Rutting and Cracking Projects per agreement with the project panel; it is included in Appendix A.



Source: National Center for Asphalt Technology

Figure 12. Locations of Projects Where Mixture Samples Were Obtained for This Study

3.6 Verification of Compliance with ASTM D2041 and ASTM D2726 Precision Limits

As part of the data analysis, the research team verified compliance with the precision limits in ASTM D2041 (G_{mm}) and ASTM D2726 (G_{mb}) for each mix sampled:

- JMF vs. QC results for G_{mm} and G_{mb} (between-laboratory d2s).
- Research laboratory results vs. QC results for G_{mm} and G_{mb} (between-laboratory d2s).
- NCAT or UNR results for G_{mm} and G_{mb} (within-laboratory 1s).

Table 13, Table 14, and Table 15 show example analyses for two mixes that met the precision limits of ASTM D2041 and ASTM D2726. Table 13 shows the comparison between the JMF and contractor QC G_{mm} and G_{mb} results. For these comparisons, if the results did not meet the d2s limits of the standards, no further action was taken.

Table 13. Example Comparison Between JMF and Contractor QC G_{mb} and G_{mm} Results

G_{mb} (ASTM D2726)				G_{mm} (ASTM D2041)			
JMF G_{mb}	QC G_{mb}	Difference	ASTM D2726 d2s Limit	JMF G_{mm}	QC G_{mm}	Difference	ASTM D2041 d2s Limit
2.442	2.412	0.030	0.042	2.530	2.513	0.017	0.044
2.419	2.415	0.004	0.042	2.507	2.496	0.011	0.044

Table 14 shows two comparisons of two sets of G_{mb} data. The left portion of the table shows the within-laboratory G_{mb} standard deviation. If the research laboratory's results did not meet the 1s limit (within-laboratory), the research team retested the G_{mb} to ensure compliance. The right portion of the table compares the contractor's and research laboratory's average G_{mb} results. If the comparison did not meet the d2s limit (between-laboratory), the research team compacted another set of specimens and tested their G_{mb}.

Table 14. Example Assessment of Research Laboratory Within-Laboratory G_{mb} Variability and Comparison of Contractor QC and Research Laboratory G_{mb} Results

G_{mb} (ASTM D2726)						
NCAT Within Lab			Contractor QC and NCAT			
Avg. G_{mb} NCAT	St. Dev. NCAT	ASTM D2726 1s Limit	Avg. G_{mb} Contractor	Avg. G_{mb} NCAT	Difference	ASTM D2726 d2s Limit
2.436	0.003	0.008	2.412	2.436	0.024	0.042
2.433	0.006	0.008	2.415	2.433	0.018	0.042

Table 15 shows comparisons of two sets of G_{mm} data. As with the G_{mb} data in Table 14, the left portion of the table shows the within-laboratory G_{mm} standard deviation. If the research laboratory's results did not meet the 1s limit (within-laboratory), the research team retested the G_{mm} to ensure compliance. The right portion of the table compares the contractor's and research laboratory's average G_{mm} results. If the comparison did not meet the d2s limit (between-laboratory), the research team tested another set of replicates and determined their G_{mm}.

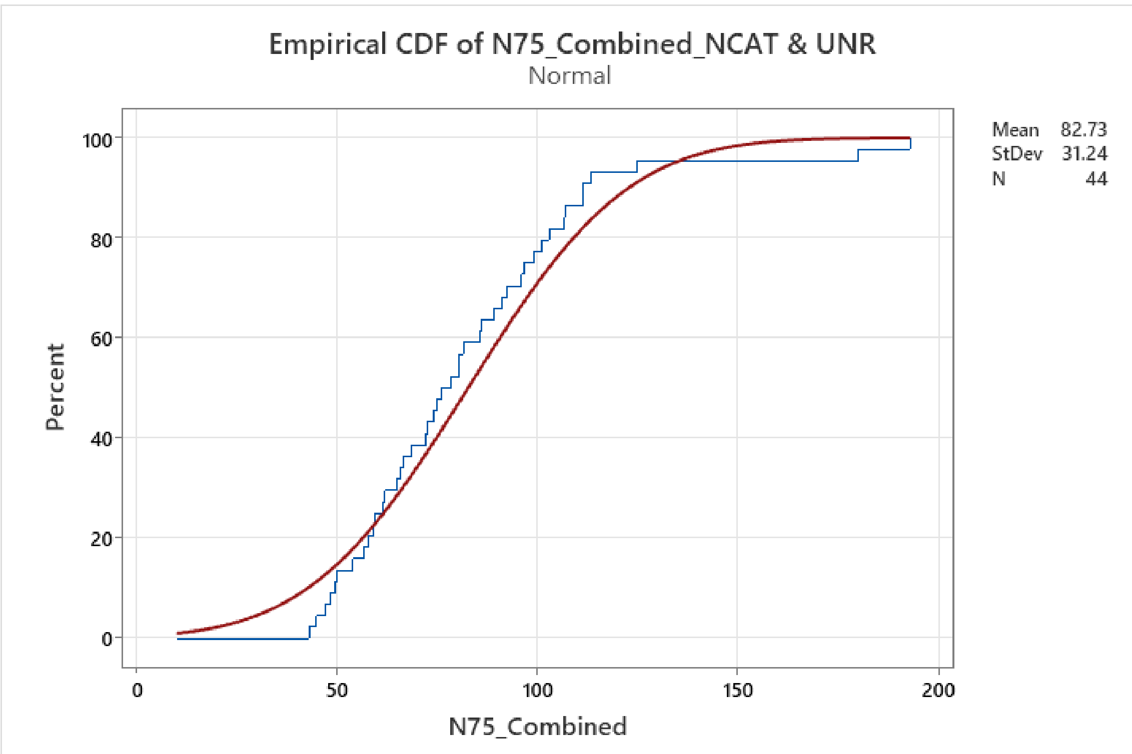
Table 15. Example Assessment of Research Laboratory Within-Laboratory G_{mm} Variability and Comparison of Contractor QC and Research Laboratory G_{mm} Results

G_{mm} (ASTM D2041)						
NCAT Within Lab			Contractor QC and NCAT			
Avg. G_{mm} NCAT	St. Dev. NCAT	ASTM D2041 1s Limit	Avg. G_{mm} Contractor	Avg. G_{mm} NCAT	Difference	ASTM D2041 d2s limit
2.539	0.004	0.008	2.513	2.539	0.026	0.044
2.494	0.006	0.008	2.496	2.494	0.002	0.044

4. Laboratory Testing and Data Analysis

4.1 Preliminary Analysis: Histograms and Cumulative Distribution Functions

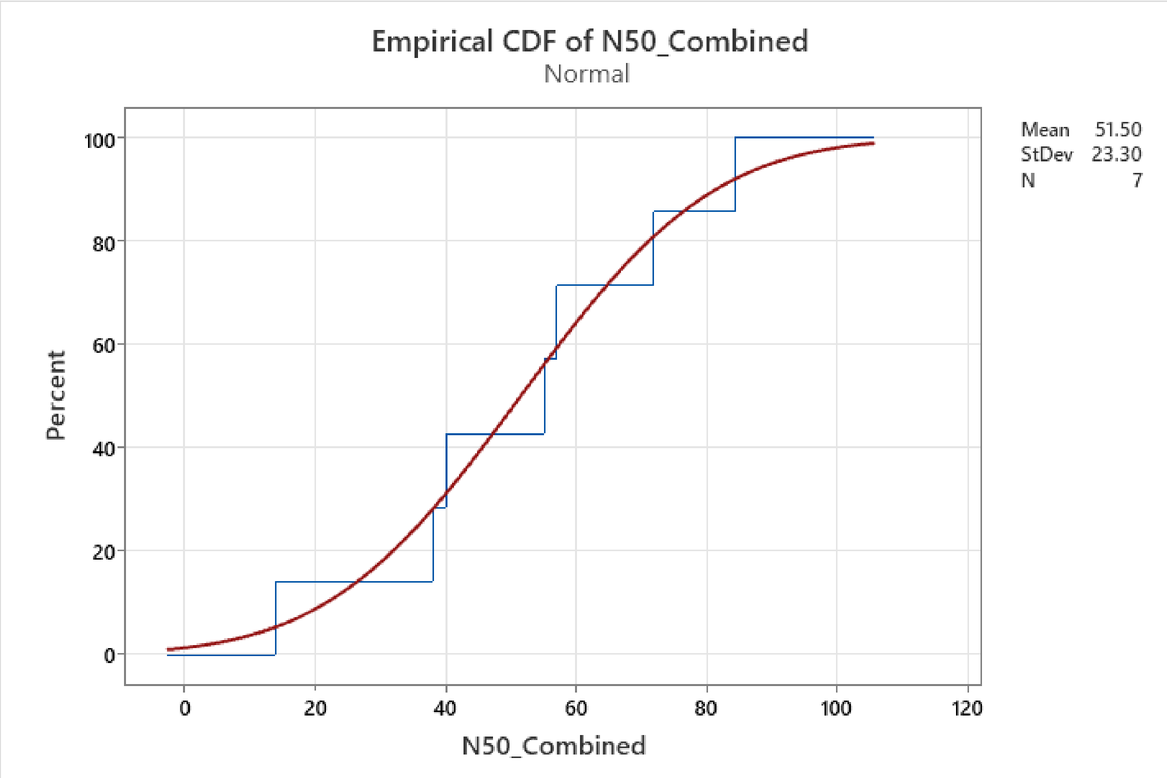
Using the N_{EQ} results of all 44 75-blow/75-gyration mixtures, a cumulative distribution function (CDF) is presented in Figure 13. This combined dataset has a mean N_{EQ} of 84 and an N_{EQ} standard deviation of 31. The range of N_{EQ} results is similar to findings from previous studies with the same objective.



Source: National Center for Asphalt Technology

Figure 13. Cumulative Distribution Functions for $N_{EQ/75}$ for Combined Database

Figure 14 shows the cumulative distribution for N_{EQ} for the seven 50-blow Marshall mixtures. Only one of these seven mixtures was tested at NCAT. This small dataset yielded an average 50-blow N_{EQ} of 52 with a standard deviation of 23.



Source: National Center for Asphalt Technology

Figure 14. Cumulative Distribution Functions for $N_{EQ/50}$ for the Combined Database

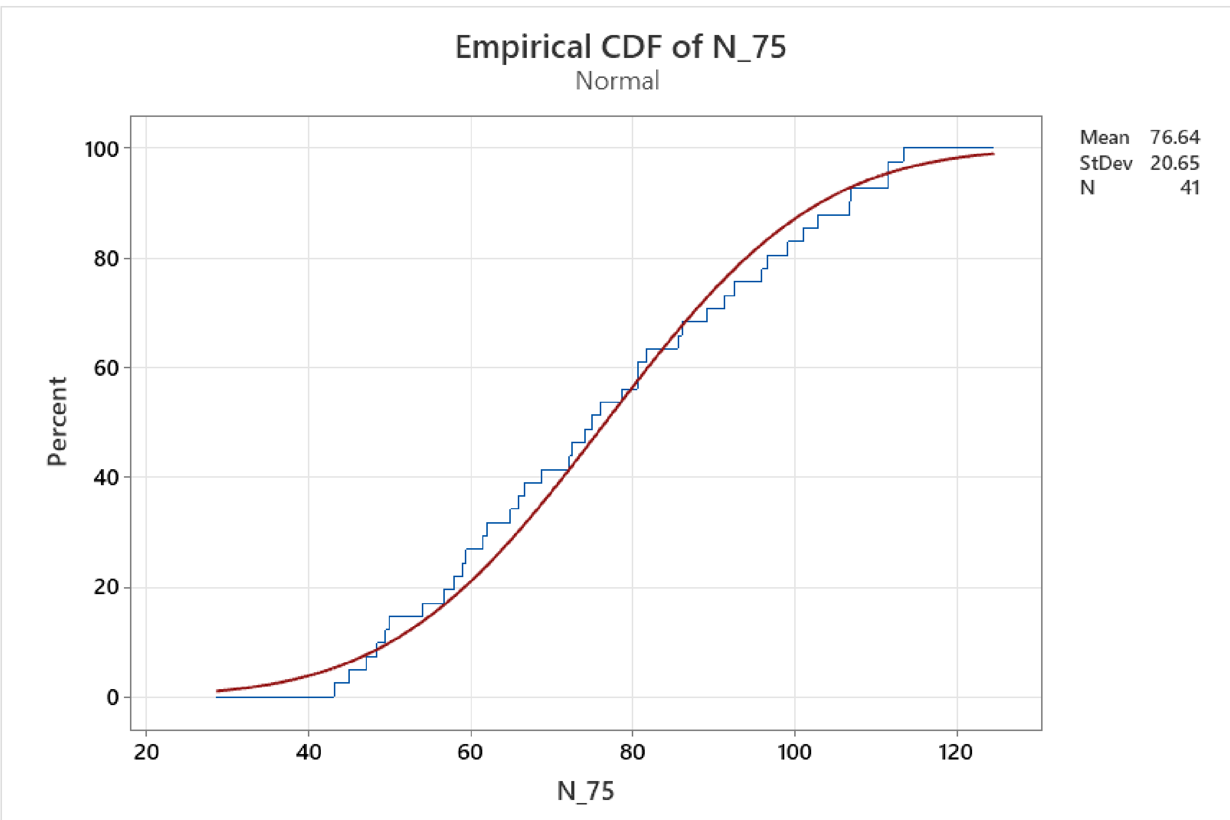
4.2 Outlier Analysis

Further analysis explored mixtures with very high N_{EQ} results as possible outliers. Of the 44 mixtures tested to determine N_{EQ-75}, three yielded N_{EQ} results outside the tested SGC compactive efforts. In other words, the calculated N_{EQ} was based on an extrapolation of the mixture's percent G_{mm} versus gyrations regression equation beyond the tested range. The three mixtures that had this occur are summarized in Table 16. In each case, the average Marshall percent G_{mm} values were higher than the percent G_{mm} of the high SGC compactive effort. As mentioned in section 3.1.1, the change in percent G_{mm} versus gyrations is not linear, but the error from assuming a linear relationship is inconsequential within the tested range. However, extrapolating the regression equation well beyond the tested range can result in an underestimate of the mixture's N_{EQ}. Therefore, the results for these three mixtures were excluded from the dataset, and the distributions were reanalyzed. These three mixtures were among the subset with ILPs occurring prior to their N_{EQ} results.

