University of Nevada, Reno

Local Agency Balanced Mix Design with Superpave Volumetric Foundation

A thesis submitted in partial fulfillment of the

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by

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ABSTRACT

Asphalt Concrete (AC) mix design has been a common challenge to provide sustainable roadways with high performance over their pavement service life. Several mix design methods have evolved with the same target of generating durable and stable pavements under various traffic and climatic conditions while considering the visco-elastic behavior of asphalt binders, which may alter pavement responses at a certain temperature and aging level . Current asphalt mixture design methods are structured around meeting a range of volumetric requirements. Although this allows for volumetric parameters to be monitored and controlled during production, it does not give much engineering insight as to how the mixture will perform in the field.

The aim of this research study is to present for the Regional Transportation Commission of Washoe County (RTC) an implementation strategy to switch from Marshall mix design method to an optimized mixture design for flexible pavement following the Balanced Mix Design (BMD), using the Superpave gyratory compactor. Shifting toward to a BMD approach based just on performance testing, could be a precarious move for any agency considering new concepts in designing asphalt mixtures. Therefore, the design analysis adopted in this study was based on the balanced mix design approach, while considering both requirements for the volumetric properties and performance thresholds known as “Volumetric Design with Performance Verification”. Eight new mixtures generated in this study were designed to meet the Superpave volumetric criteria, and subsequently verified with performance testing intended to be related to the most prevalent distresses in Northern Nevada including long-term durability (cracking and stripping resistance) while maintaining a rutting resistance test that also provides additional moisture resistance data.

I am dedicating my effort and thousands of words,

for the one who inspired me with my very first letters,

to my beloved father

George Elias.

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Last but not least, no one can be productive and decide to stay few more years here without a great team spirit and a peaceful entourage. Thank you for all my friends for all our beautiful moments and memories we are making!

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Chapter 1. Introduction

1.1 General Overview

Asphalt Concrete (AC) mix design has been a common challenge to provide sustainable roadways with high performance over their pavement service life. Several mix design methods have evolved with the same target of generating durable and stable pavements under various traffic and climatic conditions while considering the visco-elastic behavior of asphalt binders, which may alter pavement responses at a certain temperature and aging level [1]. Recently, the Superpave mix design method has become the industry standard and is a significant improvement in mix design technology. The target of Superpave volumetric mix design was to provide enough asphalt binder within the mixture for adequate long-term durability, while preserving a stable aggregate structure for high rutting resistance. Initially, the Superpave methodology was supposed to combine performance testing along with volumetric specifications, however the performance testing was not implemented for practicality reasons.

Despite the fact that the Superpave methodology was able to generate flexible pavements with high rutting resistance, most State Highway Agencies (SHAs) have indicated significant concern about long-term durability [2]. This concern of SHAs is mainly due to the lower asphalt binder content in Superpave mixtures, compared to the mixes designed with the Marshall method. Accordingly, the Superpave methodology is being subjected to continuous adjustments along with its implementation by SHAs, including supplemental stability and durability performance testing. Hence, the asphalt industry should always be updated with the latest adjustments associated with the relative impact on AC pavement performance.

One of the most recent surveys sent to the State Asphalt Pavement Associations (SAPAs), reported the latest adjustments implemented to the Superpave mix design method [2]. The main changes documented in the SAPA study include using polymer-modified asphalt binder, reducing the design air voids (AV%) level or increasing the minimum required Voids in Mineral Aggregates (VMA) to force additional binder in the mix, and reducing the compaction effort N_{Design}. The gyrations numbers used in the Superpave mix design method, were introduced by the Strategic Highway Research Program (SHRP) and recommend N_{Design} as the adequate simulation of field compaction. However, several survey respondents reported some field sections with low in-situ density within 2 to 3 years post-construction. For that reason, most SHAs are considering reducing the design compaction effort N_{Design}, and potentially improving relative field compaction for better long-term performance. Besides the volumetric mix design adjustments to Superpave methodology, supplementing it with performance testing associated with volumetric properties help ensure the required stability and long-term durability of asphalt mixtures. Hence, the asphalt industry is focused nowadays on the Balanced Mix Design (BMD) as the most recent and promising approach to design AC pavements [2].

1.2 Scope of Work

Current asphalt mixture design methods are structured around meeting a range of volumetric requirements. Although this allows for volumetric parameters to be monitored and controlled during production, it does not give much engineering insight as to how the mixture will perform in the field. The aim of this research study is to present for the Regional Transportation Commission of Washoe County (RTC) an implementation strategy to switch from Marshall mix design method to an optimized mixture design for flexible pavement following the Balanced Mix Design, using the Superpave gyratory compactor. This research study is based on a full study of different trial mixtures in terms of volumetric and performance test results. According to the Superpave methodology, the volumetric properties were computed and the optimum binder content (OBC) was selected based on the design air voids level.

With reference to performance testing, the tests conducted at OBC in this study include: the Tensile Strength Ratio (TSR) test, the Hamburg Wheel Track Test (HWTT), the short-term and long-term Ideal Cracking Test (Ideal-CT), and the Marshall Stability test. These tests were selected based on their correlation to field performance and ease of practical adoption by many agencies that are in the process of refining mix design, recycled material, and standard specifications. The overall objective of this study was to create an approach for optimized, high-performing, and durable mixture designs with the use of 15% Reclaimed Asphalt Pavement (RAP). The primary forms of pavement distress in Northern Nevada are related to poor mixture durability and result in raveling, cracking, and stripping. The approach adopted for this research effort is outlined in Figure 2.

Figure 1: High Performing Asphalt Pavement

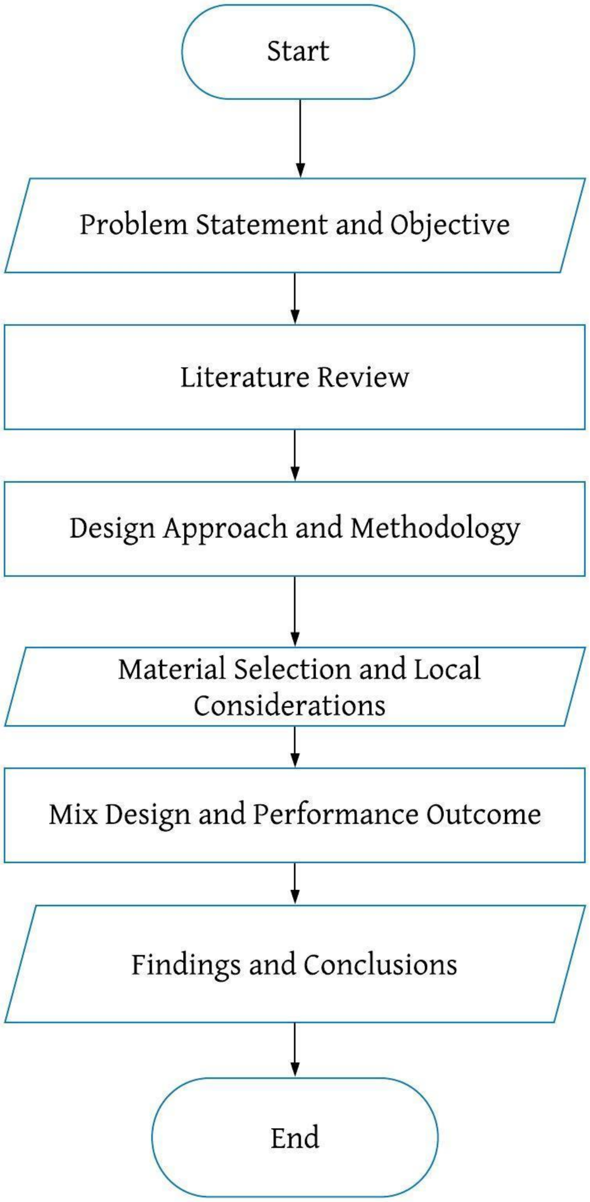

Figure 2: General Outline

Chapter 2. Literature Review

2.1 Marshall Hammer versus Superpave Gyratory Compactor

2.1.1 Marshall and Superpave Mix Performance in Alabama

The optimum asphalt content for hot-mix asphalt can be determined through adequate compaction effort during the mix design. The compaction effort of the Superpave gyratory compactor has been refined since its first development in 1994, when the number of gyrations was established for different climate conditions and traffic levels. According to the climate and traffic level, 28 different compaction levels were implemented along with 3 gyration numbers: $N_{initial}$, N_{Design}, and $N_{maximum}$. The $N_{initial}$ and $N_{maximum}$ assess the workability and quality of the mix, whereas the optimum asphalt content is selected as per N_{Design} [3].

The National Cooperative Highway Research Program (NCHRP) Project 9-9, Refinement of the Superpave Gyratory Compaction Procedure, aimed to reduce the 28 suggested gyration levels, through eliminating the climatic conditions [3]. It was concluded that the asphalt binder grades can account for the climate variation, such as stiffer asphalt grades recommended in warm climates for high rutting resistance, therefore climate variations does not highly affect the mixture compatibility and can be excluded from the gyrations level. The NCHRP 9-9 study was able to reduce the compaction levels from 28 to 4 gyrations levels, however the specified number of gyrations was not verified with field mixture performance.

The Alabama Department of Transportation (ALDOT) uses the Superpave mix design method for most of its dense-graded Hot Mix Asphalt (HMA) mixes [4]. However, Alabama DOT had a concern regarding the suggested Superpave gyrations level N_{Design}, being too high for a certain traffic level. The rutting resistance of the mix may increase at a higher number of gyrations, but workability and durability problems may arise due to the deficient binder content with such high N_{Design}. Hence, the importance of balancing between the mix rutting resistance and durability, through optimizing N_{Design}, as per field performance of Marshall and Superpave field sections. The State of Virginia had reduced the design number of gyrations based on the comparison with Marshall designed mixes, which included Superpave Performance Grade (PG) and Superpave consensus aggregate properties [4]. Based on the historical adequate rutting resistance of Marshall mixtures with a relative high binder content, it was concluded that Superpave N_{Design} can be altered and simulate appropriate rutting resistance. Alabama DOT aimed to optimize Superpave N_{Design}, thus it assessed the performance of Alabama's Marshall designed mixtures with the performance of Superpave designed mixtures. In order to highlight on the effect of gyrations level, it should me mentioned that both Marshall and Superpave mixtures utilized the Superpave PG binder system, met Superpave consensus properties, were placed under the same time period in similar climate conditions and were subjected to similar traffic levels.

Based on the job mix formulas (JMF), the average binder contents were 5.3 % and 5.6% for Superpave mixtures and Marshall mixtures, respectively. The different binder contents of the 25 Marshall projects and 25 Superpave projects are plotted in Figure 3. With respect to the maximum sieve size, the average difference in asphalt content between Marshall and Superpave was 0.5% for 19 mm mixtures, and 0.1% for 12.5 mm mixtures. Due to the lower binder content in Superpave mixtures compared to Marshall mixtures, it was expected that Superpave projects would exhibit higher cracking distress, while Marshall projects will have higher rut depths. However, the 50 projects in Alabama, designed with both methods performed well.

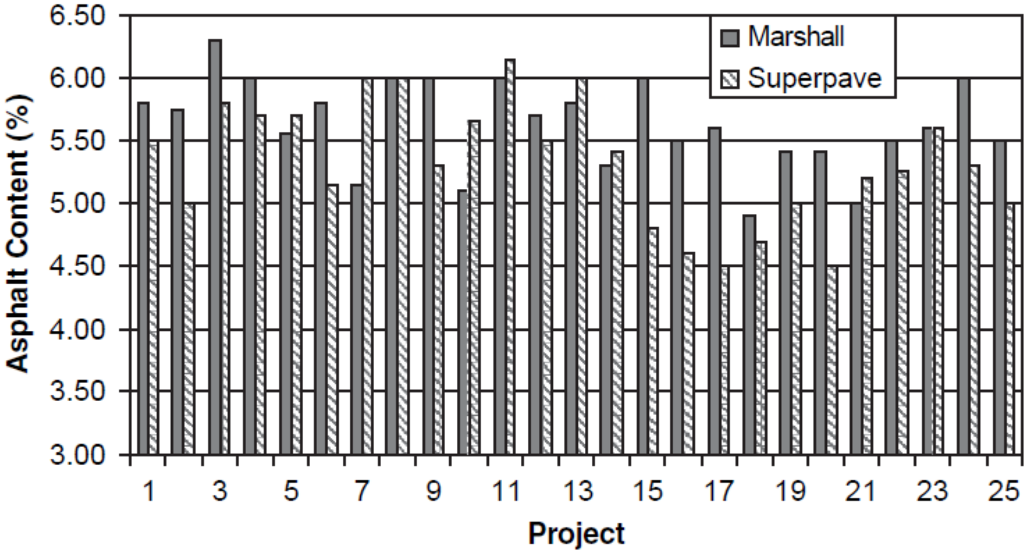

Figure 3: Asphalt Content Comparison [4]

Based on the performance evaluation of 25 Marshall projects and 25 Superpave projects, the following conclusions were made:

- Four years after construction, all the projects designed with both methods, did not exhibit very deep rutting nor extensive cracking.
- The cracking resistance was similar for both Marshall and Superpave mixtures.
- With respect to the maximum sieve size, the average rut depth was 0.09 in and 0.05 in for 12.5 mm mixes and 19 mm mixes, respectively which indicates a slight improvement for 19 mm mixes.
- Marshall mixes had an average rut depth of 0.06 in average rut depth, whereas Superpave mixes had 0.09 in.

- Four years after construction, the average air voids measured in the wheel path was 5.3% and 5.9% for Marshall and Superpave mixtures, respectively. Thus, most of Superpave and Marshall mixtures will not reach the 4% design air voids during pavement life.
- Similar air void level was reached regardless of traffic volume, due to the variation of gyrations level. Increasing the number of gyrations for high traffic volume project, will consequently reduce the binder content, resulting in the same air voids level as other traffic levels.
- Based on the similar air voids levels, the potential of high densification was reduced for high traffic volume projects.
- The geographical locations of the projects did not have a significant impact on rutting and cracking percentages of the mixes.
- The durability and field compaction of Superpave mixtures can be improved by increasing the binder content, without reducing the relative rutting resistance. Therefore, the rutting resistance should be cautiously monitored during mix design and process construction.