Table 16. Mixtures Considered Outliers Due to Extrapolated N_{EQ} Results

Airport	Calculated N_{EQ}	SGC Tested Gyration Range	75-Blow Marshall Avg. $\%G_{mm}$	Low SGC Gyration Avg. $\%G_{mm}$	High SGC Gyration Avg. $\%G_{mm}$
Columbia Gorge Regional Airport (DLS), Dallesport, WA	125	75 & 125	98.4	96.9	98.2
Rogue Valley International-Medford Airport (MFR), Medford, OR	180	75 & 130	97.8	93.4	96.7
Reno-Tahoe International Airport (RNO), Reno, NV	193	75 & 130	96.8	95.0	95.0

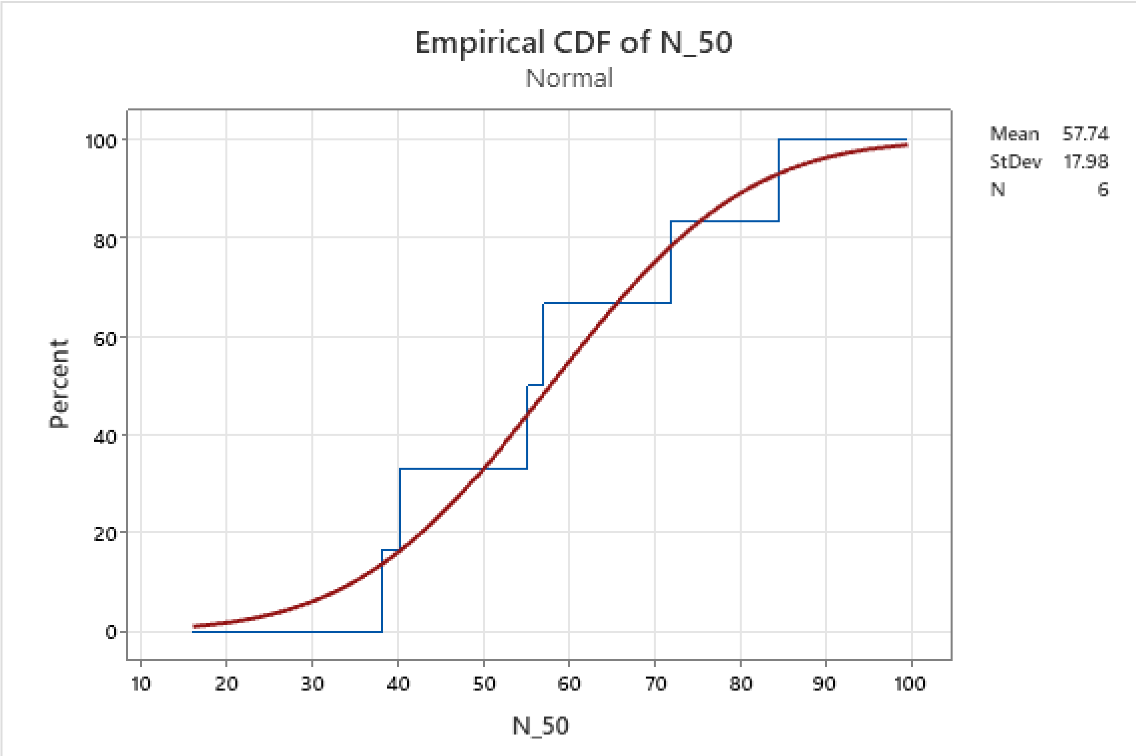
Figure 15 shows the cumulative distribution function of N_{EQ-75} from the combined NCAT-UNR database with the three outlier mixtures removed. The mean N_{EQ-75} of this dataset is 77 gyrations, with a standard deviation of 21 gyrations.



Source: National Center for Asphalt Technology

Figure 15. CDF of N_{EQ-75} for the Combined NCAT and UNR Data, Excluding the Three Outlier Results

One of the seven mixtures in the 50-blow dataset also had an N_{EQ} result that was extrapolated. The Tuskegee mix had a calculated N_{EQ} of 14 gyrations, which was well below the tested range of 40 to 50 gyrations in the experimental work. Figure 16 shows the CDF with that outlier result removed. The mean N_{EQ} was 58 gyrations, with a standard deviation of 18.



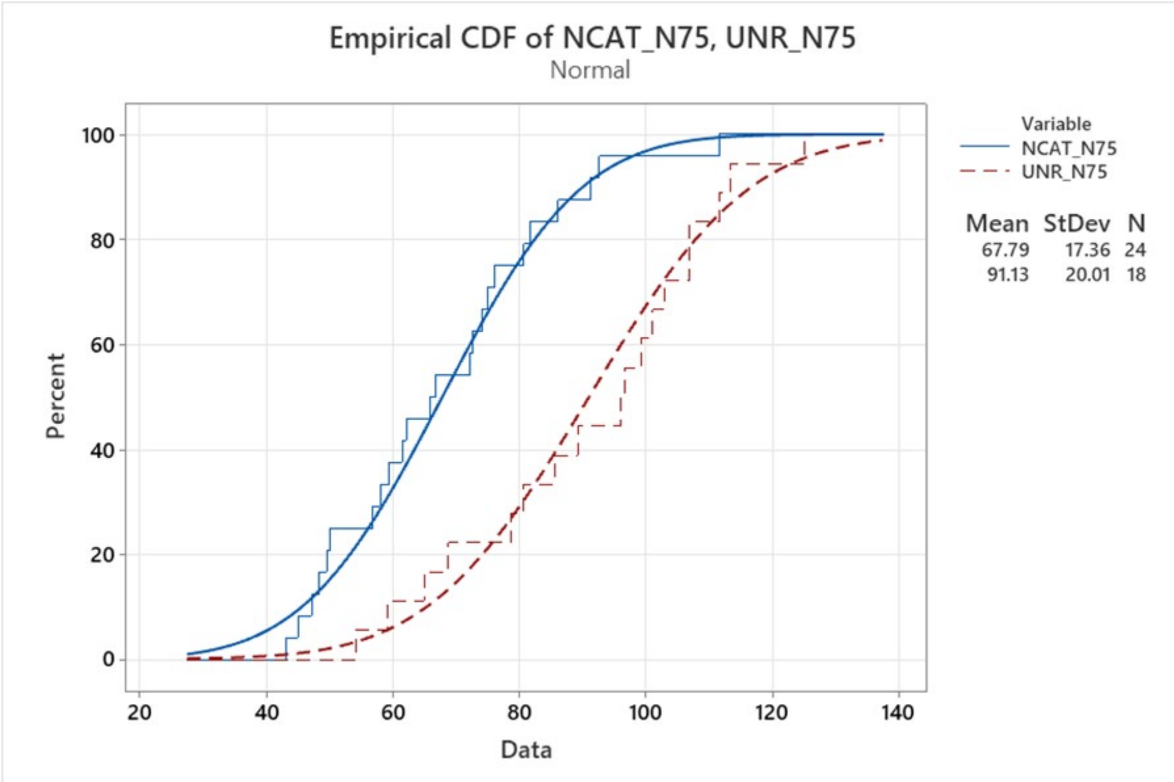
Source: National Center for Asphalt Technology

Figure 16. CDF of N_{EQ-50}, Excluding the One Outlier Result

4.3 Investigation of Between-Laboratory Differences

4.3.1 Analysis of N_{EQ} Results from NCAT and UNR Datasets

When the N_{EQ-75} results from the NCAT and UNR datasets were examined separately, significant differences were evident, as shown in Figure 17. This chart shows the distribution of N_{EQ-75} results for the mixtures tested by NCAT to be much lower than the distribution of N_{EQ-75} for the mixtures tested by UNR. The NCAT dataset had a mean N_{EQ-75} of 68 with a standard deviation of 17, while the UNR dataset had a mean N_{EQ-75} of 91 with a standard deviation of 20. This difference prompted further analysis by the research team.



Source: National Center for Asphalt Technology

Figure 17. Separated CDFs of N_{EQ-75} for NCAT and UNR Data

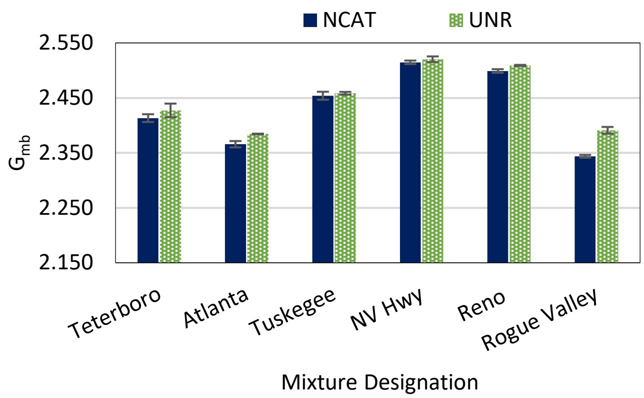
4.3.2 Assessment of Reproducibility Data

One part of the analysis to compare compaction results from NCAT and UNR involved testing split samples of mixtures by both laboratories. These laboratory-to-laboratory comparisons were conducted at several points during the project. The first comparison, presented in Section 3.4, was conducted early in this project using plant-produced mixtures from airport paving projects in Teterboro, NJ, and Atlanta, GA. The second comparison, which was conducted slightly past the midway point of the testing plan when new personnel took over the mixture testing work in both laboratories, used a mixture sampled from the Tuskegee, AL, airport and a Nevada highway mixture. The third set of comparisons used mixtures sampled from airport projects in Reno, NV (Reno-Tahoe International Airport), and Medford, OR (Rogue Valley International-Medford Airport), which had very high N_{EQ} results. Table 17 summarizes the mix designs of the six mixtures used in the laboratory-to-laboratory (reproducibility) comparisons.

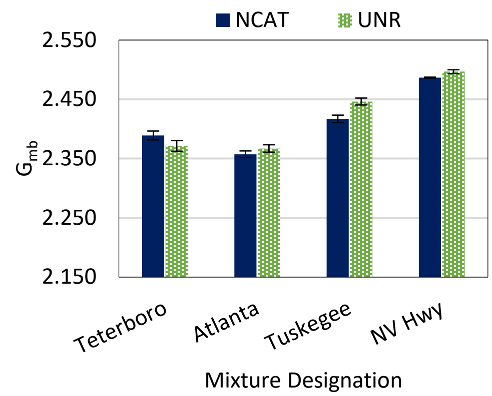
Table 17. Mix Design Properties of the Six Mixtures Evaluated at Both Laboratories

Mix Properties		Mix Designation					
		Teterboro	Atlanta	Tuskegee	NV Hwy.	Reno	Rogue Valley
Design Gradation	19.0 mm	100	100	100	100	100	100
	12.5 mm	88	96	97	100	97	97
	9.5 mm	75	85	86	89	86	88
	4.75 mm	48	63	59	58	62	69
	2.36 mm	31	50	42	39	42	51
	1.18 mm	22	48	29	29	27	32
	0.60 mm	15	38	20	22	18	20
	0.30 mm	10	27	11	15	12	13
	0.15 mm	6	12	7	10	8	9
	0.075 mm	4	4	6	8	5	7
Binder Performance Grade		PG 64-22	PG 76-22	PG 76-22	PG 64-22	PG 76-28M	PG 76-22ER
Nominal Max. Agg. Size (mm)		19.0	12.5	12.5	9.5	12.5	12.5
Optimum Asphalt Content (%)		5.3	5.9	5.2	5.5	5.8	7.3
Design Compaction Method		75 blows	75 blows	50 gyr.	50 blows	75 blows	75 gyr.
Bulk Specific Gravity		2.403	2.369	2.404	2.461	2.481	2.343
Theoretical Max. Spec. Gravity		2.483	2.470	2.490	2.564	2.596	2.424
AV (%)		3.2	4.2	3.5	4.0	3.5	3.5
VMA (%)		16.3	16.4	15.5	15.4	15.0	16.9

Figure 18 presents the laboratory-to-laboratory comparisons of G_{mb} results for the Marshall compaction method, with error bars representing ±1 standard deviation for each set of replicates. These plots show that UNR's results were higher for all six Marshall 75-blow comparisons and three of the four Marshall 50-blow comparisons. Table 18 presents the 75-blow Marshall comparisons in tabular form and includes an assessment of the differences relative to the multi-laboratory precision (d2s) limit of 0.042 per ASTM D2726. Only the Rogue Valley mixture exceeded the multi-laboratory d2s limit for the 75-blow comparisons. Table 19 presents comparisons of the 50-blow Marshall results, where the Teterboro mix was the only case in which NCAT results were higher than UNR results. Although the majority of the comparisons satisfied the d2s limit, the consistently higher Marshall G_{mb} values from UNR were likely a contributing factor for higher N_{EQ-75} values from the UNR dataset.



(a) Marshall 75 Blows



(b) Marshall 50 Blows

Source: National Center for Asphalt Technology

Figure 18. Between-Laboratory G_{mb} Comparisons for Marshall Compaction

Table 18. Comparison of G_{mb} Results for 75-Blow Marshall Compaction

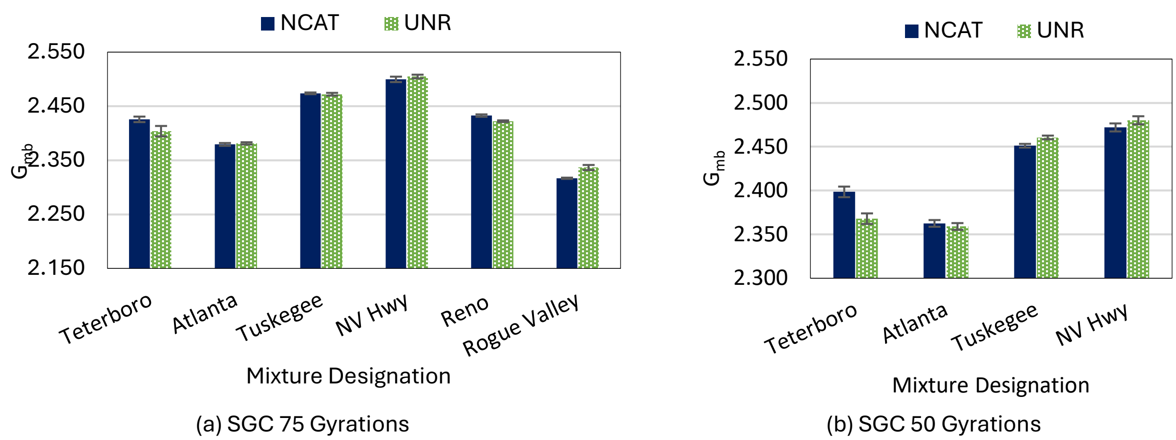
Mixture	NCAT G_{mb} Results		UNR G_{mb} Results		NCAT-UNR Difference	Within Multi-Lab d2s?
	Avg.	St. Dev.	Avg.	St. Dev.		
Teterboro	2.413	0.007	2.427	0.012	-0.014	Yes
Atlanta	2.366	0.006	2.384	0.002	-0.019	Yes
Tuskegee	2.454	0.007	2.458	0.003	-0.004	Yes
NV Hwy.	2.515	0.003	2.520	0.005	-0.005	Yes
Reno	2.499	0.003	2.509	0.001	-0.010	Yes
Rogue Valley	2.344	0.003	2.391	0.006	-0.047	No

Table 19. Comparison of G_{mb} Results for 50-Blow Marshall Compaction

Mixture	NCAT G_{mb} Results		UNR G_{mb} Results		NCAT-UNR Difference	Within Multi-Lab d2s?
	Avg.	St. Dev.	Avg.	St. Dev.		
Teterboro	2.389	0.008	2.371	0.009	0.018	Yes
Atlanta	2.357	0.005	2.367	0.006	-0.010	Yes
Tuskegee	2.417	0.006	2.446	0.006	-0.029	Yes
NV Hwy.	2.487	0.001	2.497	0.003	-0.010	Yes

Figure 19 presents the between-laboratory comparison of G_{mb} results for the SGC compaction method. These plots show that there was no consistent trend for NCAT and UNR results when the SGC was used for compaction. For half of the comparisons, NCAT results were higher, and for the other half, UNR results were higher.

Table 20 and Table 21 present the comparisons of the 75-gyration and 50-gyration results, respectively, and include assessments of the differences relative to the multi-laboratory precision (d2s) limit of 0.042 per ASTM D2726. It is important to note that none of the comparisons exceeded the multi-laboratory d2s limit.



Source: National Center for Asphalt Technology

Figure 19. Between-Laboratory G_{mb} Comparison for SGC Compaction

Table 20. Comparison of G_{mb} Results for 75-Gyration SGC Compaction

Mixture	NCAT G_{mb} Results		UNR G_{mb} Results		NCAT-UNR Difference	Within Multi-Lab d2s?
	Avg.	St. Dev.	Avg.	St. Dev.		
Teterboro	2.426	0.005	2.404	0.010	0.022	Yes
Atlanta	2.379	0.003	2.381	0.002	-0.002	Yes
Tuskegee	2.474	0.002	2.472	0.003	0.002	Yes
NV Hwy.	2.500	0.005	2.505	0.003	-0.005	Yes
Reno	2.433	0.002	2.422	0.002	0.011	Yes
Rogue Valley	2.317	0.001	2.337	0.005	-0.020	Yes

Table 21. Comparison of G_{mb} Results for 50-Gyration SGC Compaction

Mixture	NCAT G_{mb} Results		UNR G_{mb} Results		NCAT-UNR Difference	Within Multi-Lab d2s?
	Avg.	St. Dev.	Avg.	St. Dev.		
Teterboro	2.398	0.006	2.368	0.002	0.030	Yes
Atlanta	2.362	0.004	2.359	0.003	0.003	Yes
Tuskegee	2.451	0.002	2.461	0.001	-0.010	Yes
NV Hwy.	2.472	0.005	2.480	0.003	-0.008	Yes

4.3.3 Effects of Mix and Testing Design Factors

As part of the data evaluation, mixture and test variables that could potentially impact N_{EQ} results were analyzed. Data analyzed included the following:

- Aggregate consensus properties and LA abrasion.
- Aggregate gradation in terms of primary control sieve index (PCSI).
- Binder type and content (total and effective).
- Volumetric properties (VMA, VFA, G_{mm}).

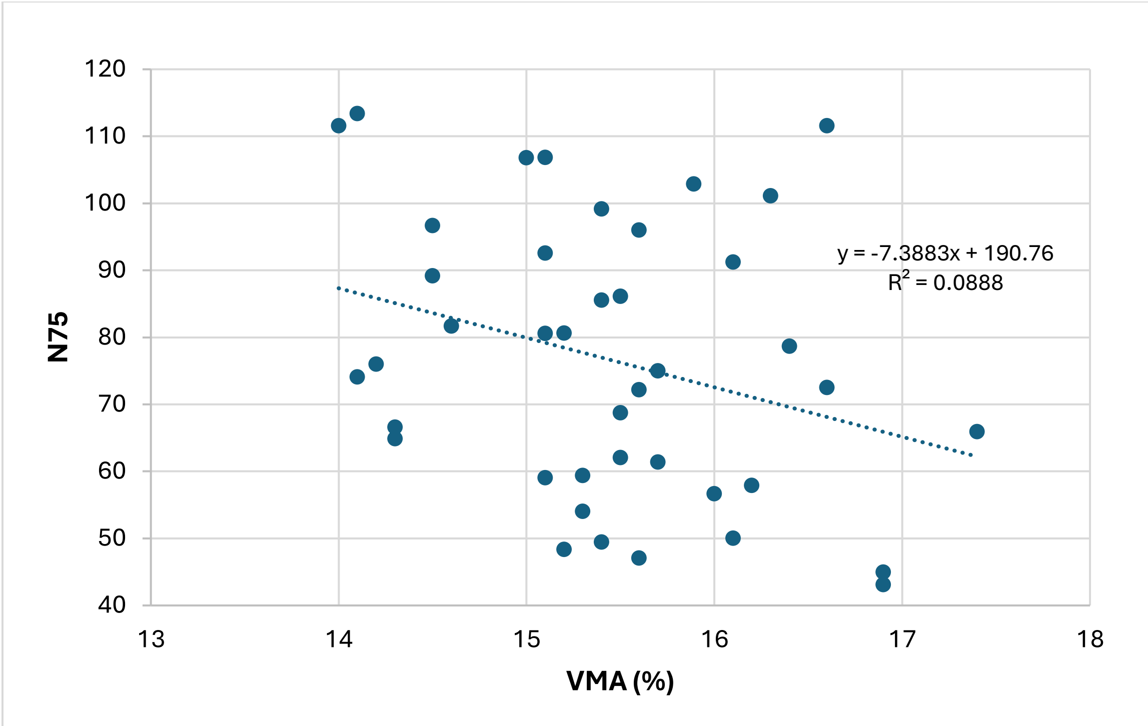
- Compaction method of original mix design (Marshall or Superpave).
- Time lag between mix sampling and mix testing.
- Production and compaction temperatures.

The analysis included assessing the effect of individual variables on N_{EQ} results using regression analysis for numerical variables and ANOVA for categorical variables. Table 22 summarizes the results of the regression analysis for the numerical variables, including the number of data points and ranges for each variable. All R^2 results were extremely low with high p-values, indicating that none of these had a meaningful impact on N_{EQ} results. Factors with the lowest p-values were VMA, VFA, and production temperature. Correlations between N_{EQ-75} and these three variables are presented in Figure 20 through Figure 22. The range of results for some factors, such as fine aggregate angularity and natural sand content, is small, which may have limited the power of the analyses.

Table 22. Summary of Results of Correlation Analyses with Numerical Variables

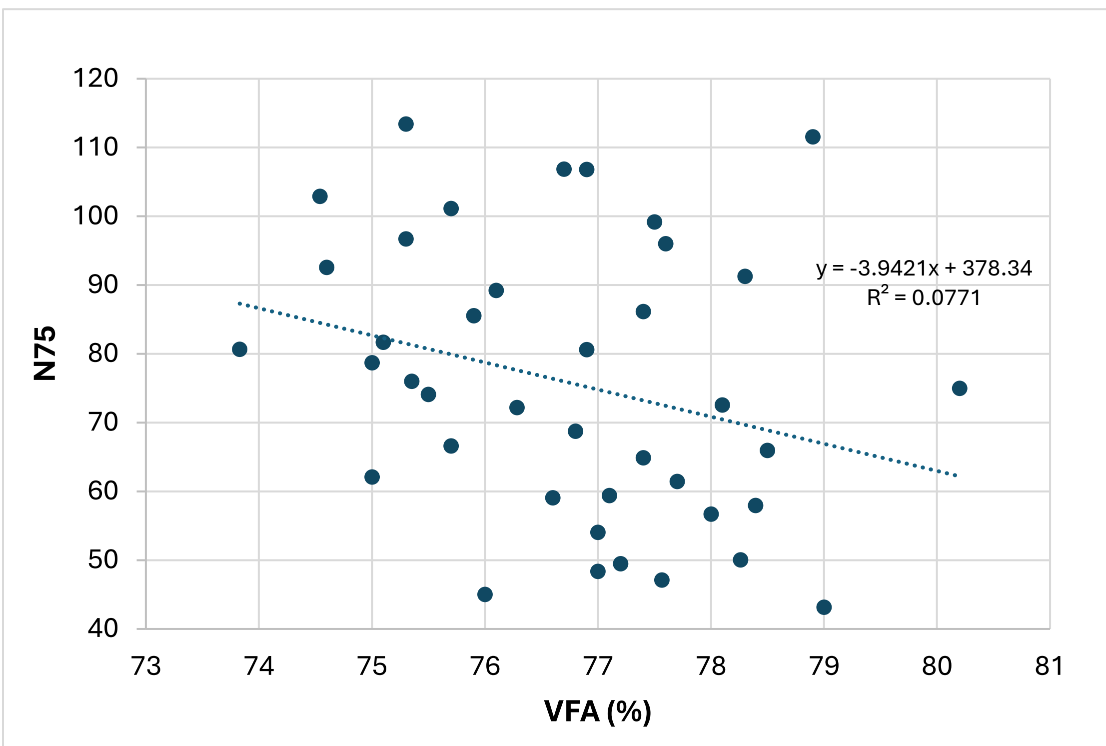
Correlation of Factors with N_{EQ}	No. of Data Points	Values Range	R^2	P-value
N_{EQ} vs. Binder Content	41	4.7–7.3%	0.020	0.379
N_{EQ} vs. P_{be}	32	4.2–5.9%	0.010	0.584
N_{EQ} vs. VMA	41	14.0–17.4%	0.089	0.060
N_{EQ} vs. VFA	41	73.8–80.2%	0.077	0.083
N_{EQ} vs. Lab Avg. G_{mb}	41	2.287–2.624	0.051	0.158
N_{EQ} vs. Lab Avg. G_{mm}	41	2.374–2.737	0.061	0.120
N_{EQ} vs. PCSI	41	−4.8–20.6	0.001	0.815
N_{EQ} vs. LA Abrasion (%)	31	14–41	0.050	0.239
N_{EQ} vs. Fine Aggregate Angularity	17	44.5–49.3	0.020	0.577
N_{EQ} vs. Sand Equivalency	34	60–99	0.016	0.475
N_{EQ} vs. % Natural Sand	35	0–8	0.035	0.274
N_{EQ} vs. Production Temperature	38	300–351 °F	0.022	0.370
N_{EQ} vs. Compaction Temperature	39	285–326 °F	0.088	0.066
N_{EQ} vs. Time Lag Between Production and Testing	39	2–459 days	0.047	0.172

P_{be} = effective binder content (% of total mix by weight).