2.1.2 Superpave Gyratory Parameters

The impact of compaction parameters on the internal structure of gyratory compacted samples, was assessed by Georgiou et al., through image based internal structure indicators [5]. Additionally, the effect of field compaction was assessed by means of field core specimens. The findings below were made based on the analysis of this study:

- Gyration angle and specimen geometry strongly affect aggregate orientation within a compacted specimen.
- Specimen preparation exhibited the highest impact on the number of stone-to-stone contact points.
- Regardless of the compaction parameters, gyratory compacted specimens were associated with some segregation.
- The best simulation of the field cores internal structure was achieved through compaction at 1.45° gyration angle, along with coring 100 mm diameter from 150 mm samples.
- A higher gyration internal angle was recommended for a better simulation of the internal structure of field compacted specimens.
- Further investigation is required to verify the correlation between the image based internal structure indicators and fundamental mechanical properties of the sample.

2.1.3 Validation of Gyratory Compactor in Iowa

Similar to many DOTs, the State of Iowa has been focusing on the validation of N_{Design} for its specific region conditions, which did lead to some alterations in the gyration effort for different traffic levels [6]. The compaction effort is an essential component in asphalt mix design process and may significantly vary from laboratory to field compaction. The over compaction effort in the laboratory may reduce the asphalt content in the mixture and consequently lead to inadequate compaction in the field. This Iowa study evaluated if the target field density was achieved under traffic with gyratory levels implemented at the time. The experimental plan for Iowa study, presented in Figure 4, begins by measuring the in-place density through volumetric testing on surface mixtures designed for 300,000 to 30,000,000 ESALs.. The gyratory slope was recalculated from QC/QA data, in order to verify the compatibility of the mixtures under the existing mix design procedures. Afterward, the post-construction compaction effort was estimated, and the theoretical N_{Design} was determined at construction and post-construction levels. Finally, optimum binder content and aggregate structures for different mixtures were analyzed with respect to N_{Design} at three different traffic levels.

The post-construction effort was assessed for a total of 20 projects within six different districts of Iowa DOT, constructed in 2011 for 300,000, 1,000,000, 3,000,000 and 10,000,000 ESAL designs along with some additional sections designed for 30,000,000 ESALs. The analysis was conducted on three sections per traffic level, through pavement cores from representative sections. Iowa DOT Pavement Management Information System (PMS) survey information and the Distress Identification Manual for the Long-Term Pavement Performance Program were used to verify the pavement condition of selected sections without any postconstruction anomalies.

The density during post-construction was determined from the comparison of QC/QA data with field densities, bulk specific gravity (Gmb), and theoretical maximum density (Gmm). Subsequently, the gyratory compactor slope can be recalculated for each mix, in order to determine the theoretical N_{Design} at construction and post-construction, which presents the theoretical amount of compaction induced by traffic load. As well, this study identifies the N_{Design} adopted for the laboratory mixed, laboratory compacted samples at various traffic levels.

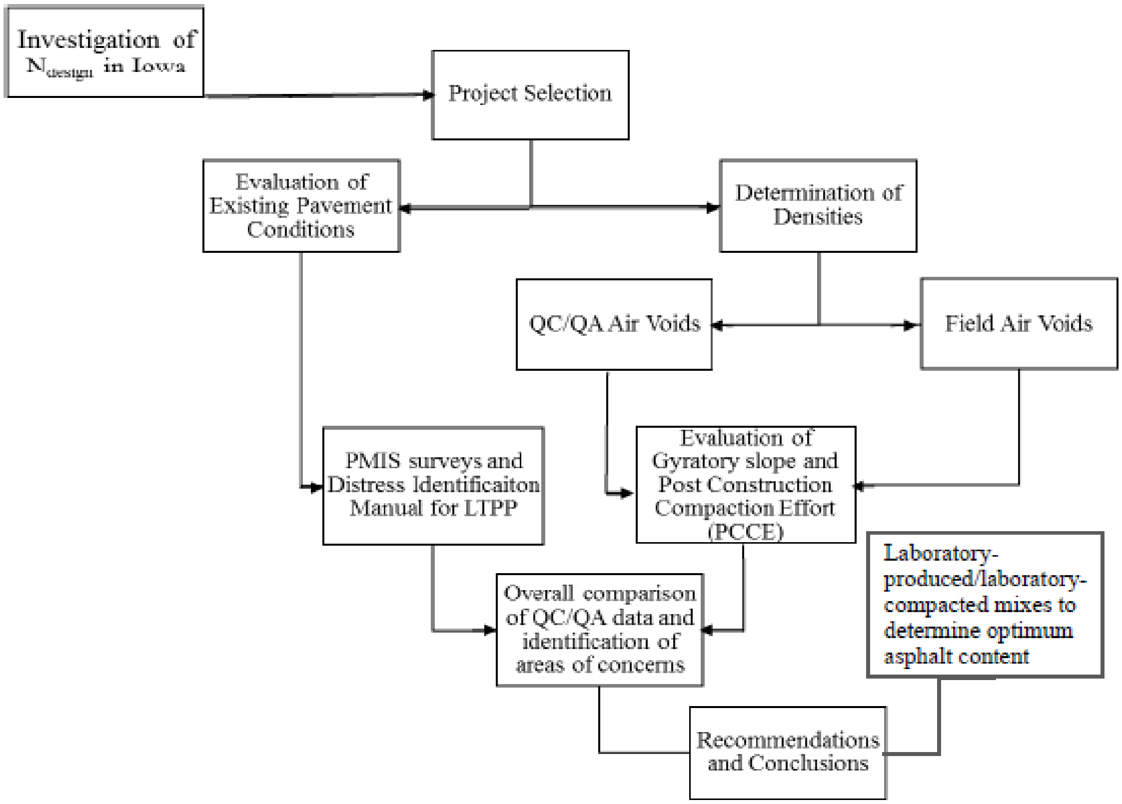

Figure 4: Flowchart of Experimental Plan for Iowa Study [6]

Conclusions and recommendations associated with the Iowa DOT study were:

- The target of 4% air voids was not reached for most of the evaluated mixtures at 1, 2, 4, and 12 years after construction.
- Conforming to previous DOT studies, the current recommended N_{Design} restricts mix from reaching 4% in-situ air voids even 4 years after construction, since this compaction effort is higher than the optimal value.
- The Gmm of the QC/QA data conformed to the Gmm of the field cores tested in the laboratory, hence the Gmm from the QC/QA can be adopted.
- Under current design gyrations, the air void analysis indicated that the sections subjected to 300,000 and 3,000,000 ESALs had higher post-construction

compaction, compared to the 1,000,000, 10,000,000, and 30,000,000 ESALs sections.

- There is a high likelihood that 25% of the HMA mixtures will not reach the ultimate pavement density 4 years after construction based on the statistical distribution of %Gmm in 2011, 2012, and 2013.
- Based on laboratory mixed/laboratory compacted specimens, the optimum asphalt content of the mixtures for the low traffic level was the highest at 5.8% for 3% air voids, followed by 5.7% and 4.8% for the medium and high traffic levels respectively at 4% air voids.
- Since Iowa DOT is reconsidering N_{Design}, the aggregates sources/types, design target air voids, and the VMA should be extensively monitored for quality control.

2.1.4 National Center for Asphalt Technology (NCAT) Study 2019

A recent NCAT study (2019) evaluated the main adjustments adopted by SHAs, to the Superpave mix design method and their effectiveness to enhance pavement performance [2]. The adjustments assessed in this study were at the mix design phase, without any performance testing. The survey sent to SAPAs, aimed to collect the main adjustments made by SHA, along with relative impact on pavement performance, bid costs and staffing requirements. A SAPA online survey was conducted at the beginning of this study, and sent to SAPAs representing contractors in 40 states in order to:

1. Determine possible alterations to enhance asphalt pavement durability, without performance testing.

2. Identify the number of these modifications were implemented by SHA.
3. Analyze the long-term durability improvement due to these adjustments, based on historical data.

The list of mix design adjustments implemented by SHAs at the time of the survey, are summarized in Table 1. According to the number responses, the multiple-stress creep recovery (MSCR) specification for asphalt binder was at the top of specification changes, followed by increasing the use of polymer-modified asphalt binder and decreasing the design compaction effort N_{Design} with 8 responses. Similar to reducing N_{Design}, reducing the design air voids, as well as increasing design VMA were some of the major mix alterations, which focus on adding more asphalt binder into the mixture. The implemented specification changes on the U.S. map (Figure 5), indicate that six SHAs implemented more than five changes, eleven agencies implemented three to four changes, and six agencies implemented one or two changes.

The impact of the specification changes with respect to mixture durability, bid costs, staffing requirements, and recycled materials use are summarized in Table 2 based SAPA representative survey responses. It can be inferred from Table 2, that reducing the compaction effort through N_{Design} got the highest improvement on mixture durability, followed by the use of modified binder and decreasing design air voids. Consequently, decreasing the design compaction effort N_{Design}, was identified as one of the top alterations to improve Superpave mix durability through additional asphalt binder, and was implemented by 26 states as per

The Virginia Department of Transportation (VDOT) is one of the 26 SHAs that has reduced NDesign to 65 Gyrations for all Superpave mixtures. Katicha and Flintsch, conducted a study in 2016 for further durability improvement of the 65-gyrations mixtures through a higher binder content [8]. Many VDOT plant produced mixtures were assessed at 50 gyrations along with 3.5% design air voids and resulted in an increment of binder content increase between 0.4% to 1.0%. These altered mixtures were further evaluated with the Flow Number (FN) test and Indirect Tensile (IDT) strength test and showed improved cracking resistance without any adverse impact on rutting resistance. Based on this study, VDOT reduced the design compaction effort NDesign of all surface mixes to 50 gyrations.

The Alabama Department of Transportation (ALDOT), is another SHA that have reduced NDesign for high volume roads (more than 30 million ESALs) from 125 to 85 gyrations, as an attempt to add more binder into the mix. Afterward, another study by ALDOT indicated that the locking point of most Superpave mixtures was reached between 45 and 55 gyrations. Hence, NDesign was additionally reduced to 60 gyrations for all traffic levels. It is worth mentioning that lower NDesign by ALDOT, generated mixes with easier field compaction, without any negative impact on rutting field performance.

Table 3 from the NCHRP Project 20-07/Task 412 report [7]. However, some agencies reported in the survey that the binder content decreased back, one or two years after construction.

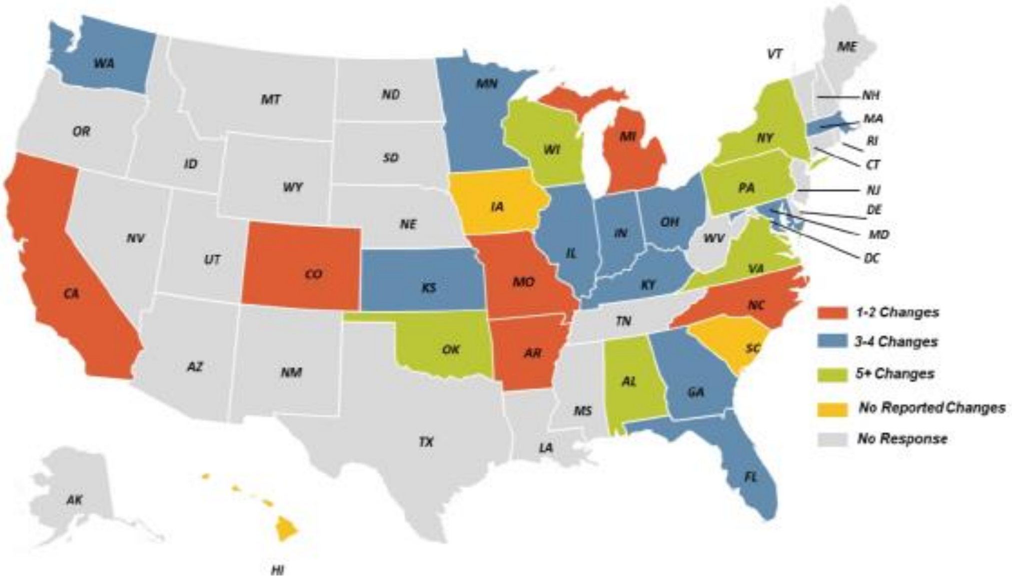

Figure 5: U.S. Map of Specification Changes Implemented by State Highway Agencies [2]

Table 1: Summary of Specification Changes Implemented by State Highway Agencies

Specification Changes implemented by State Highway Agencies	No. of Responses
Adopted MSCR specification for asphalt binders	9
Increased use of polymer-modified binders	8
Decreased N_{Design}	8
Decreased design air voids target	8
Increased design VMA	6
Set a minimum total binder content	5
Required higher or lower PG grades (either the high or low temperature)	4
Adopted regressed air voids approach	4
Set or verified specific gravity of aggregate	4
Decreased RAS content allowed	4
Changed other requirements for recycled materials	4
Made changes in mix design to potentially increase in-place density	4
Eliminated RAS	3
Increased moisture susceptibility requirements or use of antistrip	3
Decreased RAP content allowed	2
Allowed or required recycling agents	2
Set a minimum effective binder content	2
Set a minimum asphalt film thickness	2
Adopted ΔTc specifications for asphalt binder	1

Table 2: Number of SAPA Responses Indicating Impact of Each Specification Change

	Number of Responses Indicating Impact on			
Changes to Volumetric Mix Design System	Mix Durability	Bid Costs	Staffing Requirements	Recycled Materials Use
Decreased N_{Design}	9	2	-	-
Increased use of polymer-modified binders	8	5	-	2
Decreased design air voids target	6	1	-	-
Increased design VMA	6	6	1	2

The Virginia Department of Transportation (VDOT) is one of the 26 SHAs that has reduced N_{Design} to 65 Gyrations for all Superpave mixtures. Katicha and Flintsch, conducted a study in 2016 for further durability improvement of the 65-gyrations mixtures through a higher binder content [8]. Many VDOT plant produced mixtures were assessed at 50 gyrations along with 3.5% design air voids and resulted in an increment of binder content increase between 0.4% to 1.0%. These altered mixtures were further evaluated with the Flow Number (FN) test and Indirect Tensile (IDT) strength test and showed improved cracking resistance without any adverse impact on rutting resistance. Based on this study, VDOT reduced the design compaction effort N_{Design} of all surface mixes to 50 gyrations.