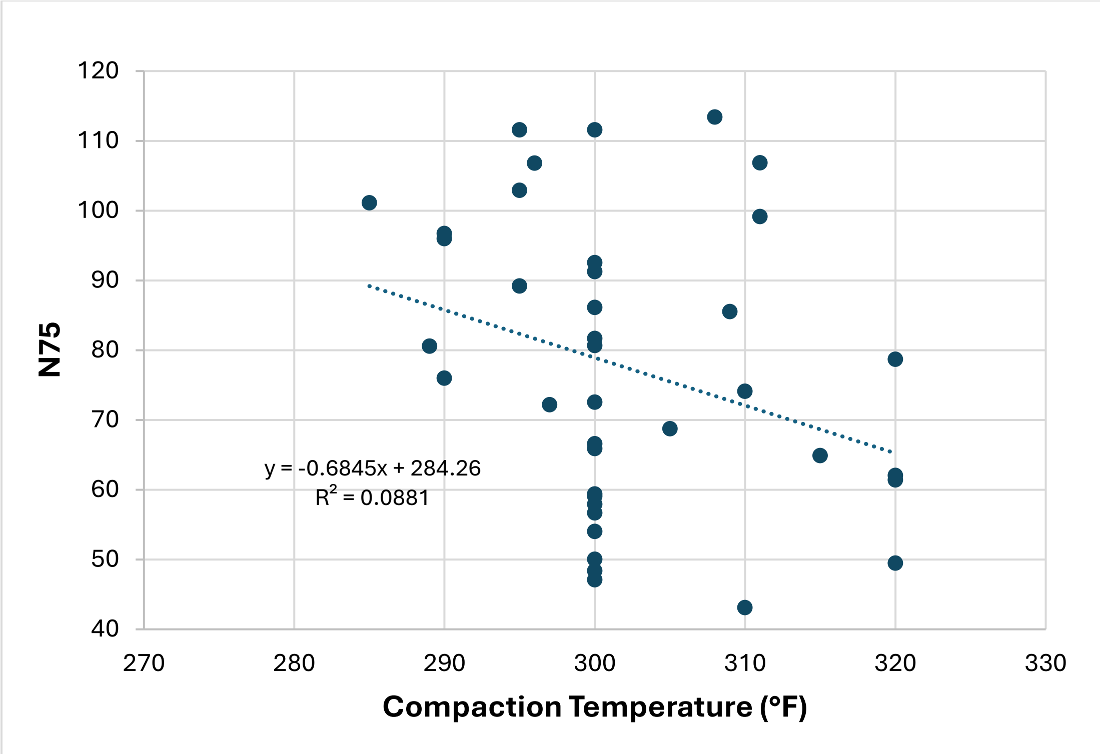
Source: National Center for Asphalt Technology

Figure 20. Correlation Between Equivalent N_{75} and VMA (percent)



Source: National Center for Asphalt Technology

Figure 21. Correlation Between Equivalent N_{75} and VFA (percent)



Source: National Center for Asphalt Technology

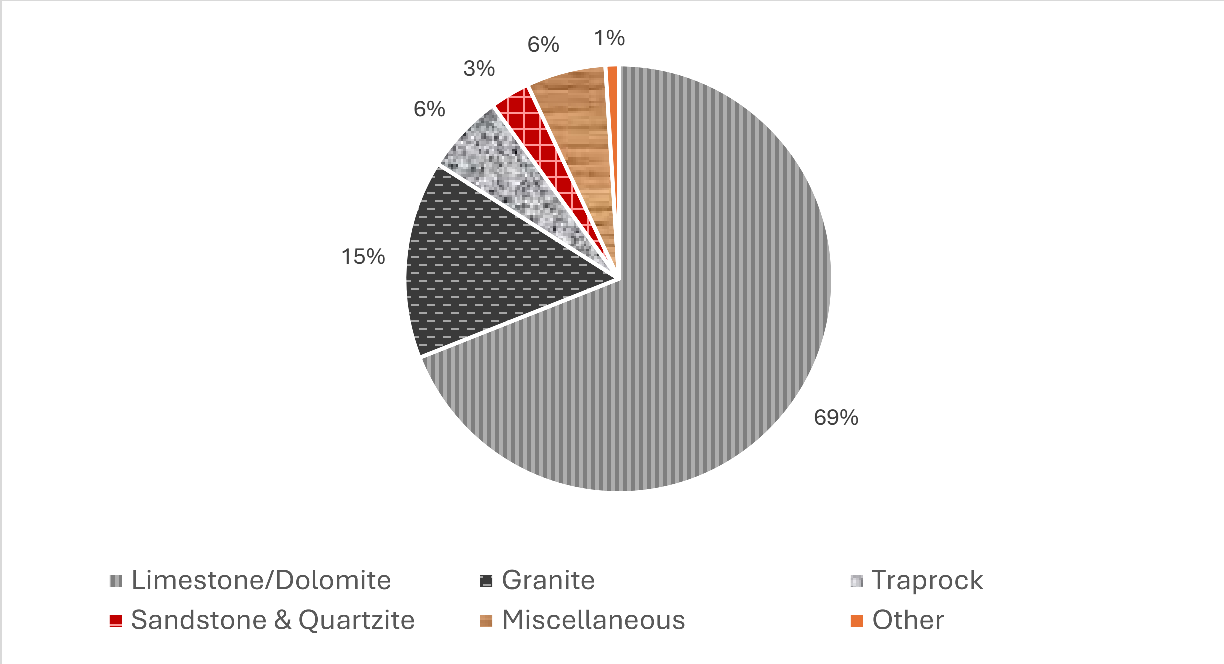
Figure 22. Correlation Between Equivalent N_{75} and Compaction Temperature (°F)

Table 23 summarizes the correlations of N_{EQ-75} with categorical mix variables. As shown in this table, no variable was found to have an impact on N_{EQ-75}.

Table 23. Summary of Results of Correlation Analyses with Categorical Variables

Correlation of N_{EQ}	No. of Data Points	Variable Levels	F-value	ANOVA P-value
N_{EQ} vs. Mix Type	41	P-401, P-403	2.16	0.149
N_{EQ} vs. Binder Type	41	Neat, polymer modified	0.45	0.506
N_{EQ} vs. NMAS	41	9.5, 12.5, and 19 mm	1.91	0.162
N_{EQ} vs. Primary Control Sieve (mm)	41	2.36, 4.75 mm	2.02	0.163
N_{EQ} vs. Design Compaction Method	41	Marshall, Superpave	0.92	0.344

Aggregate type could not be included in the categorical variable ANOVA due to the range of types, blends of types, and lack of available data. Figure 23 shows that 69 percent of the U.S. crushed stone produced in 2023 was limestone/dolomite, which is predominant in much of the country, though not as common in the western United States. The map in Figure 24 illustrates aggregate classifications by hardness, showing that aggregates in the western part of the country are medium and medium hard, whereas those in the eastern United States include soft, medium soft, medium, medium hard, and hard. This difference in aggregate characteristics could have contributed to the UNR laboratory N_{EQ-75} average being higher than the NCAT laboratory N_{EQ-75}.



Data source: U.S. Geological Survey (2024). Graph source: AAPTP.

Figure 23. U.S. Crushed Stone Production in 2023

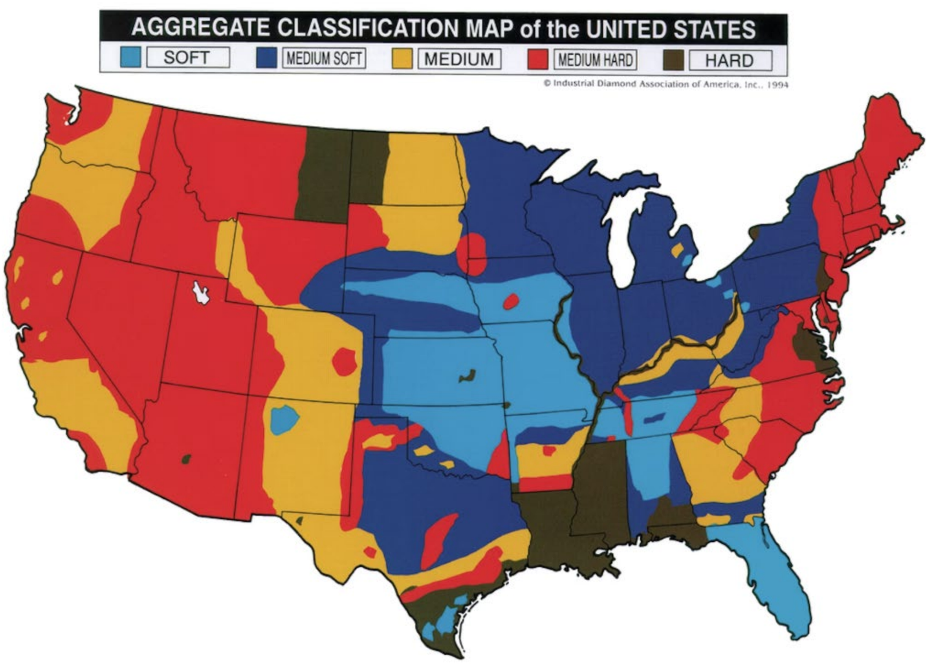


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Figure 24. Aggregate Classification by Hardness

4.3.4 Locking Point Analysis

Section 2.5 of this report provides background on the development and use of the locking point. The SGC compaction curves for all replicates of all specimens compacted per mixture used were analyzed for ILP information. Three parameters were obtained from the SGC specimen compaction curve data and analyzed:

- Gyration at which the first ILP was observed.
- Number of times the ILP was observed from the first observation to the N_{EQ} gyration.
- Change in specimen height from the first ILP observation to the N_{EQ} gyration.

The ILP data are summarized in Table 24 and Table 25.

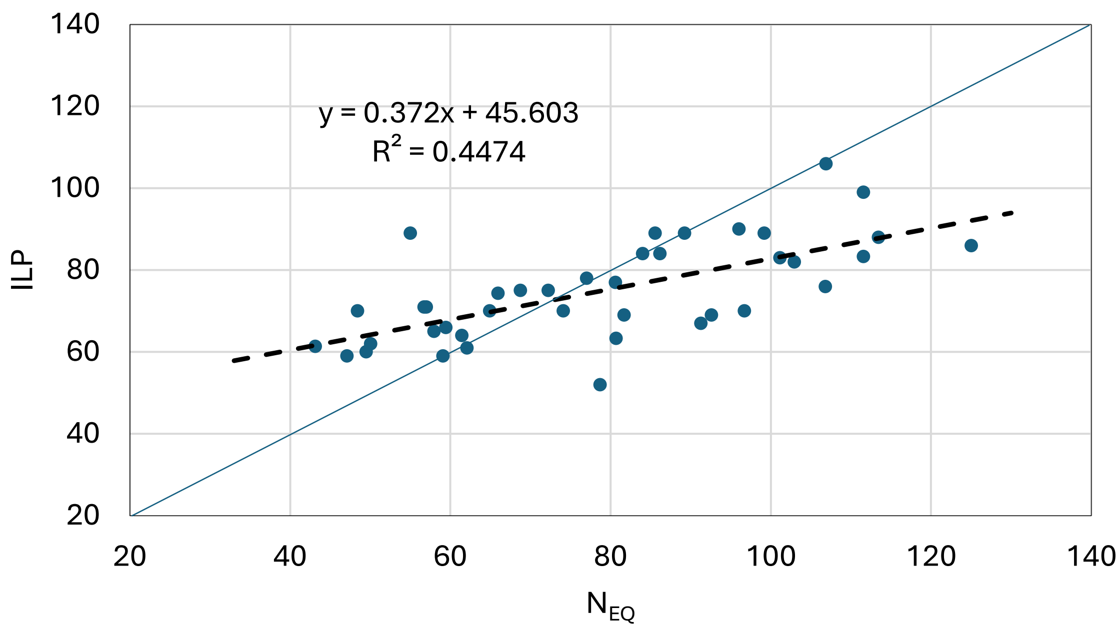
Table 24. Mixtures with ILP Results That Occurred Prior to N_{EQ}