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Table 3: List of SHAs That Have Decreased N_{Deisgn} [7]

Design ESALs (Million)	< 0.3	0.3-3	3-30	>30
AASHTO R35	50	75	100	125
AL	60	60	60	60
CA	85	85	85	85
CO	50/75	75/100	75/100	125
CT	50	75	100	100
DE	75	75	75	75
GA	65	65	65	65
IA	ST (standard traffic):50; HT (high traffic):75; VT (very heavy traffic):95			
IL	30	50-70	70-90	90
MD	50	65	80	100
ME	50	50	75	75
MO	50	75	80/100	125
MT	75	75	75	75
NC	50	50	65	100
ND	65/75	65/75	75	75
NE	SPS (shoulder mix):40; SPR (high recycle mix):65; SPH (heavy truck application):95			
NJ	50	50	50	50
OH	50	50	65	65
OK	50	50	65	80
OR	65	80	80/100	100
PA	50	75	100	100
RI	50	50	50	50
SC	50	75	75	75
SD	50	60	80	80
UT	50	75	75/100	75/100
VA	Surface mix:50; intermediate mix:65; Base mix:65			
VT	50	65	80	80
WV	50	65	80	100

In theory, when the design compaction effort is reduced, it will provide a higher optimum binder content for a fixed aggregate gradation. However, the contractor can develop cost-effective mixtures by adjusting aggregates gradation to meet all volumetric requirements at a lower N_{Design} without increasing the binder content. This approach is noticeably presented in the example of Table 4, where 3 mixes are produced from the same asphalt binder and aggregate sources with 20% RAP. The first mixture was designed to 100 gyrations, and got an OBC of 6.8%, whereas the second mixture with the same gradation got an OBC of 7.2% along with a higher VMA, when designed to 75 gyrations. The gradation of the third mixture was altered, to get similar VMA and OBC of the first mixture, even at a lower N_{Design} of 75 gyrations. The example of Table 4 justifies the observation reported by some SHAs, which noticed a higher OBC right after implementing a lower N_{Design}, then contractors started fine-tuning the gradations to generate cost-effective mixtures at lower N_{Design} and moderate OBC. In summary, reducing N_{Design} can ensure higher in-place density due to better field compaction, without significantly affecting volumetric properties of the mix such as the optimum binder content.

Table 4: Effect of N_{Design} on Mix Volumetric Properties

Mix	V_a (%)	P_b (%)	VMA (%)	VFA (%)	DP	V_{be} (%)	P 2.36 (%)
N_{Design} = 100	4.0	6.8	15.8	74.7	1.0	11.8	38.9
N_{Design} = 75 using same gradation as N_{Design} = 100	4.0	7.2	16.6	75.9	0.9	12.6	38.9
Redesign using N_{Design} = 75	4.0	6.8	15.7	74.5	1.1	11.7	41.7
M323 requirements	4.0	-	≥15	73-76	0.6-1.2	-	32-67

2.1.5 NCHRP 818: Variability of Laboratory and Field Specimen

It is recognized that differences in mixture properties can occur from mix design to plant production and plant production to field construction. The NCHRP report 818 focused on identifying factors associated with the deviations in terms of volumetric and mechanical properties, for three specimen types relative to each of the three phases [9]. The volumetric and mechanical properties of eleven mixtures across the United States, were analyzed at three different stages: design, production, and construction in order to correlate the pavement performance prediction to deviation at each stage. The volumetric properties considered in this study include gradation, AC, AV, VMA, VFA, aggregate bulk specific gravity, and mixture maximum specific gravity. Mechanical properties examined were axial dynamic modulus, Indirect Tensile Test (IDT), and HWTT.

The main process-based factors leading to variability investigated in this report were:

- Aggregate absorption
- Delay in specimen fabrication
- Return of baghouse fines
- Stockpile moisture content
- Aggregate hardness

The following conclusions were made, according to the experimental, statistical, and analysis of the evaluated mixture properties between phases [9]:

1. Significant deviations in volumetric properties such as AV, and VFA were caused by allowable gradation differences within state tolerance range.
2. As many agencies are considering performance-based specifications, HWTT was associated with the following conversion factors between different sample types:

- Conversion factor between design and production=1→No difference from laboratory mixed-laboratory compacted (LL) to plant mixed-laboratory compacted (PL).

- Conversion factor between design and construction= 0.75 → LL is 75 percent of plant mixed-field compacted (PF).
- Conversion factor between production and construction =0.75 →PL is 75 percent of PF.

  These conversion factors can indicate if the as-built mixture will be expected to meet performance indicators generated during the laboratory mix design phase. If the HWTT rut depth of a PF sample should not exceed 6 mm at 20,000 cycles, hence the rut depth of relative laboratory compacted specimen should not exceed 4.5 mm at 20,000 cycles based on the presented conversion factors.

3. According to a contractor survey, the contractors are succeeding at reducing the influence of process-based factors (aggregate absorption, baghouse fines, aggregate hardness…) on volumetric and mechanical characteristics, due to their own mixture adjustments based on their personal experiences.
4. The IDT modulus was equivalent to 80% of the modulus determined from axial testing. This difference was more evident at elevated temperature since the loading mode effect is more considerable at high temperatures.
5. The mechanical properties deviation, between three types of specimen, was primarily caused by the inconsistency of compaction effort and confinement conditions between laboratory and field compaction, rather than the process-based factors. Even at the same air void level, it was observed that field-compacted samples were significantly softer than laboratory-compacted samples.

6. According to the average difference among eleven national mixtures analyzed, this report recommended some tolerance ranges, however regional values shall be developed for more accuracy.

2.2 Balanced Mix Design (BMD)

Since the 1860s, the pavement industry has focused on achieving the ideal mixture by developing performance tests [1]. Accordingly, many research studies have been performed on binder modifiers, aggregates, mix types, compaction techniques and performance tests, as well as production and construction impact on mixture performance. In the late 2000’s the use of increased RAP and Reclaimed Asphalt Shingles (RAS), as well as some binder modifiers led to compatibility issues, poor durability and performance problems. Consequently, the BMD approach was established to evaluate rutting and cracking, by defining the OBC as in between the minimum binder content per cracking criteria and maximum binder contents per rutting criterion. There are essentially three types of balanced mix design as per NCHRP report for the Development of a Framework for Balanced Mix Design [10]:

1. Volumetric Design with Performance Verification
2. Performance-Modified Volumetric Mix Design
3. Performance Design

A few early examples follow, then a summary of current state practices is presented.

The Minnesota Department of Transportation (MnDOT) recently developed a BMD framework [11]. It follows much of the AASHTO M323, *Standard Specification for Superpave Volumetric Mix Design* in terms of the binder and aggregate selection, as well as use of the gyratory compactor and volumetric analysis with MnDOT tweaks. What is unique about it is that after identifying the asphalt content at 4 percent air voids (ACv) by volumetric analysis, specimens are prepared at the ACv, and the ACv ±0.5 percent and 7±0.5 AV for rutting and cracking performance testing. Samples are short-term aged at the defined compaction temperature for 2 hours for rutting tests, and long-term aged during 4 hours for cracking tests at relative compaction temperature.

Based on the performance test results and criteria, the selected binder content is defined as the balanced asphalt content (ACB) with allowable construction tolerances. A MnDOT study verified that the BMD approach was able to determine the influence of binder content on durability and stability for four test mixtures. This study suggested to redefining cracking and rutting performance criteria for different applications with varying traffic load, mix design, soil properties and climatic conditions. It also recommended that MnDOT introduce cracking tests into quality control and agency acceptance while monitoring field sections to validate the correlation between BMD criteria and field performance.

The effect of regressing air voids in mix design on cracking, rutting, and moisture damage resistance of asphalt mixtures was studied by Wisconsin Department of Transportation (WisDOT) [12]. Regressing air voids is a practice of selecting optimum asphalt content at an air void level less than 4 percent, such as 3 percent used by WisDOT. A total of six mixes with different RAP and RAS percentages were designed for various traffic levels. The Disc-Shaped Compacted Tension (DCT) Test was used to evaluate cracking resistance at low temperature, in conjunction with the Illinois Flexibility Index

Test (I-FIT) for cracking resistance at intermediate temperature, and the Hamburg Wheel Tracking Test to assess rutting and moisture susceptibility.

Regressing air voids led to an increase in asphalt content 0f 0.3 to 0.4 percent. This resulted in improvement in cracking resistance at intermediate temperature and a less significant impact on low temperature cracking as per I-FIT and DCT test, respectively. Although none of the six mixtures in this study showed any moisture damage in field sections, the HWTT results indicated that two mixes had stripping inflection points after 10,000 passes. The regression of air voids did not generate any rutting problems since all mixtures designed with 3% AV did not exceed the rut depth limit in HWTT.

This research indicated that regressing air voids can enhance cracking resistance without compromising mixture stability. WisDOT recommended a three-stage implementation strategy defined by: (1) full implementation of 3.0 % regressed air voids complemented by HWTT; (2) defining HWTT stripping and rutting thresholds according to traffic levels with provisions to add I-FIT; and (3) implementation of Balanced Mix Design without any volumetric criteria for mix design approval.

The Texas A&M Transportation Institute (TTI) performed a balanced RAP/RAS mix design and performance project for the Texas Department of Transportation (TxDOT) [13]. An analysis of RAP/RAS mix designs, techniques to improve cracking resistance and performance analysis of relative individual field project conditions on various test sections around Texas was performed. TTI reported that BMD method between rutting/moisture damage and cracking of RAP/RAS mixes can lead to similar or better performance than virgin mixtures. Development of project-specific mix designs considering factors affecting cracking such as traffic, climate, layer thickness and pavement structure was recommended. A RAP/RAS mix design and performance evaluation system for project-specific service conditions was proposed also. It included a balanced mix design and a performance evaluation system in which the HWTT and associated criteria are used to control rutting/moisture damage and the Texas Overlay Test (OT) and the required OT cycles determined from S-TxACOL cracking prediction with consideration of climate, traffic, pavement structure, and existing pavement conditions. The effect of softer binders on performance of RAP/RAS mixtures such as HWTT, OT cycles and engineering properties such as dynamic modulus was evaluated also. It was concluded that soft and modified asphalt binder will enhance the cracking resistance of RAP/RAS mixtures without jeopardizing the rutting/moisture damage resistance.

2.2.1 State Practice of BMD

The following section summarizes several state practice with regard to BMD [10]: California currently uses performance-based specifications coupled with a mechanistic empirical design approach when performing mixture designs for high-volume roadways. In total, seven projects have been constructed with this approach. Tests used on these projects include AASHTO T 320, *Standard Method of Test for Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST)*, AASHTO T 321, *Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending*, and AASHTO T 324, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures*. It should be noted that the performance testing is conducted on plant-mixture specimens subject to short-term aging and not on lab batched specimens.

Current Florida specifications require Asphalt Pavement Analyzer (APA) testing with a maximum rut depth of 4.5mm after 8,000 cycles. The APA test shall be performed during the mixture design phase and only on projects that are located in the Panhandle Region of the state. This is the case because the Panhandle Region of Florida experiences more rutting than any other region in Florida. Past research has also been done using the Flow Number (FN) and HWT tests to evaluate rutting. Additionally, the Indirect Tensile Test (IDT) energy Ration and OT tests have been conducted to evaluate cracking. These tests, however, are currently not implemented in the Florida DOT specification.

Current Georgia specifications require APA testing for moisture susceptibility. Based on climatic conditions and pavement location, the state of Georgia utilizes different testing temperatures. Moisture susceptibility of the asphalt mixtures is monitored though the TSR test. This test is important to the region due to stripping issues associated with the states aggregate source. Additionally, the HWTT can be conducted to evaluate stripping issues.

The current Illinois DOT specification uses a volumetric mixture design with performance verification. Mixtures are initially designed based on volumetric properties and tested for tensile strength. After completing the initial design, the mixtures are subjected to both cracking (I-FIT) and rutting (HWT) tests. At the start of production, a 300-ton test strip is constructed, and the listed performance tests are verified. Current research projects may dictate future index test thresholds. To date, the I-FIT test has a minimum index of 8.0 and the HWTT varies based on virgin binder grade.

Iowa currently uses the Superpave volumetric approach when designing asphalt mixtures, while also moving forward with the BMD approach. During the design, asphalt mixtures are subject to volumetric and HWT testing, which varied based on the traffic level, binder grade, and additives within the mixture. Traffic levels that are high or very high require more passes until the stripping inflection point than low traffic pavements and all samples must be short term aged prior to testing. Fatigue resistance of asphalt interlayers is also monitored with the Bending Beam Fatigue (BBF) test. Samples are subjected to 100,000 cycles with a micro strain of 2,000. This evaluates the resistance to bottom-up fatigue cracking within the pavement. The state of Iowa is also considering implementing a DCT test to evaluate thermal cracking potential of pavements.

Louisiana uses the HWTT to evaluate rutting resistance and the semi-circular bend test to evaluate cracking resistance. These tests are conducted alongside the conventional volumetric mixture design. The HWTT samples are short-term aged, while the Semi-Circular Bend (SCB) samples are long-term aged. Since the state of Louisiana typically does not encounter rutting issues, therefore the BMD approach generally leads to mixtures containing higher asphalt contents. In 2016 their specification was updated to include high and low volume roads with differing levels of design gyrations. This was done to increase the VMA and the Voids Filled with Asphalt (VFA) of the mixtures.

Minnesota currently uses the DCT test to evaluate low temperature cracking (thermal Cracking) within the pavement. Fracture energy requirements vary based on the pavement traffic level. Research is also underway to determine whether or not to conduct testing on plant produced or laboratory produced samples.

New Jersey uses the BMD approach for roughly ten percent of the total material produced each year. This design approach uses the traditional method of volumetric design, followed by performance testing. New Jersey conducts the APA, BBF, OT and TSR tests for performance. Each test has a different testing temperature, but all specimens are conditioned for two hours at compaction temperature prior to being compacted. All testing is conducted by the New Jersey (DOT). If the asphalt mixtures fail to meet the performance test requirements, the contractor must redesign the mixture.