Airport	Mix Type	ILP	N_{EQ}	No. of ILP Occurrences Prior to N_{EQ}	Change in Height from First ILP Occurrence to N_{EQ} (mm)
Huntsville International Airport (HSV), AL	P-401	69	82	4	1.1
Albany International Airport (ALB), GA	P-401	63	81	6	1.4
South Bend International Airport (SBN), IN	P-401	67	91	7	1.7
South Bend International Airport (SBN), IN	P-403	84	86	1	0.2
Boston Logan International Airport (BOS), MA	P-401	69	93	8	1.6
Indianapolis International Airport (IND), IN	P-403	83	112	8	2.1
Cape Girardeau Regional Airport (CGI), MO	P-403	70	74	1	0.1
Provo Airport (PVU), UT	P-401	106	107	1	0.1
Hartsfield-Jackson Atlanta International Airport (ATL), GA	P-401	52	79	8	0.8
Reno-Stead Airport (RTS), NV	P-401	76	107	10	1.2
San Francisco International Airport (SFO), CA	P-401	70	97	8	1.0
Teterboro Airport (TEB), NJ	P-403	83	101	4	0.5
Tucson International Airport (TUS), AZ	P-403	77	81	1	0.2
Pinal Airpark (MZJ), AZ	P-403	89	99	2	0.4
Tucson International Airport (TUS), AZ	P-401	90	96	2	0.3
Santa Maria Public Airport (SMX), Santa Maria, CA	P-401	99	112	2	0.2
Columbia Gorge Regional Airport (DLS), Dallesport, WA	P-401	86	125	9	1.0
Rogue Valley International-Medford Airport (MFR), OR	P-401	86	180	13	1.6

Table 25. Mix 14 (Indianapolis P-403, N_{EQ} = 112 Gyrations) ILP and Specimen Height Data

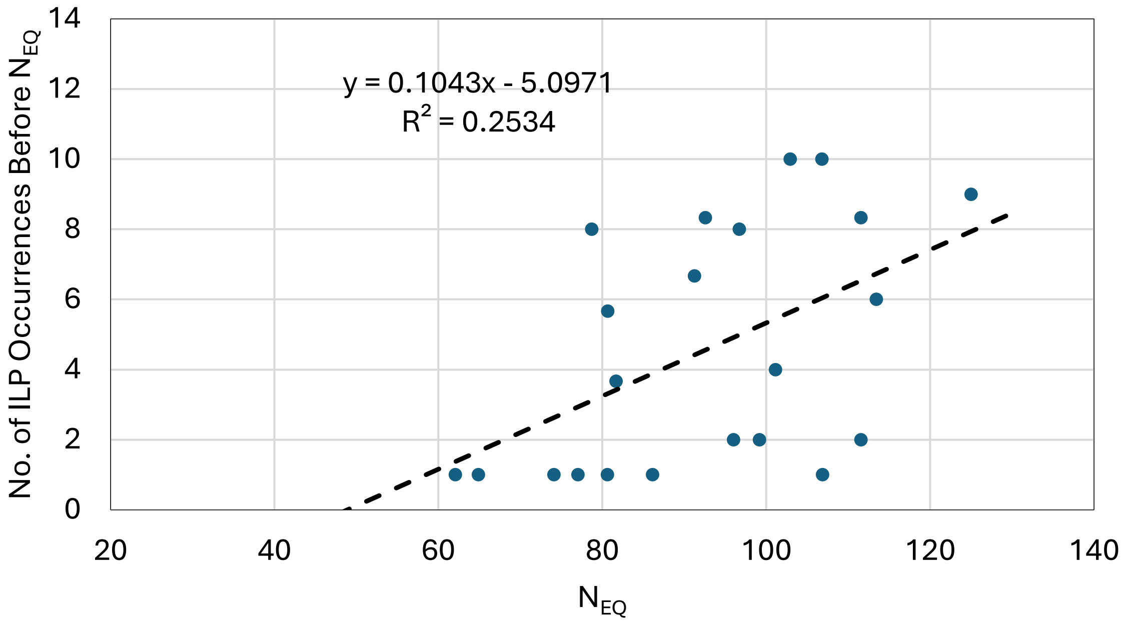
SGC Gyration	ILP Occurrence	Specimen Height (mm)	Change in Height from Previous ILP Occurrence (mm)	Change in Height (mm)	Change in Height (mm) per Gyration
1	0	138.2	n/a	25.8	0.310
83	1	112.4	25.8		
90	2	112.1	0.3	1.1	0.038
95	3	111.9	0.2		
100	4	111.7	0.1		
103	5	111.6	0.1		
106	6	111.5	0.1		
109	7	111.4	0.1		
112	8	111.3	0.1		
115	9	111.2	0.1	0.2	0.020
122	10	111.1	0.1		
123	n/a	111.1	0.0	0.0	0.000
124	n/a	111.1	0.0		
125	n/a	111.1	0.0		

Figure 25 shows the relationship (R^2 = 0.45) between ILP and N_{EQ} for the combined dataset (all mixtures tested) with the ILP observed prior to the N_{EQ} for 20 of the mixtures tested. Data points below the line of equality represent mixtures for which the ILP occurred prior to N_{EQ}. Figure 26 shows the number of ILP occurrences prior to the N_{EQ} for the combined dataset, with the number ranging from 1 to 10 occurrences. The correlation among this data is much weaker.



Source: University of Nevada, Reno

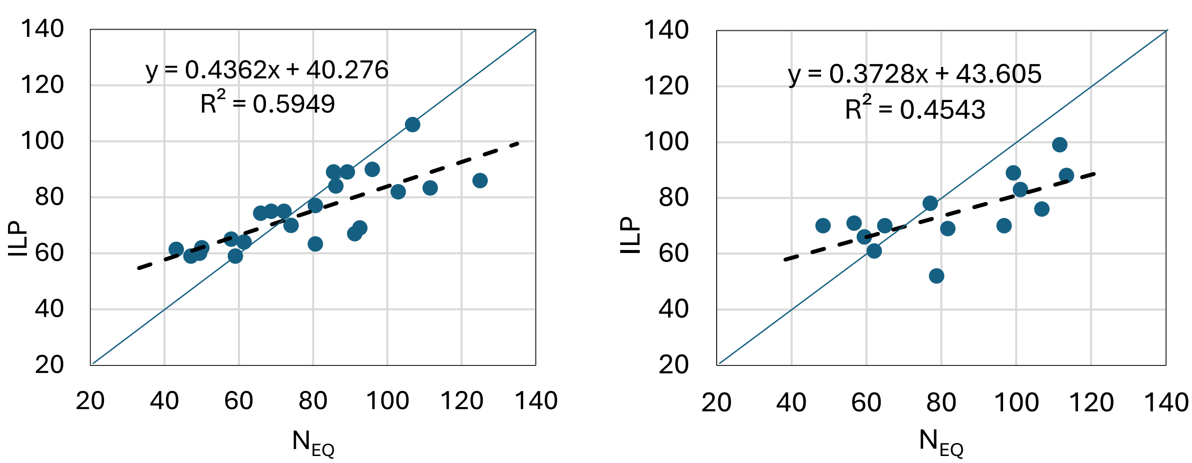
Figure 25. ILP vs. N_{EQ} for Combined Dataset



Source: University of Nevada, Reno

Figure 26. Number of ILP Occurrences vs. N_{EQ} for Combined Dataset

Figure 27 shows the relationships between ILP and N_{EQ} for the Marshall- and Superpave-designed mixtures separately. Of the 28 SGC (75-gyration) mixtures, 24 exhibited locking points, while 14 of 16 Marshall (75-blow) mixtures exhibited locking points. The ILP occurred prior to N_{EQ} for 11 of the Superpave mixtures and 8 of the Marshall mixtures tested. The overall N_{EQ} values were similar for both mix design methods, and the correlation was slightly stronger for the Superpave-designed mixtures than the Marshall-designed mixtures.



(a) SGC 75 Gyrations

(b) Marshall 75 Blows

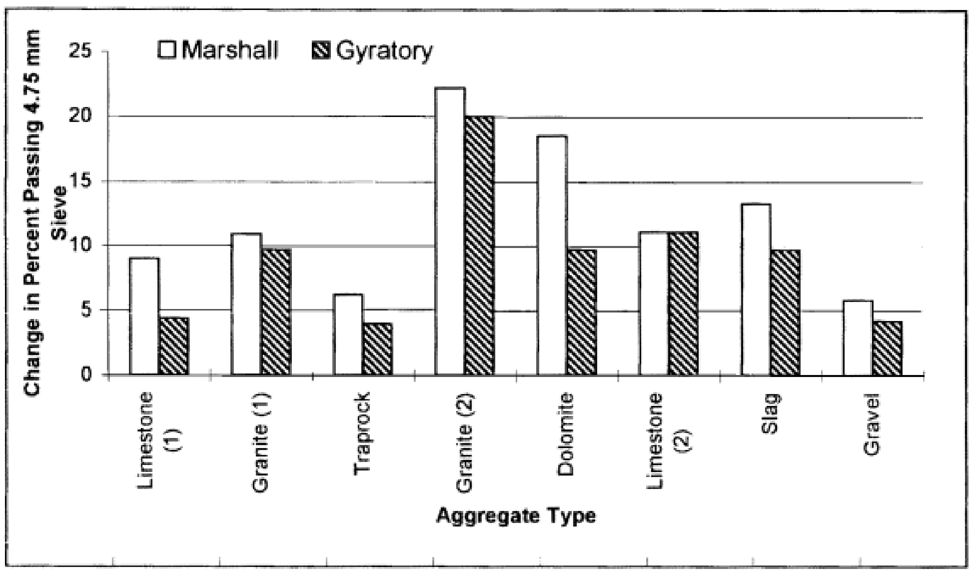
Source: University of Nevada, Reno

Figure 27. ILP vs. N_{EQ} Plots for Each Design Compaction Method

In summary, mixtures with one or more occurrences of the ILP prior to the N_{EQ} had higher N_{EQ} values than those for which N_{EQ} was not observed. This is apparent from the slope of the regression lines being flatter than the lines of equality in the figures above. When mixtures reach the ILP, especially repeatedly, the propensity for aggregate breakdown occurs, which could impact specimen density.

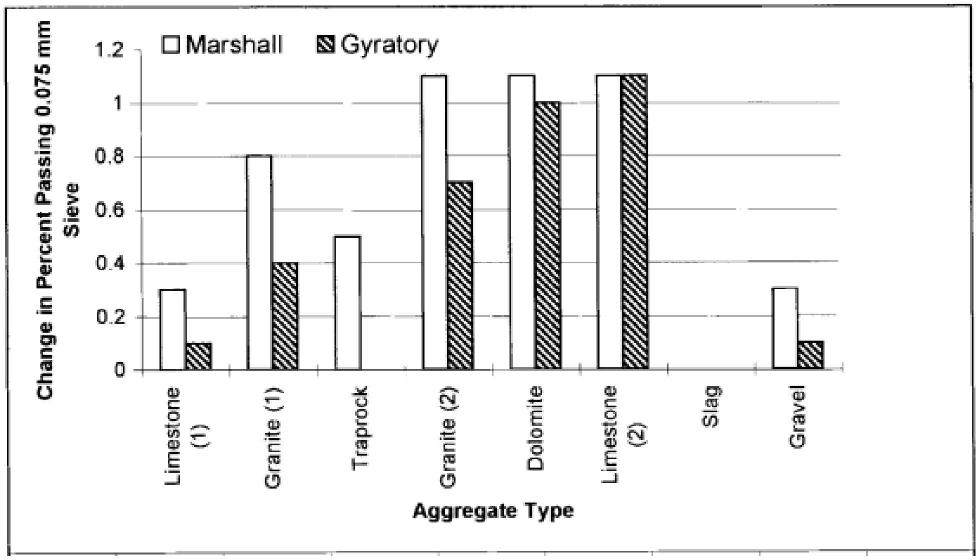
4.3.5 Analysis of Aggregate Breakdown

Studies have shown that the Marshall hammer tends to cause more aggregate breakdown compared to the SGC. Marshall compaction uses impact energy from the dropping hammer, while the SGC applies shearing and compressive forces. Brown et al. (1997) reported this for SMA mixtures compacted to 100 SGC gyrations and 50 Marshall hammer blows, illustrated in Figure 28 and Figure 29 for an assortment of aggregate types. Aggregate breakdown was quantified by the change in percent passing the 4.75 mm and 0.075 mm sieves from compacted samples after extraction.