New Mexico is currently only using the BMD approach for test sections of existing projects. The DOT wants to evaluate the performance of the mixtures prior to implementing any new mixture design approach. If implemented the plan is to develop a performance specification for the HWTT. This test would be used to evaluate mixture stripping and rutting potential. It is likely that different binder grades would be tested at varying temperatures.

Current mixture designs in Ohio utilize the APA test to evaluate mixture rutting for mixtures that do not comply with the fine aggregate angularity criteria. These mixtures are short-term aged for two hours at compaction temperature prior to compaction. Depending on the stress level of the pavement, different mixtures are required to resist varying rut depths after 8,000 cycles. For mixtures being placed on bridge decks, the BBF test must be conducted in addition to the APA test.

Oklahoma currently follows the Superpave volumetric mix design process and additionally requires the HWT and TSR tests. Preliminary specifications are currently being drafted for the implementation of the BMD Performance-Modified Volumetric Design. Before the specification can be drafted, field mixture performance must first be monitored and validated. Oklahoma plans to monitor performance of both mixture design and production samples using the HWT, I-FIT, Cantabro, and TSR tests. Short-term aging of the HWT and TSR tests will be conducted at compaction temperature for two hours. A long-term aging protocol for the I-FIT and Cantabro tests has yet to be determined.

South Dakota currently uses the Superpave volumetric mixture design method coupled with the APA and TSR tests. During production, the contractor will monitor performance though these tests and the agency will verify their results. APA testing is conducted at the PG high temperature of the binder and the TSR criteria is a minimum of 80 percent. Research is ongoing using the DCT and SCB tests to evaluate low temperature cracking.

Texas currently uses the Volumetric design with performance verification approach on a percentage of its premium mixtures. Once a volumetric design is completed, performance verification using the HWT and OT tests is conducted. Regardless of binder PG, HWT tests are conducted at 50 degrees Celsius. Additionally, samples for both performance tests are aged for two hours at compaction temperature prior to compaction. After 3 binder contents are evaluated, the optimum binder is selected where both HWTT and OT requirements are satisfied.

Current Utah mixture design processes follow the Superpave volumetric approach. The HWTT is additionally run on short-term aged samples to evaluate rutting and moisture resistance of the asphalt mixture. HWT test temperature is dictated by the PG high temperature of the asphalt binder. Consideration to include a BMD approach is currently underway. Utah is investigating the use of mixture specimens in the bending beam rheometer for low temperature cracking. The DOT is also investigation the use of the I-FIT test to evaluate mixture performance at intermediate temperatures. Thresholds for these tests are yet to be determined.

On pilot projects within Wisconsin, the State has developed specifications for the HWTT, SCB, DCT, TSR, and extracted binder analysis. It is important to note the agency has implemented these mixtures that contain more than 25 percent RAP and lower design air void level of 3.5 percent on the pilot projects. Short-term aging of 4hr at 135 degrees Celsius is done on HWTT samples and long-term aging of 12 hours at 135 degrees Celsius is done on the DCT and SCB loose mixture samples. These specifications have been implemented on some projects at the city level, as well as the pilot projects. Further testing is being done using the FN and I-FIT tests, but no specifications have been developed yet. The HWTT is used to evaluate moisture susceptibility and rutting, while the DCT and SCB tests are used to evaluate low temperature and intermediate temperature cracking, respectively.

2.2.2 FHWA Pavement Engineered Program (PEP)

Managed by the Federal Highway Administration (FHWA), in coordination with state highway agencies, academia and industry, the FHWA Pavements Program aims to design flexible and rigid pavements at a high level of safety and cost effectiveness with durable long-term performance. Therefore, the FHWA currently considering the Performance Engineered Pavements (PEP) concept, which aim to include long term pavement performance into all project phases: starting with structural mix design, to mixture design, followed by the construction and finally the materials acceptance specifications. It is illustrated int Figure 6. The PEP concept is applicable for flexible as for rigid pavements and focuses on optimizing pavement materials and structure with respect to traffic load and climatic conditions. Therefore, FHWA has been publishing information about PEP design and accepting specifications, in addition to the current development of FHWA software and informational guidance for Performance Related Specifications (PRS) [14].

The pavement community is interested in including pavement performance into design and acceptance, since federally funded agencies are looking forward to meet the performance targets according to the Transportation Performance Management (TPM) of the nation’s highway. All distress mechanisms can be truly evaluated when the materials selection, mixture design, and acceptance specifications are linked to pavement performance. Therefore, mixture components can be optimized to expected load level and climatic conditions, based on performance testing in the mix design process. As well, mixture components including modified asphalt binders, recycled materials percentages, and other new products could be adequately assessed through performance testing. Subsequently, integrating performance in the construction phase and the agency Quality Assurance (QA) program will guarantee meeting the design expectations at a certain tolerance level. The Performance-Engineered Mixture Design (PEMD) comprises an engineering analysis of asphalt or concrete pavement with respect to pavement design specifications and performance lifecycle.

The main goals of the PEP concept are to:

- Ensure the long-term durability and high-performance level of the nation’s roadways.
- Stimulate the agencies to conduct specific performance tests according to the prevalent distresses encountered within the network.
- Minimize the agency’s risk when incorporating recycled materials into pavements.

- Emphasize on the contractor’s innovation during the materials selection and mix design.
- Evaluate design performance during production.
- Reduce user delays and safety exposure from major pavement repairs.

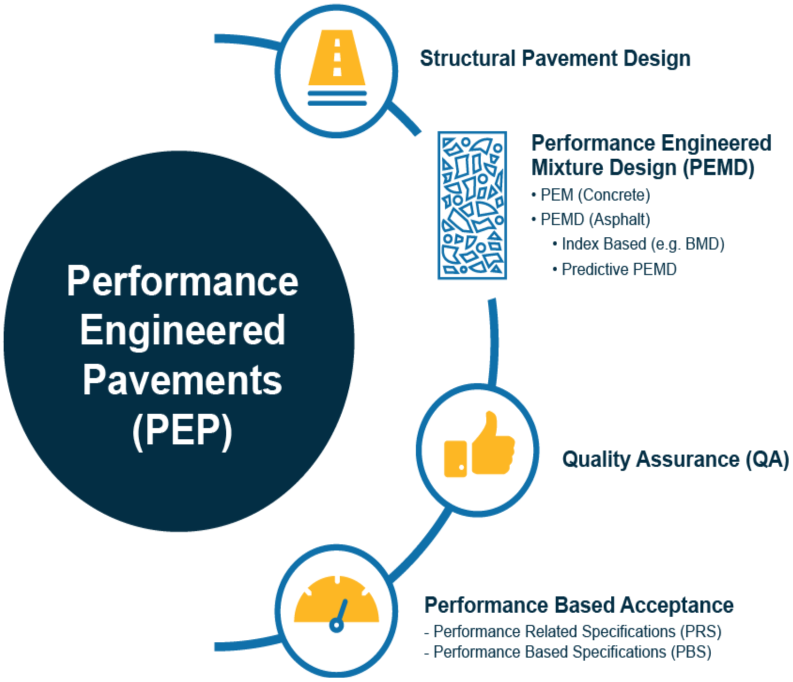


Figure 6: Performance Engineered Pavements[14]

For flexible pavements, the PEMD has two approaches:

- The predictive approach based on performance tests with Mechanistic-Empirical (ME) prediction models.
- The index-based approach which predicts the long-term performance independently of ME modeling, known by many states Department of Transportation as the Balanced Mix Design.

Conventional mixtures designed per volumetric properties alone, cannot ensure high performance levels especially when it comes to modern mixtures with additives, polymers, and recycled materials. The PEMD method supplements conventional mix design, with performance testing to evaluate multiple failure mechanisms with respect to the subjected traffic, climate, and aging conditions. The main target of PEMD is to optimize the mixture components (binder and aggregates) to achieve the required performance of many distresses for project specific conditions.

For rigid pavements, the Performance Engineered Mixtures (PEM) aims to evaluate concrete durability with the aim of avoiding early roadways failure. The durability assessment is based on many parameters such as strength, cracking, freeze-thaw resistance, aggregate durability, and permeability.

The appropriate application of PEP requires meeting the performance criterion during the design process, and the construction activities during the production phase. Hence, the performance characteristics shall be implemented into the agency's QA program, which includes the agency acceptance and the contractor's QC testing. The QA program can include incentives and disincentives added to the performance testing to ensure better production quality. However, incorporating performance at the acceptance level will require defining the agency and contractor responsibilities, performance test frequencies and acceptance limits, and determine if the performance tests will be used in a performance predictive approach or in an indexed based (go – no go system).

The Performance Related Specifications (PRS) comprise QA specifications that define required quality characteristics such as permeability of rigid pavements or AV % in flexible pavements, which can be measured during construction and help predict pavement performance. According to the predicted difference between the as-designed and the as-constructed expected service life from ME modelling, the PRS applies the calibrated predictive ME performance models to assign rational pay adjustments.

Many efforts have been recently emphasizing to implement PEMD at the mix design and acceptance level, along with performance test procedures for prevalent distresses such as: rutting, cracking, and moisture damage. Interestingly, this significant effort indicates the pavement industry's interest to complement or even replace volumetric properties with the mixture performance during the mix design and acceptance processes. Moreover, the FHWA has been focusing mostly, on implementing performance tests into acceptance standards, which could help lead to further adoption the PRS program for acceptance and pay factors. The performance related specifications will provide a well-defined understanding of performance and the risk associated by adjusting the paying factors to the real constructed product.

As mentioned earlier, the PEMD has two different approaches:

1. The predictive PEMD which addresses a wide range of pavement distresses and aims to enhance pavement performance based on mechanistic response models. The mechanistic models, which comprise mechanistic-oriented parameters, can predict future pavement performance and denote the acceptance basis for a PRS. The performance testing conducted, address several failure mechanisms at a specified expected traffic, climate conditions, location of the mix within the pavement and mixture aging conditions.
2. The second index-based approach, which is generally known as the Balanced Mix Design, relies on index parameters from performance testing as well. However, the

BMD focuses on balancing the conditioned sample behavior with respect to the most critical and contradictory distresses: rutting and cracking. A correlation between the index parameters and relative field performance should be verified before including the pavement performance into design (go/no-go) and acceptance.

2.2.3 FHWA Index Based PEMD State of the Practice

A draft AASHTO Standard Practice for Balanced Design of Asphalt Mixtures was presented in NCHRP Project 20-07/Task 406. The scope of AASHTO draft standard is to develop four approaches for BMD methodology or index-based PEMD based on mixture volumetric properties and/or performance-based test results per the flowcharts shown in Figure 7 and Figure 8 [15].

- **Approach A, Volumetric Design with Performance Verification**: This approach states that the optimum binder content should meet the volumetric requirements of AASHTO R35, *Standard Practice for Superpave Volumetric Design for Asphalt Mixtures*, as well as performance set criterion.
- **Approach B, Volumetric Design with Performance Optimization**: Similarly, to Approach A, this approach starts by selecting the optimum binder content according to AASTHO R35, then performance tests are conducted at the preliminary OBC and few additional binder contents until meeting the required performance.
- **Approach C, Performance-Modified Volumetric Design**: This approach relies initially on AASHTO R35 just to define the preliminary aggregate structure and OBC. Moreover, mixture components such as OBC and aggregates can be adjusted

based on performance tests results. Hence, the final mix design could be out of Superpave volumetric specifications.

- **Approach D, Performance Design**: The preliminary binder content and aggregate gradation are selected according to the Long-Term Pavement Performance (LTPP) software and AASHTO M323, *Standard Specification for Superpave Volumetric Mix Design*, respectively. Afterward, mixture components are defined by the performance test results, and volumetric properties could be reported just for information purposes.

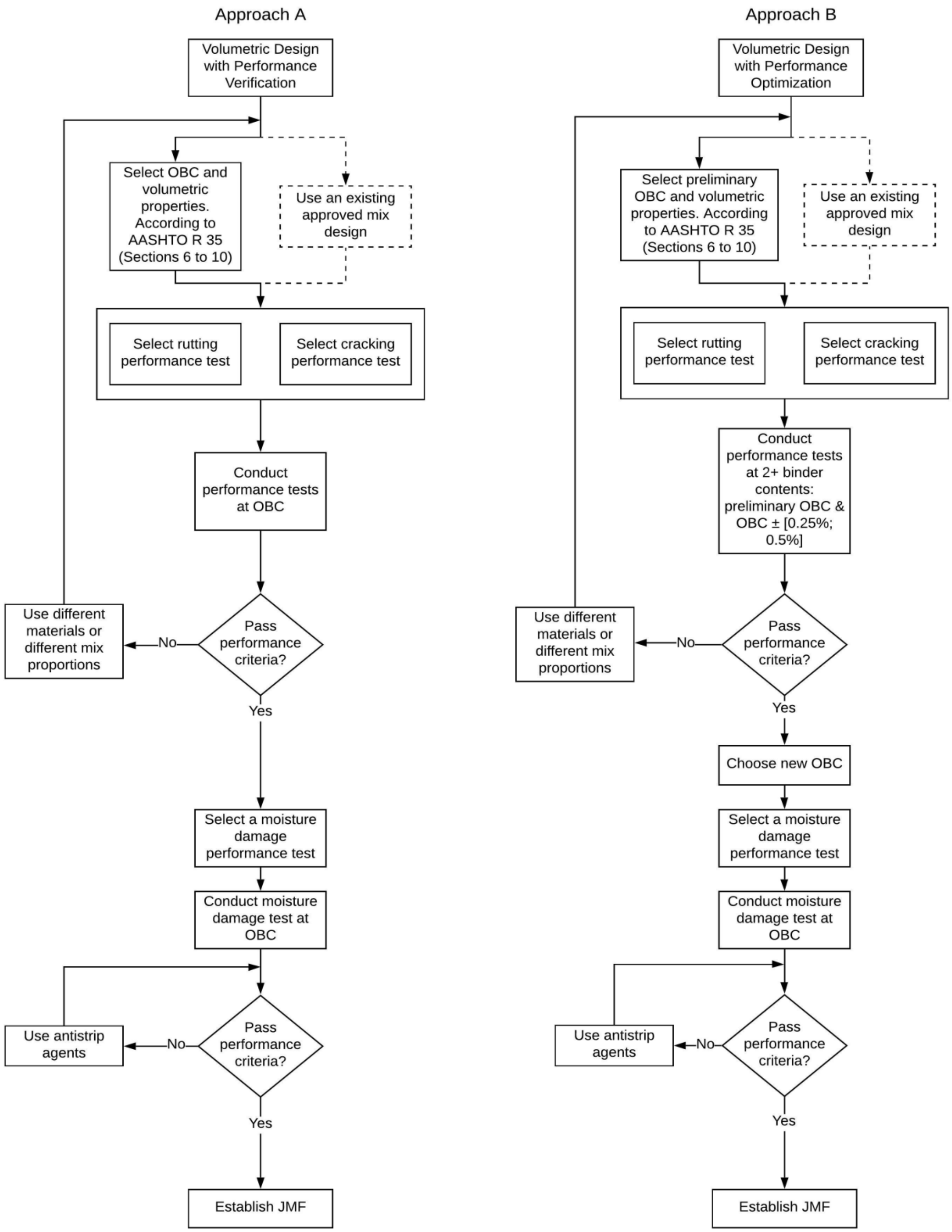
The performance tests criteria, with adequate correlation to field performance, represent the key component for a successful implementation of the index-based PEMD approach. Furthermore, these performance criteria should be set with respect to several parameters such as: expected traffic level, local aggregates quality, project climatic conditions, aging conditions location of the mixture within the pavement, etc.

This report recommends a five-step procedure to select the appropriate performance tests in an index-based PEMD methodology as following:

- **Step 1**. Determine the most critical failure mechanisms to be considered, based on common field distresses, mix design, and the project application (new construction, rehabilitation, recycling).
- **Step 2**. Define suitable performance tests, that can adequately evaluate the mode of distresses identified in Step 1.
- **Step 3**. Evaluate the general applicability of the candidate performance tests from Step 2, in terms of sample preparation, testing training requirement, equipment cost,

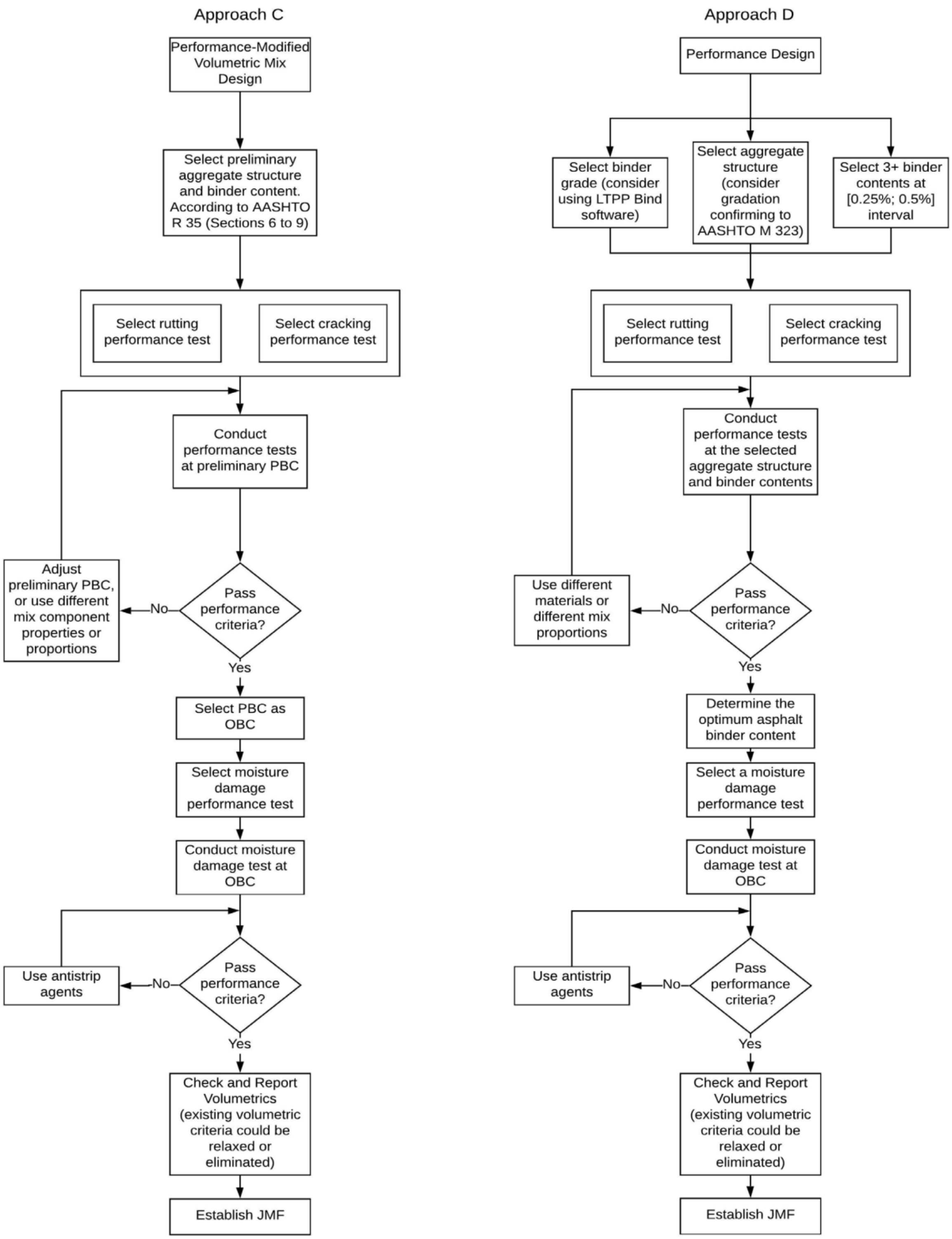
field correlation, sample conditioning, repeatability. Consequently, a single performance test will be selected to evaluate relatively each mode of distress.

- **Step 4.** Analyze if the selected performance test is ready to be fully implemented, based on the nine essential steps recommended by NCHRP Project20-07/Task 406: (1) draft test method and prototype equipment; (2) sensitivity to materials and laboratory measured properties; (3) preliminary field performance correlation; (4) ruggedness experiment; (5) commercial equipment specification and pooled fund purchasing; (6) interlaboratory study (ILS) for precision and bias; (7) robust validation of the test to set criteria for specifications; (8) training and certification; and, (9) implementation into engineering practice.
- **Step 5**. Assess the impact of the performance tests implementation on the SHA and the contractor as well, including: the risk associated with index-based PEMD during mix design approval and construction quality assurance, properties discrepancy between mixtures designed as per previous specifications and mixtures designed as per index-based PEMD, the additional effort and time associated with the index-based PEMD method and establishing appropriate criteria for index parameters.



Notes: OBC = optimum asphalt binder content; PBC = preliminary asphalt binder content; JMF = job mix formula

Figure 7: State-of-the Practice for Index Based PEMD Approaches A&B[15]



Notes: OBC = optimum asphalt binder content; PBC = preliminary asphalt binder content; JMF = job mix formula

Figure 8:State-of-the Practice for Index Based PEMD Approaches C&D[15]

2.2.4 Cyclic Fatigue Index Parameter (S_{app}) for FHWA Asphalt PEMD

Considering that fatigue resistance is one of the most critical parameters in designing asphalt mixtures, in August 2019 the FHWA presented a cyclic fatigue index parameter determined using the Asphalt Mixture Performance Tester, along with index threshold values [16]. The fatigue parameter known as "Sapp", can be determined from the cyclic fatigue tests using 100-mm diameter specimens (AASHTO TP 107, *Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test*) or 38 mm diameter small specimens (AASHTO TP 133, *Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using Small Specimens in the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test*) cored and cut from gyratory-compacted samples. Subsequently, Sapp will be calculated by importing these tests results into the FlexMAT™ program (available from FHWA), and hence presents a genuine fatigue cracking indicator in performance engineered mixture design (PEMD). The tests are conducted at the average temperature of the high and low performance grades, as per LTPPBind Online at the project location, minus three degrees Celsius.

The simplified viscoelastic continuum damage (S-VECD) model is used to characterize the mix fatigue resistance, based on material properties loaded into pavement structural analysis and long-term performance evaluation. However, engineers may require an index parameter that can promptly characterize the fatigue characteristics, rather than a detailed structural analysis. Consequently, the Sapp parameter was developed and comprises many of the S-VECD model perquisites. The Sapp parameter can assess the fatigue damage that a material can handle at a certain load level, according to the material stiffness and relative modulus. The parameter threshold values shown in Table 5, were established based on the evaluation of 105 mixtures, including polymer-modified mixtures, different warm mix asphalt (WMA) technologies, and HMA at different RAP percentages [16].

These thresholds limits were set according to the correlation between Sapp values and the pavement performance outcome of field sections, test roads, test tracks, designed traffic level, numerical performance simulation, and general performance feedback from state highway agencies. However, these values can be refined for local considerations (materials and climatic conditions) for a better correlation to cracking resistance. Since a high fatigue resistance is designated by an increased Sapp value, the limits of Table 5 can estimate the allowable traffic level with respect to equivalent single-axle loads (ESALs).

Table 5: Recommended Threshold Values for Sapp [16]

Traffic (million ESALs)	*Sapp* Limits	Tier	Designation
Less than 10	*Sapp* > 8	Standard	S
Between 10 and 30	*Sapp* > 24	Heavy	H
Greater than 30	*Sapp* > 30	Very Heavy	V
Greater than 30 and slow traffic	*Sapp* > 36	Extremely Heavy	E

It is worth mentioning that Sapp was put through a sensitivity analysis with respect to compaction effort, aging conditions, and mixture components such as binder content, RAP content, aggregate gradation, and other factors. Based on the mechanistic S-VECD theory, the cyclic fatigue index parameter helps with predicting long-term pavement performance, comparing different mixtures, and indicating the appropriate traffic level and project location for the tested sample.

2.3 Hamburg Wheel Track Test (HWTT)

The Hamburg Wheel Track test was selected to evaluate the rutting performance of the mixtures in this research study. This test is used widely across the United States and many other parts of the world. Ten states currently use the test to evaluate both rutting and moisture susceptibility of mixtures [10]. Important testing conditions outlined in AASHTO T324, are listed below [17]. Test temperature was added to the list and was selected after a close evaluation of DOT specifications currently using the HWTT. States with similar climates to Reno were heavily weighted when deciding what temperature to use.

- Test Temperature 50^{o}C for PG 64 binder
- Short-term aging on loose mixture: 4 hours at 135°C as per AASHTO R30, *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)* [18]
- Target air void content 7 ± 0.5%
- 150 mm diameter, 60 ± 2 mm height specimen
- Load on the wheel 705 ± 4.5 N

Testing thresholds were also chosen based on current DOTs using the test. DOTs that utilized the same performance graded binders as Reno received the most amount of consideration. Maximum rut depth and number of cycles to failure were the two performance test thresholds defined. The states that received the most amount of consideration were California, Illinois, Oklahoma, and Texas. The rut depth used for each of those states was 12.5mm [10]. The minimum number of passes to failure ranged from 7,500 to 15,000. A higher value was selected as the minimum threshold with the intent of creating a more rut resistant mixture.

The selected criteria are:

- Maximum rut depth 12.5mm
- Cycles to failure 20,000

Below are additional advantages to using the Hamburg Wheel Track Test:

- Test Equipment: the main equipment costs are the Hamburg Wheel-Tracking Device and a saw to cut the specimens. Together these pieces of equipment are less than most machines that evaluate rutting. Because the Gyratory Compactor is commonly used by many DOTs, its cost was not considered in the evaluation.
- Practicality: operation of the equipment is relatively strait forward because there are not many steps involved with testing. Total cuts that need to be made per test is 2, which few compared to other rutting tests.
- Repeatability: the coefficient of variation (COV) ranges from 10-30%. Compared to other rutting tests such as Flow Number, > 30% COV, this is relatively low.
- Correlation to field performance: the test is appropriately correlated with field rutting and stripping issues.

2.4 Ideal Cracking Test (Ideal-CT)

The Indirect Tensile Asphalt Cracking test was selected to evaluate the cracking susceptibility of different mixtures. This test was chosen because it is the only cracking test that could potentially, practically, be implemented for mix design, QC, and acceptance during production. The Ideal-CT was originally designed to examine the cracking resistance with the use of recycled materials within the mixtures and has been correlated with current cracking tests. Testing conditions were selected based on the American

Society for Testing and Materials (ASTM) standard D8225-19, *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature* and listed below [19]:

- Test Temperature: 25°C
- Specimen Size: 150mm diameter x 95mm height
- Indirect Tension: 50 mm/min
- Freeze/thaw cycles No: 0 and 1 cycle
- Short term aging on loose mixture: 16 hours at 60℃, or 4 hours at 135°C as per AASHTO R30, *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)* [18]
- Long term aging on compacted mixture: 5 days at 85°C [18]
- Target air void content 7 ± 0.5%

Below are additional advantages when using the Ideal-CT versus other cracking tests:

- Simplicity: no cutting, gluing, drilling, or notching is required. This significantly reduces sample preparation time and cost, as well as the amount of operator error involved with testing.
- Practicality: the test requires minimum training for routine operations. Additionally, if the operator knows how to run tensile strength specimens, there is little to no training at all.
- Efficiency: the test can be completed within 1 min. After compaction and aging take place results can quickly be evaluated.

- Test equipment: the testing equipment involved in breaking the samples costs less than $10,000. This is significantly lower compared to many other cracking tests.
- Repeatability: coefficient of variation (COV) is less than 20 %.
- Sensitivity: sensitive to changes in asphalt binder as well as recycled materials, which is applicable for this study with 15% RAP.
- Correlation to field: limited, but positive correlation with field cracking.