Source: National Center for Asphalt Technology

Figure 28. Aggregate Type vs. Change in Percent Passing 4.75 mm Sieve (Brown et al., 1997)

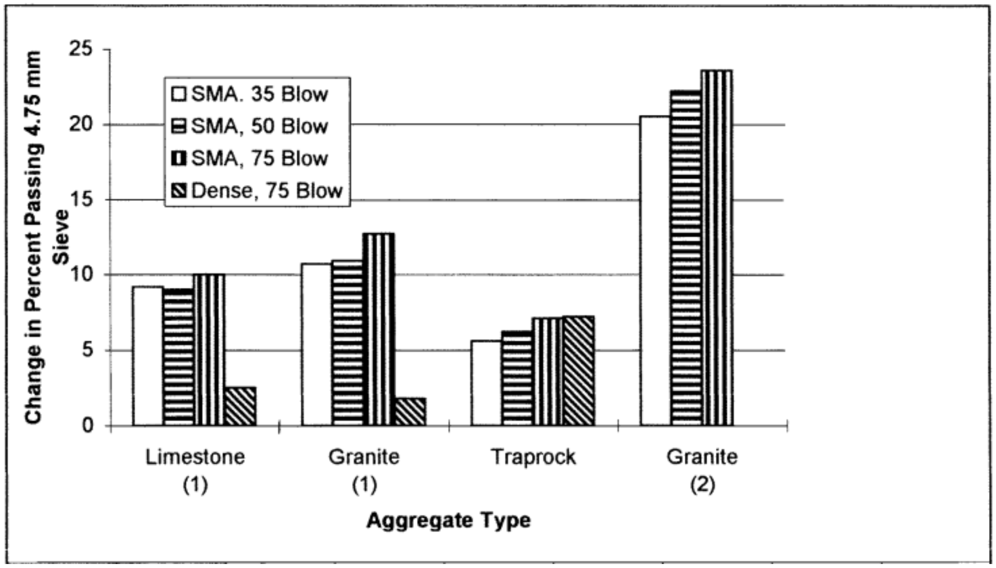


Source: National Center for Asphalt Technology

Figure 29. Aggregate Type vs. Change in Percent Passing 0.075 mm Sieve (Brown et al., 1997)

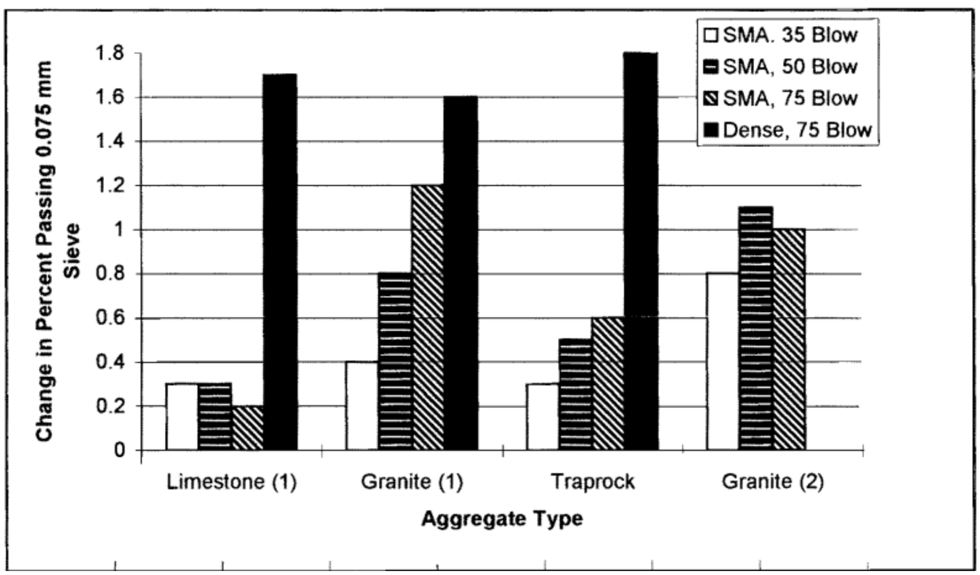
Figure 30 and Figure 31 compare aggregate breakdown for SMA mixtures after 35, 50, and 75 Marshall blows, as well as a dense-graded mixture after 75 blows. Aggregate breakdown on the percentage passing the 4.75 mm sieve (Figure 30) was significant for the SMA mixtures, and it increased as the number of blows increased, while the breakdown on the 4.75 mm sieve for the dense-graded mixtures was much lower. The stone-on-stone gradation for SMA creates higher point-of-contact stresses between the coarse aggregate particles.

Figure 31 shows that significantly more material passing the 0.075 mm sieve was observed for the dense-graded mixture compared to the SMA mixtures. The authors hypothesized that the dense-graded mixtures have a well-graded aggregate structure, which results in more points of contact between particles, and those points of contact create more frictional wear than particle fracturing. Strong correlations between the change in percent passing the 4.75 mm sieve and LA abrasion and F&E particles were observed for both SGC- and Marshall-compacted mixtures.



Source: National Center for Asphalt Technology

Figure 30. Aggregate Type vs. Change in Percent Passing 4.75 mm Sieve (Brown et al., 1997)



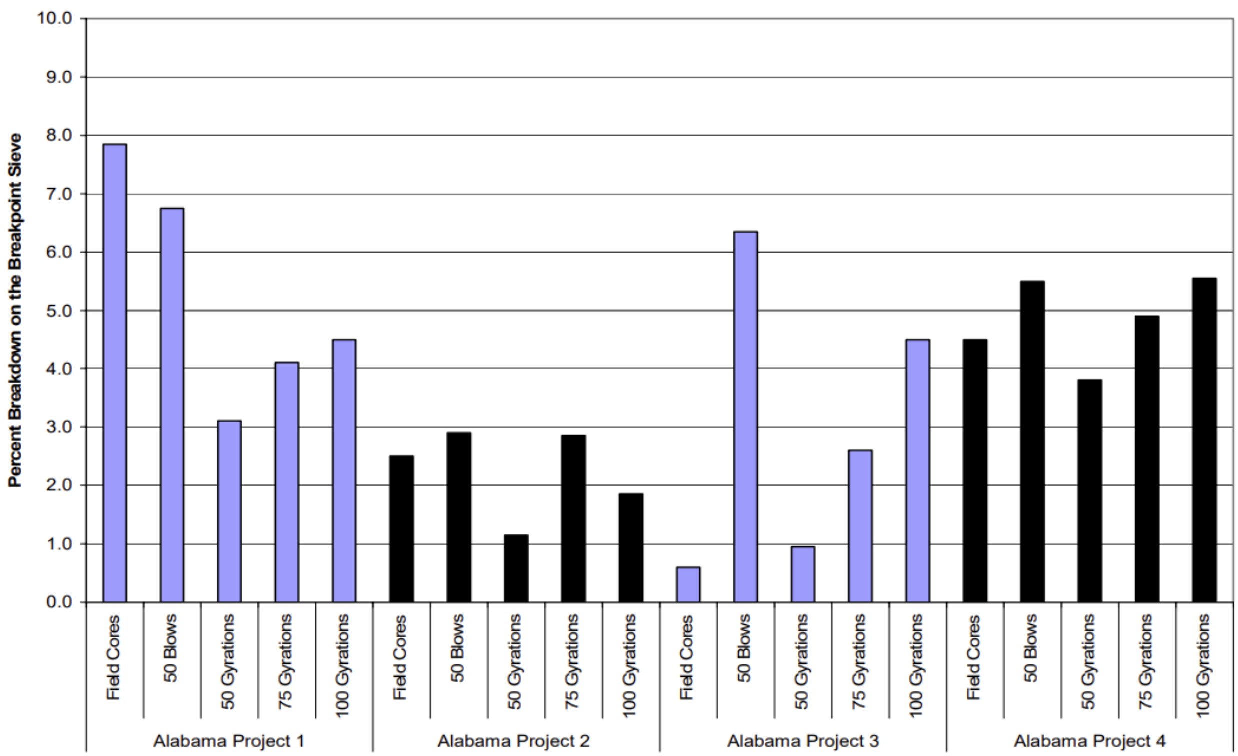
Source: National Center for Asphalt Technology

Figure 31. Aggregate Type vs. Change in Percent Passing 0.075 mm Sieve (Brown et al., 1997)

While establishing an SGC design number of gyrations correlated with 50-blow Marshall compaction for SMA mixtures in Alabama, West and James (2005) evaluated four plant-produced mixtures using 50 Marshall blows and 50, 75, and 100 SGC gyrations. Cores were obtained from each of the projects. The study evaluated aggregate breakdown due to compaction for the laboratory-compacted specimens and field cores of each mixture, as shown in Figure 32.

The breakpoint sieve is the sieve size that defines a break in the aggregate gradation between the fine aggregate and the coarse aggregate and is a function of the NMAS. The breakpoint sieve is the No. 4 sieve for 1-inch, 3/4-inch, and 1/2-inch NMAS mixtures; the No. 8 sieve for 3/8-inch NMAS mixtures; and the No. 16 sieve for 4.75-mm NMAS mixtures.

Aggregate breakdown was consistently higher for Marshall than for SGC compaction, and it increased as the number of SGC gyrations increased. Interestingly, the aggregate breakdown in field cores compared to the breakdown in laboratory-compacted specimens was inconsistent among the four projects.



Source: National Center for Asphalt Technology

Figure 32. Percent Passing the Breakpoint Sieve for Field Cores and Laboratory-Compacted Field Mixture (West & James, 2005)

Airey, Hunter, and Collop (2008) observed similar aggregate breakdown and correlations to LA abrasion and F&E particles for Marshall-compacted specimens with a range of blows on gap- and dense-graded mixtures to those observed by Brown et al. (1997) and West and James (2005).

Vavrik et al. (1999) compared the aggregate breakdown in SMA mixtures caused by SGC compaction to breakdown caused through the stages of construction (from quarry to paving). The study focused on changes in the F&E percentage from the quarry through field compaction and included different paving lift thicknesses. The degree of degradation observed depended on the initial F&E percentage and the LA abrasion loss, as illustrated in Figure 33. For the materials included in this study, the SGC compaction caused more degradation than the field construction processes.

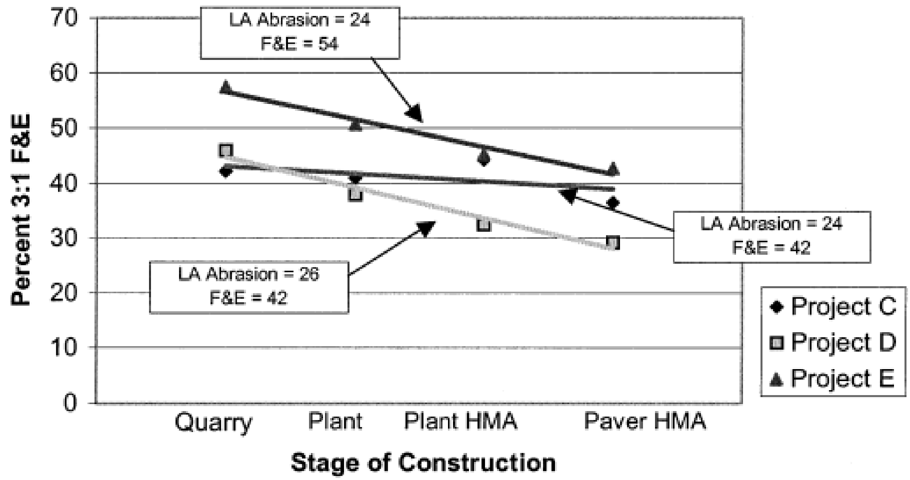


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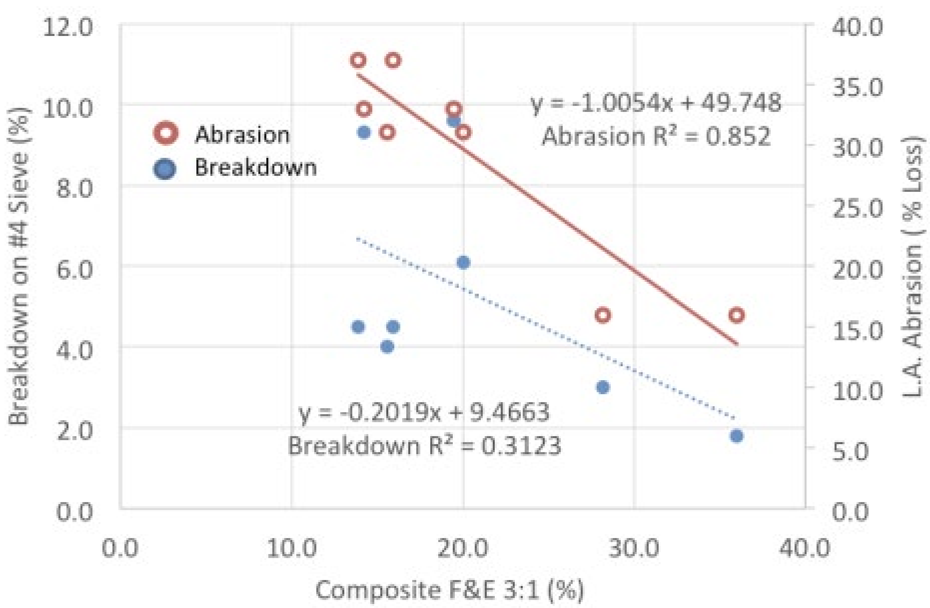
Figure 33. Interaction Among F&E Percentage, LA Abrasion Loss, and Aggregate Breakdown

Note: From "Effect of Flat and Elongated Coarse Aggregate on Characteristics of Gyratory Compacted Samples," by W. R. Vavrik, R. J. Fries, and S. H. Carpenter in *Transportation Research Record, 1681*(1), 1999, 28–36. Used with permission.