2.5 Ideal Rutting Test (Ideal-RT)

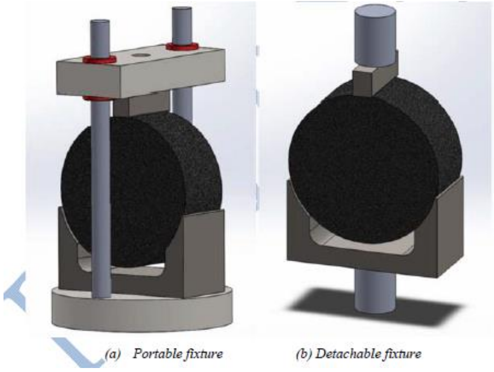
Since 1920, asphalt industry has been focusing on improving asphalt mixture rutting resistance for better pavement performance and road safety. Due to the limitations of historical rutting tests, an effort was undertaken to develop the Ideal Rutting test (Ideal-RT) for mix design purposes, as well as QC and acceptance testing [20]. The target of this implementation is to provide along with the Ideal-CT, a simple and practical performance-related rutting test for the BMD approach and quality assurance. The Ideal-RT exhibits a high correlation with the most common rutting tests adopted: Hamburg Wheel Track Test and the Repeated Load Permanent Deformation Test.

Interestingly, a good correlation was noticed as well between the Ideal-RT and the field rutting performance data from WesTrack, MnRoad, and Texas test sections. The Ideal-RT is a very efficient and practical test that can be done in less than two minutes, without any special instrumentation or sample preparation (coring, cutting, gluing, ets.). The test is conducted with an ideal shear fixture under a loading rate of 50 mm/min on gyratory compacted cylindrical specimens (150 mm diameter and 62 mm or other heights), at the relative high temperature. As well, this test is characterized by a coefficient of variance less than 5% within 3 replicates for most mixes. Additionally, this test is sensitive to many volumetric properties and mix components such as aggregates type, binder type and content, air voids and amount of recycled materials [20].

The main desirable characteristics of the Ideal-RT are:

- Simplicity: no requirement for instrumentation, coring, cutting, or notching samples.
- Efficiency: test completion within 2 min.
- Practicality: applicable for both laboratory samples and field cores with minimal training.
- Low cost: minimum cost to modify existing test equipment. The same indirect tensile strength test equipment or any other loading frame (such as MTS, UTM, or Interlaken) can be used for the Ideal-RT.
- Repeatability: small coefficient of variation (COV).
- Sensitivity: sensitive to asphalt mix components (in terms of aggregate, binder, recycled materials), air voids, and aging.
- Manifesting rutting mechanism: this test is a shear-based test and rutting is caused mainly by shear stress.
- Good correlation with field rutting performance: relatively strong correlation with measured field rutting performance associated to the new suggested rutting parameter.

The Ideal-RT aims to simulate shear stress to the test sample, in order to manifest the shear rutting mechanism as shown in Figure 9. There are two forms developed of the new ideal shear rutting fixture: portable and detachable shear fixtures. This new shear rutting fixture proposed is inspired by the 3-point bend beam test in terms of shearing feature, and by the Ideal-CT in terms of simplicity and practicality, however it is different from both of these tests in terms of how the stress is induced. The main alteration from the Ideal Cracking test is the stress distribution within the sample, due to the extra bottom supports added for the Ideal-RT. Ideal-CT has 1 bottom support, whereas Ideal-RT has 2 bottom supports as shows Figure 10. In a nutshell, the rutting resistance of asphalt mixes can be assessed now through an easy and fundamental manner of shear rutting mechanism applied on simple test specimens.



(a) Portable fixture

(b) Detachable fixture

Figure 9:Two Types of Ideal Shear Fixtures

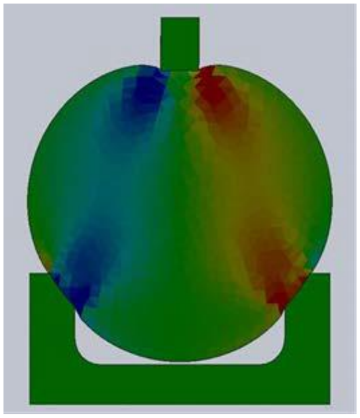


Figure 10: Shear Stress Distribution Within Ideal-RT Specimen [21]

Similar to the HWTT and Asphalt Pavement Analyzer, the Ideal-RT in conducted at the same high temperature selected, with a loading rate of 50 mm/min. The diameter of cylindrical specimen tested can be either 100mm or 150mmm, whereas the height can vary between 38, 50, 62, 75 mm, etc. It should be noted that the cylindrical samples prepared for mix design and acceptance testing shall be at 7±0.5 percent air voids. The typical Ideal-RT result curve is represented in Figure 11, in addition to the three deformation stages.

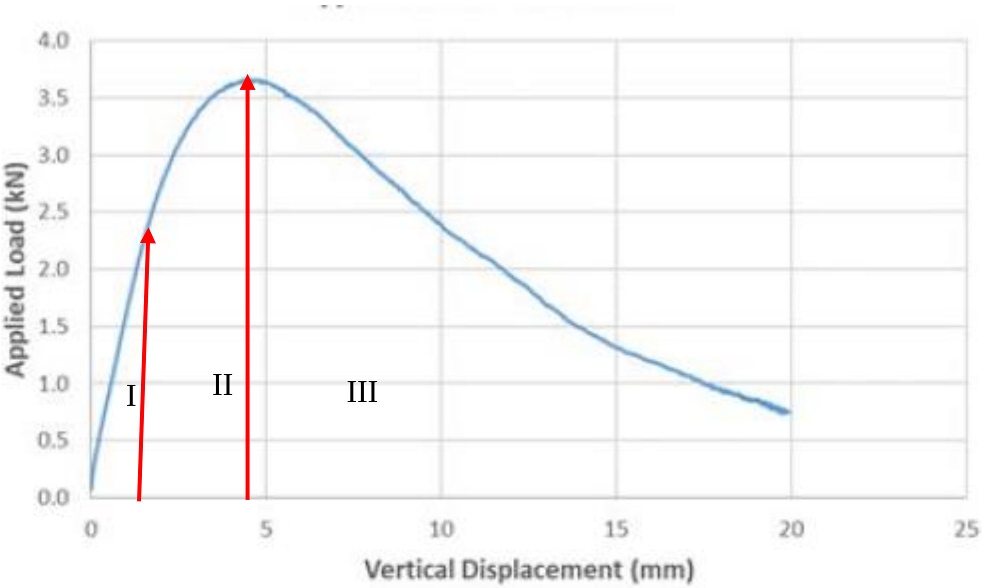


Figure 11: Ideal-RT Result

The analysis of the load displacement curve in Figure 11, can be divided into three stages:

- **Stage I Damage free stage**: At this initial phase, the specimen tested is free of damage and the load is increasing proportionally to measured displacement. These observations indicate that the sample deformation is within the elastic or viscoelastic range.

- **Stage II−Deformation damage stage**: The deformation at this stage indicates some damage induced to the sample, therefore a higher deformation was perceived comparing to the previous stage under the same load, however the specimen is still able to carry the applied load with a higher rate of deformation. This second phase known as “strain hardening” where the sample enters the plastic or visco-plastic stage, endured until the peak load is observed in the curve.
- **Stage III−Crack damage stage**: This “strain softening” phase is mainly characterized by a visible crack and load decreasing right after the peak load.

Since the rutting mechanism is concerned with the permanent deformation, the rutting parameter for the test is selected based on the load-displacement curve up to the peak load, where the damage manifests in the form of high deformation under the same load. Consequently, the rutting parameter corresponds to the shear strength based on the measured peak load. The rutting resistance of asphalt mixtures increases proportionally to the estimated shear strength.

According to the analytical solution of the specimen stress distribution, the maximum shear stress (equivalent to 0.356 x contact stress) at the peak load, is equal to the shear strength of the sample. The viscoelastic properties highlighted in Stage I, and the permanent deformation highlighted in Stage II are both included in the shear strength, which justifies the fact that shear strength is a reliable parameter to assess rutting. In addition, the shear strength has been historically endorsed as a rutting parameter for mix design and rutting performance models.

Chapter 3. Design Approach and Methodology

3.1 Review of Project Phase I

This research study divided into two phases, aimed to implement the BMD method and develop a guide to assist the Washoe County Nevada, RTC with this implementation. Phase I focused on finding a correlation between the number of blows applied with the Marshall hammer and the number of gyrations with the Superpave gyratory compactor for mixes commonly used in Northern Nevada. This was important since RTC has historically used the Marshall method. Eight mixtures were evaluated with performance tests to validate the relationship observed and develop a guide for the RTC to implement the Superpave mix design method were all considered [22].

Materials for eight different mixtures including virgin aggregate, binder, and reclaimed asphalt pavement (RAP) were sampled from the three producers in the Reno-Sparks area. The producer mix designs were verified, the number of gyrations correlating to Marshall blows were determined, and performance tests were ultimately conducted on gyratory compacted specimens to validate the correlation. Moreover, plant mix from the same producers was sampled to verify if the density of the plant produced mix was similar to laboratory mix densities, and for performance testing [22].

The majority of densities for the field mix laboratory compacted samples were found to be higher than the mix design target densities, which lead to the conclusion that changes from laboratory mix design to plant production caused these variations. In addition, the number of gyrations needed to reach the same density of the compacted Marshall samples and the mix design target air voids on the plant produced materials did not present a clear trend among the mixes. However, the number of gyrations for mixtures incorporating PG 64-28NV binder were close to the mix design Marshall blows, to reach the same density for the plant produced mix. The optimum asphalt content found in the University of Nevada Reno (UNR) laboratory was close and sometimes equal to the producer, but the gyrations number of the laboratory produced mixtures, to reach the same optimum asphalt content was determined to be lower than the minimum compaction level in the AASHTO R35 [23]. For these mixes, the locking point was not reached under the number of gyrations required to obtain the same optimum asphalt content observed using Marshall mix design method.

Mixes with PG 64-28NV binder were compacted at 50 gyrations to find the optimum asphalt content. The optimum asphalt content from the Marshall Mix designs were higher as expected. Observed differences in optimum asphalt contents between the Marshall and Superpave methods were 0.5% to 1.5%, with the optimums for the Superpave method always being lower than for the Marshall method. Volumetric properties of these mixes were evaluated and for some the VMA did not meet the requirements at the design air void level of 4%. This indicates that when using 50 gyrations, the gradation needed to be adjusted for those mixtures to meet all Superpave volumetric criteria. Interestingly the volumetric properties for Superpave designed mixtures at a design air void level of 3% air voids met the specifications.

The performance tests completed were dynamic modulus, tensile strength ratio (TSR), Hamburg Wheel Track Test (HWTT) and Ideal-CT. The first two, were performed on field mix and laboratory mix specimens. The dynamic modulus was similar for both laboratory and field produced mixes. The TSR results showed higher values for some laboratory mixes; however, it was possible to determine that the compaction method does not significantly affect TSR. The Ideal-CT and HWTT were evaluated on the field mix and it was recommended to correlate the results with field performance.

Determining a number of gyrations that correlates to 50 and 75 blows with a Marshall hammer for Laboratory Mixed Laboratory Compacted (LMLC) and Field Mixed Laboratory Compacted (FMLC) sample types revealed the compaction sensitivity to combined mixture variables such as mix type, binder type, and NMAS. Additionally, the conclusions below were drawn following the analysis study for the Project Phase I:

- The gyrations required to obtain similar densities and asphalt contents to those observed with the Marshall method for both FMLC and LMLC samples were significantly different.
- Comparison of Marshall and gyratory compaction data showed the number of gyrations required for LMLC specimens ranged between 25 and 36, which is lower than the minimum specified in AASHTO R35. The literature indicated similar observations have been found across the country but have not been implemented as most agencies use a minimum of 50 gyrations.
- The locking point was not reached for LMLC samples which were compacted to 50 gyrations.
- Compaction effort is dependent on the variables that compose the mixture, but no clear relationship was found between mix type, NMAS and/or producer.
- The compaction effort in one gyration is greater than one blow of a Marshall hammer.

- Marshall Compaction results in greater specimen variability in Gmb, thus %AV, and VMA comparing to Superpave compaction. The compaction hammer with its manual operation, and smaller sample size contributes to the higher variability.
- Mixes compacted to 50 gyrations with a target air voids level of 4% did not meet the Superpave VMA and DP specifications. This means the gradation of the aggregates must be adjusted in order to meet the volumetric requirements.
- Significantly lower optimum asphalt contents were observed for mixes compacted with 50 gyrations compared to 50 and 75 Marshall blows. However, the Superpave volumetric requirements were not met at these lower asphalt contents, thus requiring that gradations be adjusted to fulfil adequate VMA and acceptable DP which is achievable.
- The gradation of mixtures used in this research should be adjusted to produce mixes fulfilling the Superpave volumetric requirements under 50 gyrations.
- Transition to the Superpave mix design method with a single N_{Design} level of 50 gyrations was recommended, though it should be validated with performance testing prior to implementation.
- The RTC Orange Book acceptance criteria should be revised to include asphalt content, gradation, and DP to have better control of the final produced mixtures.

3.2 Experimental Design

The design analysis adopted in the Project Phase II, was based on the balanced mix design approach, while considering both requirements for the volumetric properties and performance thresholds. This followed approach known as “Volumetric Design with

Performance Verification," states to select the OBC based on Superpave volumetric specifications. Subsequently, the mixture performance shall be verified to meet the set criterion at selected OBC, otherwise the mixture components shall be adjusted to meet both volumetric properties and performance requirements. Accordingly, an iterative process may be required to reach the optimum mixture components, meeting performance testing protocols and volumetric properties simultaneously. This specific perspective of the balanced mix design methodology may require more effort during the mix design process. However, it affords the mix designer the opportunity to optimize the OBC and ensure high durability and rutting resistance. Throughout this research project, the primary mix design practices followed were:

- Limit the mixture components to locally available materials and sources in Northern Nevada.
- Marinate the virgin aggregates with hydrated lime as per field marination process of 48 hours prior to mixing, stated by Nevada Department of Transportation (NDOT) [24].
- Design common mixture types used in Northern Nevada with 12.5 mm and 19 mm NMAS within Superpave control points, also meeting RTC Orange Book specifications for Type 2 and Type 3 mixes [25].
- Start the mix design process following the Superpave mix design using the gyratory compactor, highlighted in AASHTO M323 and AASHTO R35([7], [23]).
- Limit the compaction effort to 50 gyrations for all traffic levels, as per the Phase I findings [22].

- Meet Superpave volumetric properties including VMA, VFA and limit the total aggregates passing #200 sieve to meet the dust proportion, while including the added lime with 87% p200 in the blend gradation.
- Include 15% RAP in all designed mixtures, relative to common recycling percentages adopted by RTC.
- Use performance tests that could be implemented in practice. Thus, the HWTT was selected to assess the rutting performance, the Ideal-CT test for cracking long-term performance and the TSR test to evaluate stripping resistance.
- Long-term aging of cracking test specimens, for an adequate assessment of long-term durability.
- Include the Marshall Stability test as an additional verification step for the transition process from Marshall to Superpave mix design methods.

Considering that poor durability is the primary driver of asphalt pavement distresses in Northern Nevada, the long-term cracking resistance was evaluated with the Ideal-CT test by means of fracture energy index. The rutting resistance was assessed through the HWTT based on rut depth criteria of 12.5 mm after 20,000 cycles. Additionally, TSR was included due to a long history of better success with it than other stripping tests with the local aggregates. These tests are easy to perform, require little sample preparation, have relatively low variability, and have low initial equipment costs.

3.3 BMD Flowchart

The main target of the BMD approach followed during this study, was to achieve a durable and stable mixture without jeopardizing the volumetric properties, as illustrated in the flowchart of Figure 12.

1. The initial step in the flowchart includes selecting appropriate materials in terms of binder grade and RAP amount as per local considerations of the project.
2. The gradation type shall meet Superpave broadband specifications presented in AASHTO M323 relative to each NMAS [7]. Additionally, the aggregates for asphalt mixtures shall conform to the applicable requirements of Table 200.02.03-I stated in RTC Orange Book specifications [25].
3. Following 48 hours margination with hydrated lime, the mix shall be designed as per the conventional Superpave mix design method, in order to determine the OBC at 4% air voids. The volumetric properties of the mixture at OBC, shall be within Superpave limits set for VMA, VFA, and DP presented in AASHTO M323, otherwise the aggregate structure must be redesigned and evaluated again [7].
4. Once the volumetric properties are met (OBC determined), the mixture must be evaluated with the following performance tests: TSR, HWTT, Ideal-CT (short-term conditioned, short-term unconditioned and long-term aged), and Marshall stability test.

5. If the performance results at OBC conform to the criteria limits, the final job mix formula (JMF) can be generated correspondingly. Otherwise the aggregate skeleton shall be restructured, and the mixture must be redesigned to meet Superpave volumetric properties as well as performance test requirements at the observed OBC.

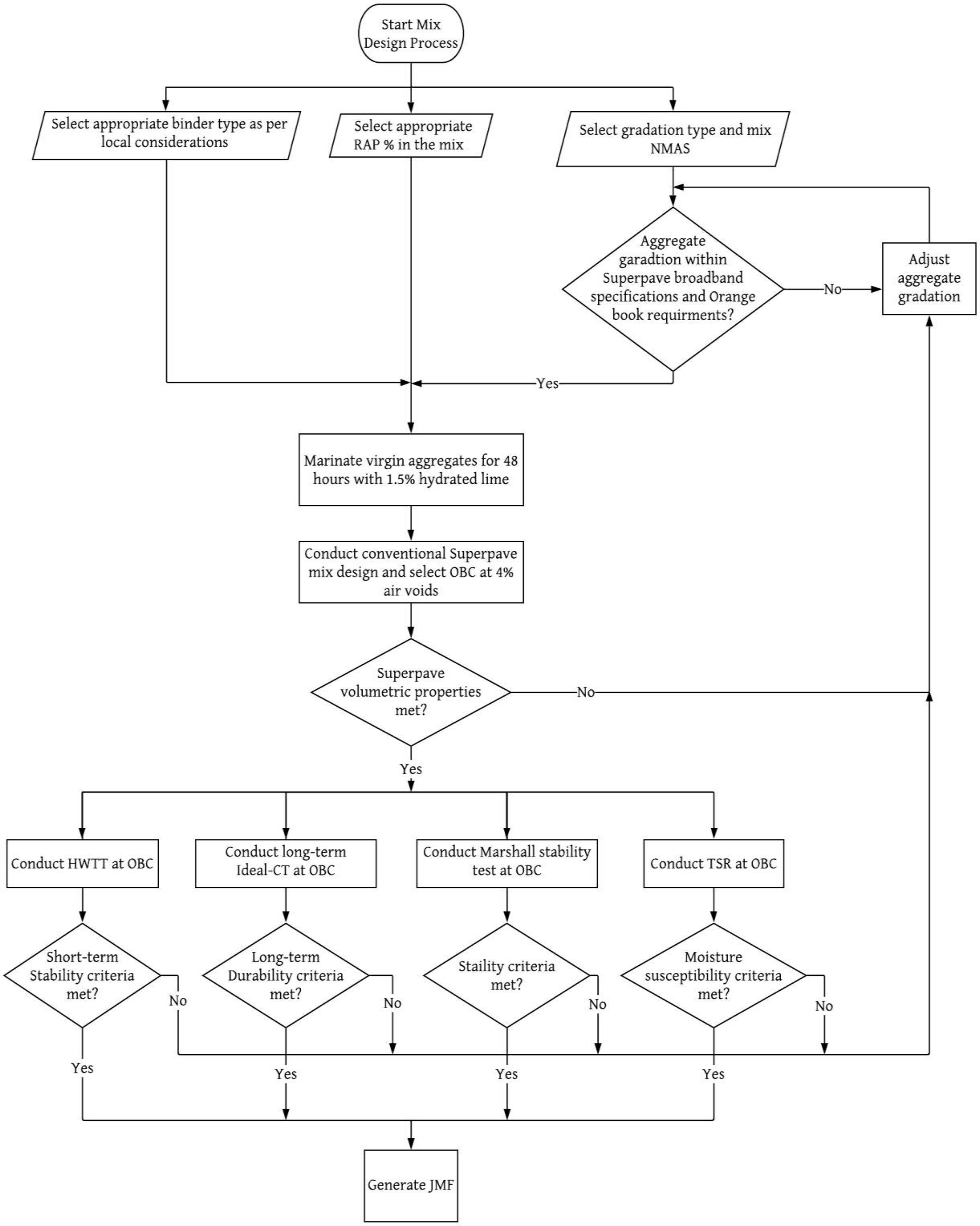


Figure 12: BMD Flowchart

Chapter 4. Materials Selection

The purpose of the material selection process was to generate new Superpave designed mixtures, with typical combinations of gradation types, asphalt binder grades, and RAP percentage commonly used by RTC. The mixture components used throughout this study consisted of:

- Virgin aggregates and RAP stockpiles collected from three different local producers identified in this report as Producers A, B and C.
- High-Calcium hydrated lime used for virgin aggregates marination, obtained from *Lhoist North America, Inc.*
- Asphalt binder with two different grades: PG64-28NV and PG64-22, from *Paramount Nevada Asphalt.*

Typical RTC Type 2 and 3 mix JMF were provided by each producer. However, this research could not rely on any of these JMF for several reasons. The most provoking fact is that none of the JMF included the lime within the mixture gradation, while one of the challenges with the effort was meeting the DP including the hydrated lime. Furthermore, some of the producers JMF did not meet Superpave volumetric criteria and used the effective specific gravity of RAP when determining the aggregate plus RAP blend combined specific gravity. Therefore, eight new mixtures summarized in Table 6 were developed from scratch to meet the intent of this study. Note that producers were randomly identified as A, B and C, rather than by name. It should be noted that all the mixtures contained 15% RAP, and were designed only to 4% AV since RTC is trying to reduce current mix design combinations specified in RTC Orange Book as shown in Table 7.

Table 6: Summary of Evaluated Mixtures

Mix ID	Producer	NMAS	RTC Orange Book Gradation Type	Binder Type
2036	A	1/2"	Type 3	PG64-28NV
2036-X	A	1/2"	Type 3	PG64-22
2121	A	3/4"	Type 2	PG64-28NV
T3	B	1/2"	Type 3	PG64-28NV
T2	B	3/4"	Type 2	PG64-28NV
T2-X	B	3/4"	Type 2	PG64-22
S2	C	3/4"	Type 2	PG64-28NV
S2-X	C	3/4"	Type 2	PG64-22

The wet sieve analysis was conducted as per AASHTO T27, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates for all the virgin aggregates stockpiles, as well as for the RAP stockpiles after centrifuge extraction [26]. The sieve analysis results for the entire stockpiles, along with the common hydrated lime used, are presented for the three producers in Table 8, Table 9, and Table 10

Table 7: Current Mixtures Specifications in the RTC Orange Book [25]

Test or Property	Test Method	Requirements			
		50 Blows per side		75 Blows per side	
Air Voids, Total Mix (%)[1]	ASTM D3203	3	4	3[2]	4
Voids in Mineral Aggregate (%)[3]	MS-2	Per Table 7.3 of MS-2			
Voids Filled with Asphalt (%)[3]	MS-2	-	65-78	-	65-75
Marshall Stability (pounds)	ASTM D6927	1800 Minimum			
Marshall Flow (0.01 inch)	ASTM D6927	8-20[4]			

[1] Target Value

[2] Unless directed by the Engineer, mix designs with the target air void value of 3% shall not be used for the surface course or within the zone affected by rutting when the Design ESAL>10^4.

[3] At target air void percentage

[4] Marshall Flow requirements do not apply when polymer modified binders are used

Table 8: Producer A Stockpile Gradations

Sieve size		Stockpiles							
US	SI	3/4"	1/2"	3/8"	Washed Sand	Crush. Dust	3/8 RAP	#4 RAP	Lime
1"	25.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	19.0	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	40.1	100.0	100.0	100.0	100.0	99.9	100.0	100.0
3/8"	9.5	7.3	64.2	99.7	100.0	100.0	84.4	100.0	100.0
#4	4.75	1.2	1.1	19.2	99.8	99.9	32.2	95.6	100.0
#8	2.36	0.9	0.7	1.7	85.0	80.5	19.6	78.2	100.0
#10	2	0.8	0.7	1.4	76.8	72.3	18.1	73.2	100.0
#16	1.18	0.8	0.6	0.9	55.3	53.4	15.4	59.2	100.0
#30	0.60	0.7	0.6	0.7	32.9	37.0	12.8	44.6	100.0
#40	0.42	0.7	0.6	0.6	21.8	31.4	11.5	37.9	100.0
#50	0.30	0.7	0.6	0.6	13.1	27.2	10.1	31.3	100.0
#100	0.15	0.6	0.6	0.6	3.7	21.4	7.6	22.0	99.0
#200	0.075	0.6	0.5	0.5	1.5	17.0	5.3	14.5	86.8

Table 9: Producer B Stockpile Gradations

Sieve size		Stockpiles						
US	SI	3/4"	1/2"	3/8"	Washed Sand	C Sand	RAP	Lime
1"	25.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	19.0	97.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	38.7	100.0	100.0	100.0	100.0	99.9	100.0
3/8"	9.5	8.9	79.7	100.0	100.0	100.0	94.2	100.0
#4	4.75	1.7	6.3	13.1	96.1	99.8	60.6	100.0
#8	2.36	1.6	1.7	3.4	62.0	85.4	43.0	100.0
#10	2	1.6	1.6	3.2	55.7	79.5	39.9	100.0
#16	1.18	1.5	1.4	2.8	40.3	60.8	32.8	100.0
#30	0.60	1.5	1.3	2.6	27.1	37.9	26.0	100.0
#40	0.42	1.5	1.3	2.5	21.9	26.9	22.8	100.0
#50	0.30	1.5	1.2	2.4	17.7	17.9	19.8	100.0
#100	0.15	1.4	1.2	2.2	10.7	6.7	14.4	99.0
#200	0.075	1.3	1.1	1.9	7.1	3.7	9.9	86.8

Table 10: Producer C Stockpile Gradations

Sieve size		Stockpiles						
US	SI	3/4"	1/2"	3/8"	Sand	CF	RAP	Lime
1"	25.0	98.5	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	19.0	57.3	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	5.1	70.9	100.0	100.0	100.0	100.0	100.0
3/8"	9.5	3.8	34.5	99.4	100.0	99.8	99.2	100.0
#4	4.75	2.9	3.0	4.6	99.6	76.7	65.4	100.0
#8	2.36	2.1	2.1	1.9	99.1	34.4	40.7	100.0
#10	2	2.0	2.0	1.8	98.8	29.0	37.5	100.0
#16	1.18	1.8	1.8	1.7	97.5	17.7	29.7	100.0
#30	0.60	1.8	1.6	1.6	87.7	10.4	22.7	100.0
#40	0.42	1.6	1.6	1.6	74.4	8.5	19.4	100.0
#50	0.30	1.6	1.6	1.5	57.3	7.3	16.4	100.0
#100	0.15	1.5	1.6	1.5	25.3	5.9	11.6	99.0
#200	0.075	1.5	1.5	1.4	11.7	5.1	8.3	86.8

4.1 Washing Stockpiles

Some of the virgin stockpiles with high percentages of p200 required washing to meet the DP ratio limited by Superpave between 0.6% to 1.2%. The inclusion of the hydrated lime with 87% p200 in the blend gradation, restrained the allowable amount of p200 from the virgin stockpiles. Therefore, the crusher fines stockpile of Producer C, as well as both sand stockpiles sampled from Producer B and Producer C were subjected to partial washing in the laboratory. Every 4000 g of the Producer C crusher fines were washed in the laboratory for two minutes, to drop the p200 from 7.1% to 1.4%. The Producer B sand stockpile was subjected to two minutes washing for 3000 g, in order to reduce the p200 from 7.1% to 1.4%. Whereas, five minutes washing to 3000 g of the Producer C sand stockpile reduced the p200 from 11.7% to 3.8 %. The gradation of the crusher fines and both sand stockpiles, prior and following to the washing process are shown in Table 11, Table 12, and Table 13.