Watson and Julian (2017) also investigated the effect of F&E percentage on SMA performance and suggested that F&E percentage and LA abrasion loss be considered together when specifying SMA aggregate requirements, as shown in Figure 34.



Source: National Center for Asphalt Technology

Figure 34. Comparison of the Effect of F&E Percentage on Aggregate Breakdown and LA Abrasion Loss (Watson & Julian, 2017)

Amirkhanian, Kaczmarek, and Burati (1991) investigated the influence of LA abrasion on samples compacted with 25, 50, 75, and 100 Marshall blows. Four granite aggregate sources with LA values ranging from 28 to 55 were used. Indirect tensile strength, resilient modulus, and aggregate breakdown were investigated. For the dense-graded mixes, aggregate breakdown was only significant for the percent passing the No. 100 and No. 200 sieves.

The original WesTrack test sections included coarse-graded and fine-graded surface mixtures (Hand, 1998). There were eight coarse-graded test sections and nine fine-graded test sections. Five cores were obtained from each test section, and the post-ignition oven gradations were determined. The core gradations were finer than the targets for both the coarse- and fine-graded mixtures, as shown in Table 26. The data in the table represent the averages of 40 coarse-graded cores and 45 fine-graded cores.

It is important to note that asphalt plants are equipped with baghouses that collect airborne fine aggregates during the mixture production process. These fine aggregates can be wasted, or a portion or all of them may be reintroduced to the mixture just prior to the addition of asphalt binder in the mixing process to optimize the fine aggregate gradation, particularly the percent passing the No. 200 sieve.

Table 26. WesTrack Original Construction Surface Course Mix Gradation Comparisons (Hand, 1998)

Sieve Size	Coarse-Graded Mix Target	Coarse-Graded Mix Cores (n=40)	Difference (n=40)	Fine-Graded Mix Target	Fine-Graded Mix Cores (n=40)	Difference (n=40)
3/4"	100	100	0	100	100	0
1/2"	82.4	79.2	−3.2	88.5	88.1	−0.4
3/8"	64.6	65.0	0.4	75.4	76.6	1.2
#4	41.3	41.8	0.6	48.9	51.1	2.2
#8	27.8	28.6	0.8	38.4	39.5	1.4
#16	19.7	21.0	1.3	33.9	35.2	1.3
#30	14.6	16.1	1.5	27.6	28.7	1.1
#50	10.8	12.2	1.4	15.7	16.1	0.4
#100	7.7	9.0	1.3	6.8	8.1	1.3
#200	5.1	6.6	1.5	3.5	5	1.5

In summary, the literature indicates that coarse aggregate breakdown in dense-graded mixtures is not consistent with SMA mixtures, which exhibit greater coarse aggregate breakdown in compaction. For SGC compaction, the literature also suggests that aggregate breakdown in dense-graded mixtures is more evident in the percent passing the No. 200 sieve than for SMA mixtures.

In this study, aggregate breakdown was evaluated with P-401 mixtures from four airfield paving projects: Hartsfield-Jackson Atlanta International Airport (ATL), GA; Florence Regional Airport (FLO), SC; Reno-Stead Airport (RTS), NV; and Rogue Valley International-Medford Airport (MFR), OR. The mixture design and gradation information of these mixtures are presented in Table 27. The Atlanta and Florence mixtures contain softer aggregates with LA abrasion losses of 41 percent and 35 percent, respectively. The other two mixtures, Reno and Rogue Valley, had unusually high N_{EQ} values of 193 and 180, respectively. In this analysis, aggregates were extracted from both Marshall and SGC specimens using the solvent extraction method, followed by sieve analysis on the extracted aggregates. SGC and Marshall gradations were compared to the contractor's QC gradations.

Table 27. Aggregate and Mix Design Volumetrics of Mixtures for Breakdown Analysis

Mix Properties		Mix Designation			
		Atlanta	Florence	Reno	Rogue Valley
Aggregate Type		Granite	Granite	Basalt	Alluvial
LA Abrasion (%)		41.0	35.0	18.4	15.0
NMAS (mm)		12.5	19	12.5	12.5
Design Compaction Method		75 blows	75 gyrations	75 blows	75 gyrations
Design Gradation	19.0 mm	100.0	100.0	100.0	100.0
	12.5 mm	96.0	97.0	96.6	97.0
	9.5 mm	85.0	86.5	86.4	88.0
	#4	63.0	63.6	61.8	69.0
	#8	50.0	44.7	41.6	51.0
	#16		32.6	27.2	32.0
	#30		22.9	17.8	20.0
	#50		14.4	11.8	13.0
	#100		7.8	7.8	9.0
	#200	4.0	3.5	5.4	6.6
Binder Performance Grade		PG 76-22		PG 76-28M	PG 76-22ER
Optimum Asphalt Content (%)		5.9	5.2	5.8	7.3
Bulk Specific Gravity (G_{mb})		2.369	2.403	2.481	2.343
Theoretical Specific Gravity (G_{mm})		2.470	2.469	2.596	2.424
AV (%)		4.2	3.5	3.5	3.5
VMA (%)		16.4	15.6	15.0	16.9

4.3.5.1 Breakdown Analysis of Atlanta and Florence Mixtures

The comparisons of gradations before and after compaction for the Atlanta and Florence mixtures containing high LA abrasion loss aggregates are presented in Table 28 and Table 29, respectively. Note that in the *Difference in Gradations* columns, a negative value indicates that the post-compaction gradation is finer than the contractor's QC gradation, indicating a breakdown of aggregates during laboratory compaction. Likewise, for the difference between SGC and Marshall gradations, a negative value indicates that the Marshall gradation is finer than the SGC gradation.

For the Florence mix results, it appears that the post-compaction gradations are coarser than the contractor's QC gradation. This may be due to the QC sample being taken at a different time than the samples obtained for this study. Nonetheless, from the results in Table 28 and Table 29, it can be seen that Marshall compaction caused more breakdown for both mixtures.

Table 28. Comparison Between QC and Post-Compaction Gradations of the Atlanta Mixture

Sieve Size (mm)	Gradation			Difference in Gradations		
	QC	SGC	Marshall	QC – SGC	QC – Marshall	SGC – Marshall
19.0	100.0	100.0	100.0	0.0	0.0	0.0
12.5	97.0	96.8	96.4	0.2	0.6	0.4
9.5	86.5	83.9	87.8	2.6	−1.3	−3.9
4.75	63.6	56.4	63.0	7.2	0.6	−6.6
2.36	44.7	43.0	48.7	1.7	−4.0	−5.7
1.18	NA	35.8	40.3	NA	NA	−4.5
0.60	NA	29.6	33.2	NA	NA	−3.6
0.30	NA	20.0	22.4	NA	NA	−2.4
0.15	NA	8.6	9.9	NA	NA	−1.2
0.075	3.5	3.3	3.9	0.3	−0.4	−0.7

NA = not available.

Table 29. Comparison Between QC and Post-Compaction Gradations of the Florence Mixture

Sieve Size (mm)	Gradation			Difference in Gradation		
	QC	SGC	Marshall	QC – SGC	QC – Marshall	SGC – Marshall
19.0	100.0	100.0	100.0	0.0	0.0	0.0
12.5	97.0	96.2	97.3	0.8	−0.3	−1.1
9.5	86.5	86.9	86.4	−0.4	0.1	0.6
4.75	63.6	59.8	60.3	3.8	3.3	−0.5
2.36	44.7	41.5	42.5	3.2	2.2	−1.0
1.18	32.6	30.7	31.7	1.9	0.9	−1.0
0.60	22.9	21.5	22.5	1.4	0.4	−1.0
0.30	14.4	13.7	14.6	0.7	−0.2	−0.9
0.15	7.8	8.0	8.8	−0.2	−1.0	−0.7
0.075	3.5	4.3	5.0	−0.8	−1.4	−0.6

4.3.5.2 Breakdown Analysis of Reno and Rogue Valley Mixtures

Comparisons of post-compaction gradations of the Reno and Rogue Valley mixtures that had unusually high N_{EQ} values are presented in Table 30 and Table 31. For the Reno mixture, the Marshall gradation is consistently finer than the SGC gradation, indicating more breakdown with Marshall hammer compaction. However, the Rogue Valley mixture had smaller differences between post-compaction gradations from Marshall and SGC.

Table 30. Comparison Between QC and Post-Compaction Gradations of the Reno Mixture

Sieve Size (mm)	Gradation			Difference in Gradation		
	QC	SGC	Marshall	QC – SGC	QC – Marshall	SGC – Marshall
19.0	100.0	100.0	100.0	0.0	0.0	0.0
12.5	96.6	95.7	96.6	0.9	0.0	−0.9
9.5	86.4	85.1	88.1	1.3	−1.7	−3.0
4.75	61.8	61.0	63.3	0.8	−1.5	−2.3
2.36	41.6	42.0	44.3	−0.4	−2.7	−2.3
1.18	27.2	27.2	29.1	0.0	−1.9	−1.9
0.60	17.8	17.9	19.4	−0.1	−1.6	−1.5
0.30	11.8	11.8	12.8	0.0	−1.0	−1.0
0.15	7.8	7.4	8.1	0.4	−0.3	−0.7
0.075	5.4	4.7	5.3	0.7	0.1	−0.6

Table 31. Comparison Between QC and Post-Compaction Gradations of the Rogue Valley Mixture

Sieve Size (mm)	Gradation			Difference in Gradation		
	QC	SGC	Marshall	QC – SGC	QC – Marshall	SGC – Marshall
19.0	100.0	100.0	100.0	0.0	0.0	0.0
12.5	97.0	98.0	97.1	−1.0	−0.1	0.9
9.5	88.0	89.3	88.9	−1.3	−0.9	0.4
4.75	69.0	68.6	69.0	0.4	0.0	−0.4
2.36	51.0	51.8	51.9	−0.8	−0.9	−0.1
1.18	32.0	33.4	33.7	−1.4	−1.7	−0.3
0.60	20.0	21.5	21.7	−1.5	−1.7	−0.2
0.30	13.0	14.5	14.4	−1.5	−1.4	0.1
0.15	9.0	10.4	10.3	−1.4	−1.3	0.1
0.075	6.6	7.9	7.6	−1.3	−1.0	0.3

5. Findings, Conclusions, and Recommendations

5.1 Recommendations from Previous Studies and Current Practice

Current FAA specifications for compaction of airfield mixtures allow the engineer to select either the Marshall hammer (ASTM D6926) or the SGC (ASTM D6925) as the method of asphalt mixture compaction for mix design and quality assurance testing. For airfield pavements designed to support aircraft up to 60,000 lb, the required laboratory compactive effort is either 50 blows with the Marshall hammer or 50 gyrations with the SGC. For airfield pavements designed for aircraft above 60,000 lb, the required laboratory compactive effort is either 75 blows with the Marshall hammer or 75 gyrations with the SGC.

This framework implies that the two compactive efforts are essentially equivalent and interchangeable. However, these two methods are distinctly different with regard to compaction energy and specimen size. Although a national proficiency sample program has shown that both methods exhibit similar within-laboratory variability statistics, SGC compaction consistently has a lower between-laboratory variability than Marshall compaction. This indicates that larger differences between laboratories can be expected when comparing volumetric properties when using Marshall compaction.

Several past projects evaluated the equivalent number of SGC gyrations to Marshall compaction efforts. The following findings were drawn from those studies:

- Cooley et al. (2009) evaluated asphalt mixtures from 10 airports and found 43–40 gyrations to be equivalent to 75-blow Marshall compaction, and 32–40 gyrations to be equivalent to 50-blow Marshall compaction, based on an analysis of compaction densities. Additionally, they evaluated N_{design} to achieve the highest asphalt content without compromising rutting resistance, which led to recommendations of 50, 65, and 80 gyrations for aircraft tire pressures of <100 psi, 100–200 psi, and >200 psi, respectively.
- Rushing (2011) evaluated 32 mix design combinations to determine N_{design} values to obtain 3.5 percent AV at the same asphalt content as with Marshall compaction. The author found that the equivalent N_{design} ranged from 25 to 125 gyrations and recommended the mean value of 70 gyrations. Rushing also recommended eliminating the Superpave $N_{initial}$ and $N_{maximum}$ design criteria for airfield mixtures.
- Christensen et al. (2010) evaluated eight FAA mix designs and recommended 70 SGC gyrations as equivalent to 75 blows of the Marshall hammer.

5.2 Distribution and Mean Values for N_{EQ} for 75 and 50 Blows

The results of this research, based on an analysis of 44 P-401 and P-403 mixtures, indicate that the number of gyrations in an SGC necessary to provide equivalent volumetric properties as 75-blow Marshall hammer compaction follows a wide distribution, with a mean value of 77 gyrations. Similarly, an analysis of a much smaller set of mixtures found the distribution of equivalent SGC gyrations for 50-blow Marshall hammer compaction had a mean value of 52 gyrations.

These findings confirm the results of previous studies that have led to the current FAA P-401 and P-403 specifications, which allow either 50-blow or 50-gyration mix designs for airports servicing aircraft with a maximum gross weight of 60,000 lb, and either 75-blow or 75-gyration designs for all other FAA airport facilities.

5.2.1 Discussion of Impacts to Current Marshall Mix Designs

As noted in Section 3.5, based on the mixtures collected and evaluated in this study, the majority of P-401 and P-403 mix designs prepared for airport projects are based on SGC compactive efforts. However, a significant number of airport engineers still specify mix designs based on Marshall hammer compaction. If the FAA were to phase out Marshall compaction as an option, it would impact future mix designs in those areas that have historically used Marshall methods. There are two scenarios to consider when converting from Marshall to SGC compaction.

The first scenario is for Marshall mixtures that have an N_{EQ} above the specified SGC compactive effort (either 75 or 50 gyrations). Although mix designers will not know whether their historical mix design has a high or low N_{EQ}, if they use the same mix design materials and proportions and compact the samples in an SGC to 75 gyrations (or 50 gyrations where specified), they may find their volumetric properties to be quite different than when using Marshall compaction.

If the SGC compacted G_{mb} is lower than the Marshall G_{mb}, then that mix would have had an N_{EQ} above 75 gyrations. If the SGC G_{mb} is significantly lower than the Marshall G_{mb}, the AV and VMA would be too high. In this case, the mix designer would need to increase the asphalt content or adjust the blend to achieve the target AV content and minimum VMA. In practice, given the low-bid contracting environment, mix designers will typically try to achieve a mix design with the lowest asphalt content, so adjusting the blend will be the most likely choice. In the case that a contractor chooses to simply add more asphalt to the existing mix design to achieve the AV target, the additional P-401/P-403 requirement that the mix design must pass the APA (or other rutting tests) provides safeguards against the higher asphalt content resulting in a mixture that is susceptible to permanent deformation. Mixtures with higher asphalt content would tend to be more compactable and more durable.

In the second scenario, if the SGC-compacted G_{mb} is higher than the historical Marshall G_{mb}, then that mix would have had an N_{EQ} below 75 gyrations. If the SGC G_{mb} is significantly higher than the Marshall G_{mb}, the AV and VMA values would be too low. In this case, the mix designer would have no choice other than to adjust the blend to achieve the target AV content and minimum VMA with SGC compaction.

The bottom line is that changing the compaction method or the compactive effort is unlikely to significantly affect the optimum asphalt content of P-401/P-403 mix designs. Existing Marshall mix designs with high or low N_{EQ} will likely be redesigned with different gradations to achieve the specified volumetric requirements.

5.3 Recommendations for Final N_{EQ} for 75 and 50 Blows

The overall findings of this rigorous research study, incorporating an analysis of over 50 airfield mixtures from across the country with a wide array of aggregate types, asphalt binders, and mixture properties, validate the existing P-401/P-403 options for compactive efforts for asphalt mix designs. Table 32 presents the recommended Marshall and SGC compactive efforts for airport pavements servicing aircraft above and below 60,000 lb.

Table 32. Recommended Compactive Efforts for P-401 and P-403 Mix Designs

Aircraft Limits	Marshall Hammer Compactive Effort ASTM D6926	SGC Effort ASTM D6925
≤60,000 lb	50 blows	50 gyrations
>60,000 lb	75 blows	75 gyrations

The literature review revealed that historical correlations between Marshall and SGC compaction have been established in single laboratories, likely with single operators and with a limited number of mix designs. By contrast, this research included multiple laboratories and, in most cases, 10 or more times the number of mixtures used than in past research efforts. The results confirmed similar correlations between Marshall blows and SGC gyrations as reported in past studies but also integrated multi-laboratory variability. This factor is important to consider because, in practice, within a given State or region multiple qualified laboratories could be developing P-401 or P-403 mixtures, rather than a single facility.

Only a limited number of 50-blow Marshall mix designs were obtained from across the country, as they are used only for airfields servicing relatively low-weight aircraft.

6. References

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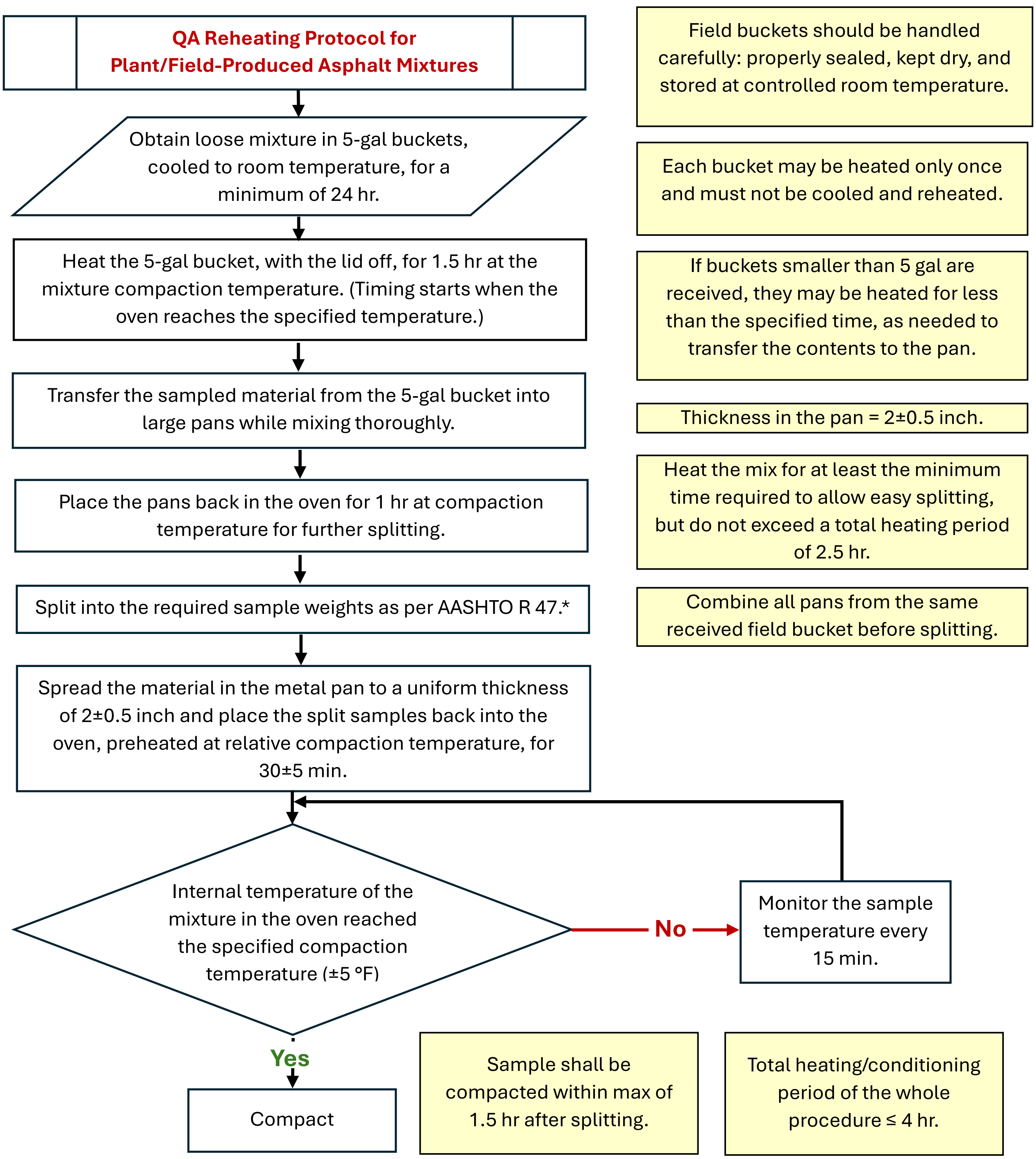
Appendix A. Reheating Procedure



*AASHTO R 47-22: Standard Practice for Reducing Samples of Asphalt Mixtures to Testing Size

Source: Adapted from Elias et al. (2023)

Figure 35. Reheating Protocol for Plant- or Field-Produced Asphalt Mixtures

Appendix B. Airport Locations and Mix Information

#	State	Airport	NMAS	Mix Type	Binder Grade	Design Compaction
1	AL	Huntsville Executive (MDQ)	12.5	P-401	PG 67-22	75 blows
2	AL	Tuscaloosa National (TCL)	12.5	P-401 (Surface)	PG 76-22	75 blows
3	AL	Tuscaloosa National (TCL)	12.5	P-401 (Binder)	PG 67-22	75 blows
4	AZ	Pinal Air Park (MZJ)	12.5	P-403	PG 76-16	75 blows
5	CA	San Francisco International (SFO)	19.0	P-401	PG 76-22	75 blows
6	CA	Santa Maria Public (SMX)	19.0	P-401	PG 76-16	75 blows
7	CO	Eagle County Regional (EGE)	12.5	P-401	PG76 -28	75 blows
8	CA	Truckee-Tahoe (TRK)	19.0	P-401	PG 76-28	75 blows
9	GA	Augusta Regional (AGS)	12.5	P-401	PG 76-22	75 blows
10	GA	Hartsfield-Jackson Atlanta International (ATL)	12.5	P-401	PG 76-22	75 blows
11	KY	Louisville Muhammad Ali International (SDF)	19.0	P-403	PG 64-22	75 blows
12	NJ	Newark International (EWR)	19.0	P-401	PG 82-22	75 blows
13	NJ	Teterboro (TEB)	19.0	P-401	PG 64-22	75 blows
14	NV	Reno-Stead (RTS)	12.5	P-401	PG 64-28	75 blows
15	NV	Reno-Tahoe International (RNO)	12.5	P-401	PG 76-28	75 blows
16	TX	San Antonio International (SAT)	12.5	P-403	PG 76-22	75 blows
17	AZ	Tucson International (TUS)	12.5	P-403	PG 64-22	75 gyrations
18	AZ	Tucson International (TUS)	19.0	P-401	PG 76-22	75 gyrations
19	AZ	Tucson International (TUS)	12.5	P-401	PG 76-22	75 gyrations
20	CA	Sacramento International (SMF)	12.5	P-401	PG 76-22	75 gyrations
21	CO	Greeley-Weld County (GXY)	12.5	P-401	PG 70-28	75 gyrations
22	FL	Gainesville Regional (GNV)	12.5	P-401	PG 76-22	75 gyrations
23	GA	Southwest Georgia Regional (ABY)	12.5	P-401	PG 76-22	75 gyrations
24	IN	South Bend International (KSBN)	12.5	P-401	PG 76-22	75 gyrations
25	IN	South Bend International (KSBN)	12.5	P-403	PG 70-28	75 gyrations
26	IN	DeKalb-Peachtree (PDK)	12.5	P-401	PG 70-22	75 gyrations
27	IN	DeKalb-Peachtree (PDK)	19.0	P-401	PG 70-22	75 gyrations
28	IN	Indianapolis International (IND)	12.5	P-403	PG 64-22	75 gyrations
29	MA	Boston Logan International (BOS)	19.0	P-401	PG 76-28	75 gyrations
30	MI	Selfridge Air National Guard Base (MTC)	12.5	P-401	PG 70-28	75 gyrations
31	MN	St. Cloud Regional (KSTC)	12.5	P-401	PG 58V-34	75 gyrations
32	MN	St. Cloud Regional (KSTC)	12.5	P-401	PG 58E-34	75 gyrations
33	MO	Cape Girardeau Regional (CGI)	12.5	P 403	PG 70-22	75 gyrations

#	State	Airport	NMAS	Mix Type	Binder Grade	Design Compaction
34	NY	Albany International (ALB)	12.5	P-401	PG 64V-22	75 gyrations
35	OH	John Glenn International (CMH)	19.0	P-401	PG 76-22	75 gyrations
36	OK	Tulsa Riverside (RVS)	12.5	P-401	PG 70-28	75 gyrations
37	OR	Rogue Valley International-Medford (MFR)	12.5	P-401	PG 76-22ER	75 gyrations
38	SC	Pickens County (LQK)	12.5	P-401	PG 76-22	75 gyrations
39	SC	Florence Regional (FLO)	19.0	P 401	PG 76-22	75 gyrations
40	UT	Provo Municipal (PVU)	12.5	P-401	PG 70-28	75 gyrations
41	VA	Manassas Regional (HEF)	12.5	P-401	PG 82-22	75 gyrations
42	VA	Manassas Regional (HEF)	9.5	P-401	PG 82-22	75 gyrations
43	WA	Columbia Gorge Regional (DLS)	12.5	P-401	PG 64H-28	75 gyrations
44	WY	Central Wyoming Regional (RIW)	12.5	P-401	PG 70-28	75 gyrations
45	ID	Cascade (U70)	19.0	P-401	PG 64-34	50 blows
46	WY	Fort Bridger (FBR)	12.5	P-403	PG 64-34	50 blows
47	AL	Tuskegee Moton Field Municipal (06A)	12.5	P 401	PG 76-22	50 gyrations
48	IA	Forest City Municipal (FXY)	19.0	P-401	PG 58-28H	50 gyrations
49	SD	Canton Municipal (7G9)	12.5	P-403	PG 58-34	50 gyrations
50	SD	Custer County (CUT)	19.0	P-403	PG 58-34	50 gyrations
51	WA	Paine Field (PAE)	12.5	P-403	PG 58H-22	50 gyrations