Table 11: Laboratory Washing of Producer C Crusher Fines Stockpile

Sieve Size	Percent passing before washing, %	Percent passing after washing, %
1"	100.0	100.0
3/4"	100.0	100.0
1/2"	100.0	100.0
3/8"	100.0	99.9
#4	96.1	95.6
#8	62.0	59.4
#10	55.7	53.4
#16	40.3	36.2
#30	27.1	22.4
#40	21.9	17.5
#50	17.7	12.6
#100	10.7	5.1
#200	7.1	1.4

Table 12: Laboratory Washing of Producer B Washed Sand Stockpile

Sieve Size	Percent passing before washing, %	Percent passing after washing, %
1"	100.0	100.0
3/4"	100.0	100.0
1/2"	100.0	100.0
3/8"	100.0	99.9
#4	96.1	95.6
#8	62.0	59.4
#10	55.7	53.4
#16	40.3	36.2
#30	27.1	22.4
#40	21.9	17.5
#50	17.7	12.6
#100	10.7	5.1
#200	7.1	1.4

Table 13: Laboratory Washing of Producer C Sand Stockpile

Sieve Size	Percent passing before washing, %	Percent passing after washing, %
1"	100.0	100.0
3/4"	100.0	100.0
1/2"	100.0	100.0
3/8"	100.0	100.0
#4	99.6	99.4
#8	99.1	98.6
#10	98.8	98.3
#16	97.5	96.7
#30	87.7	86.1
#40	74.4	71.3
#50	57.3	51.8
#100	25.3	17.9
#200	11.7	3.3

4.2 Stockpiles Modifications

Some modifications to the virgin aggregate stockpile gradations were required to meet the gradation control points set by Superpave in AASHTO M323, and RTC Orange Book specifications for type 2 and type 3 mixtures ([26], [25]). The ½” NMAS stockpile from Producer B was coarsened to reduce the percent of aggregates passing the 3/8” sieve from 80% to 69%. This had to be done to get a blend gradation within Superpave broadband specifications for ½” NMAS mixture. The ½” stockpile gradations before and after coarsening are summarized in Table 14.

Table 14: Modified Gradation of Producer B 1/2" Stockpile

Sieve Size	Percent passing before modification, %	Percent passing after modification, %
1"	100.0	100.0
3/4"	100.0	100.0
1/2"	100.0	99.9
3/8"	79.7	69.0
#4	6.3	7.2
#8	1.7	2.1
#10	1.6	2.0
#16	1.4	1.9
#30	1.3	1.8
#40	1.3	1.8
#50	1.2	1.7
#100	1.2	1.7
#200	1.1	1.5

Chapter 5. Mixture Designs and Performance Tests

5.1 Gradation

The mix designs generated throughout this research study required altering the mixture components, particularly stockpile percentages, through several trials in order to obtain adequate VMA to meet Superpave volumetric property thresholds in AASHTO M323 [7]. Overall blend gradation adjustments remain restricted by control points on multiple sieves, defined by Superpave broadband specifications in AASHTO M323 (12.5 mm and 19 mm NMAS), and by RTC Orange Book requirements (type 2 and type 3 mixes), as shown in Table 15 and Table 16 respectively ([7],[25]).

Table 15: Superpave Broadband Specifications [7]

Sieve Size, mm	37.5 mm		25.0 mm		19.0 mm		12.5 mm		9.5 mm	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
50.0	100	-	-	-	-	-	-	-	-	-
37.5	90	100	100	-	-	-	-	-	-	-
25.0	-	90	90	100	100	-	-	-	-	-
19.0	-	-	-	90	90	100	100	-	-	-
12.5	-	-	-	-	-	90	90	100	100	-
9.5		-	-	-	-	-	-	90	90	100
4.75	-	-	-	-	-	-	-	-	-	90
2.36	15	41	19	45	23	49	28	58	32	67
1.18	-	-	-	-	-	-	-	-	-	-
0.075	0	6	1	7	2	8	2	10	2	10

Table 16: RTC Orange Book Gradation Specifications [25]

Sieve size	Percentage by Weight, Passing Sieve			
	Type 2	Type 2C [(1)]	Type 3C	Type 3
1 inch	100	100		
3/4 inch	90-100	88-95	100	
1/2 inch		70-85	90-99	100
3/8 inch	63-85	60-78	70-90	85-100
No. 4	45-65	43-60	48-65	50-75
No. 10	30-44	30-44	32-50	35-52
No. 16				
No. 40	12-22	12-22	12-26	12-26
No. 200	3-8	3-8	3-8	3-8

1. Unless directed or approved by Agency or Engineer, Type 2C shall not be used as the final (top) lift of the structural section.

Correspondingly, the asphalt mixtures developed in the Project Phase II and designed as per Superpave methodology, can be classified into two main categories:

- Category A: Mixes meeting Superpave 19 mm NMAS control points and RTC Orange Book Type 2 requirements summarized in Table 17.
- Category B: Mixes meeting Superpave 12.5 mm NMAS control points and RTC Orange Book Type 3 requirements summarized in Table 18.

The blended aggregate gradations of the eight mixtures including 15% RAP and 1.5% hydrated lime by dry weight of virgin aggregates (dwa), as specified in Nevada Silver Book, are summarized in Table 19 [24]. With the aim of simultaneously meeting Superpave broadband specifications and RTC Orange Book control points with mixtures possessing adequate volumetric properties, the gradation of most mixes had a backbone shape when plotted on the 0.45 power chart as shown in Figure 13 for mix T2. It is noteworthy that mixes 2036, T2, and S2 are comprised of the same aggregate gradations as mixes 2036-X, T2-X, and S2-X respectively. The only mixture difference is the substitution of the binder grade from PG64-28NV polymer modified asphalt binder to PG64-22 neat binder.

Table 17: Gradation Specifications for Category A Mixes

Sieve Size		Type 2 Spec (RTC Orange Book)		Superpave Spec limits for 19 NMAS	
inch	mm				
1"	25.00	100	100		
3/4"	19.00	90	100	90	100
1/2"	12.50				90
3/8"	9.50	63	85		
#4	4.75	45	65		
#8	2.36			23	49
#10	2.00	30	44		
#16	1.18				
#30	0.60				
#40	0.425	12	22		
#50	0.30				
#100	0.15				
#200	0.075	3	8	2	8

Table 18: Gradation Specifications for Category B Mixes

Sieve Size		Type 3 Spec (RTC Orange Book)		Superpave Spec limits for 12.5 NMAS	
inch	mm				
3/4"	19.00				100
1/2"	12.50	100	100	90	100
3/8"	9.50	85	100		90
#4	4.75	50	75		
#8	2.36			28	58
#10	2.00	32	52		
#16	1.18				
#30	0.60				
#40	0.425	12	26		
#50	0.30				
#100	0.15				
#200	0.075	3	8	2	10

Table 19: Blended Aggregates Gradation

Sieve Size		% Passing				
inch	mm	2036 2036-X	2121	T3	T2 T2-X	S2 S2-X
1"	25.00	100.0	100.0	100.0	100.0	100.0
3/4"	19.00	100.0	100.0	100.0	99.5	100.0
1/2"	12.50	100.0	88.6	100.0	89.6	89.6
3/8"	9.50	88.9	78.0	89.7	83.6	78.9
#4	4.75	58.8	57.2	61.0	60.3	49.9
#8	2.36	47.6	46.0	47.9	45.0	32.5
#10	2.00	43.3	41.9	44.5	41.5	30.0
#16	1.18	32.5	31.4	34.6	32.1	24.8
#30	0.60	21.4	20.7	23.3	22.0	19.8
#40	0.425	16.2	15.7	17.9	17.4	16.5
#50	0.30	11.9	11.6	13.5	13.5	12.8
#100	0.15	6.9	6.7	7.6	8.1	6.8
#200	0.075	4.8	4.6	4.8	4.5	3.8

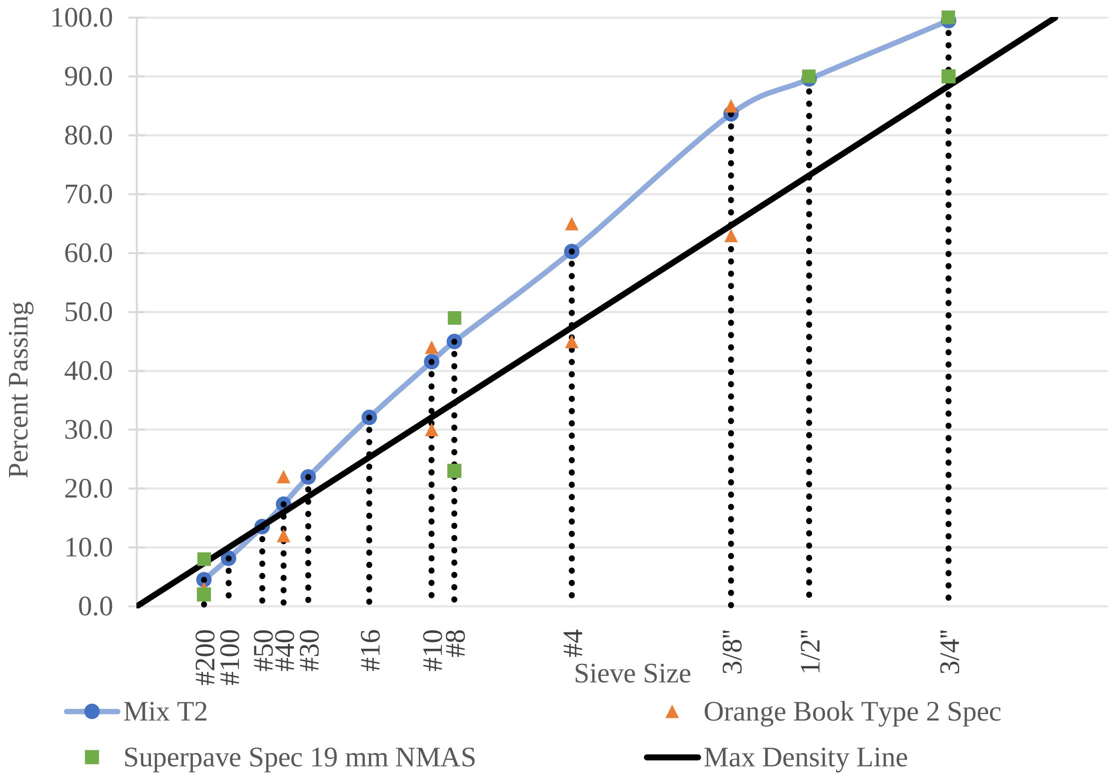


Figure 13: 0.45 Power Chart for Mix T2

5.2 Volumetric Properties

The Superpave methodology for asphalt mix design, outlined in AASHTO M323, and AASHTO R35 defines certain criteria for the mix volumetric properties depending on traffic level as shows Table 20 ([7],[23]). For each of the eight mixtures, two or three replicates of mix design specimens at each asphalt content were prepared and compacted in a Superpave gyratory compactor to N_{Design} resulting in compacted specimens with heights ranging from 110 mm to 120 mm and a diameter of 150 mm.

Initially, the aggregate stockpiles were quartered, split, and batched to specific gradations on multiple sieves prior to sample preparation. In order to select the optimum binder content at 4% AV, 5000 g samples were mixed at a range of binder contents and compacted to N_{Design} of 50 gyrations according to the Project Phase I findings. The mix design specimens were tested to obtain bulk specific gravity (Gmb) after compaction and maximum theoretical specific gravity (Gmm) on loose mix so volumetric properties including AV, VMA, VFA and DP could be obtained.

With the Superpave mix design method, plots of volumetric properties versus asphalt binder content are used to select the OBC at 4% AV while meeting the remaining volumetric property requirements. Once selection of OBC at 4% AV was completed, three mix design samples were mixed at the OBC interpolated from the plots and compacted at $N_{Design,}$ to verify the AV % and volumetric properties.

Based on the correlation of the compaction effort between Marshall blows and Superpave gyrations, established in the Project Phase I, the transition to the Superpave mix design method was recommended for Phase II with a single N_{Design} level of 50 gyrations

[22]. The job mix formula of any mixture shall be generated once the volumetric properties are verified at the selected OBC with 4% AV, otherwise the aggregates gradation shall be adjusted iteratively.

Table 20: Superpave Volumetric Criteria [7]

20-Year Design ESALs (millions)	Relative Density Criteria, % Gmm			VMA, Percent Minimum					VFA Range, Percent	Dust Proportion (DP) Range
	Nin	Ndes	Nmax	NMAS, mm						
				37.5	25	19	12.5	9.5		
< 0.3	≤91.5	96	≤ 98.0	11	12	13	14	15	70–80	0.6–1.2
0.3 to < 3	≤90.5								65–78	
3 to < 10	≤ 89.0								65–75	
10 to < 30										
≥ 30										

The OBC and the volumetric properties of each mixture developed are summarized in Table 21, along with the mixture source, NMAS, binder grade and RTC Orange Book type. The VMA, VFA, and DP are plotted for category A and category B mixes in Figure 14 and Figure 15 respectively, along with the relative OBC. It can be inferred that all mixture properties are within the set VFA range of 65-78, the DP range of 0.6-1.2, and meet the minimum VMA of 13 for category A mixes and 14 for category B mixes [7]. Additionally, $N_{initial}$ was verified based on the Superpave gyratory compactor data to ensure good workability and field compaction of the mixtures. Figure 16 illustrates how the OBC increases progressively with the amount of p200 in the aggregate blends, indicating that cleaner stockpiles (lower amount of material passing the #200 sieve) with less surface area can slightly drop the OBC while including the hydrated lime in the gradation. The detailed volumetric measurements and graphs are presented in Appendix A: Volumetric Properties

Table 21: Volumetric Properties Summary

Mix ID	Source	NMAS	Orange Book Type	Binder Grade [(1)] PM/Neat	Volumetric Properties			
					OBC %	VMA %	VFA %	DP %
2036	A	1/2"	3	PM	5.6	14.3	70	1.1
2036-X	A	1/2"	3	Neat	5.7	14.0	71	1.1
2121	A	3/4"	2	PM	5.2	13.7	71	1.1
T3	B	1/2"	3	PM	5.5	14.4	71	1.1
T2	B	3/4"	2	PM	5.1	13.0	70	1.2
T2 -X	B	3/4"	2	Neat	5.2	13.5	69	1.2
S2	C	3/4"	2	PM	4.6	13	70	1.0
S2-X	C	3/4"	2	Neat	4.6	12.9	69	1.0

1. PM: Polymer modified binder PG64-28NV.
   Neat Binder: PG64-22

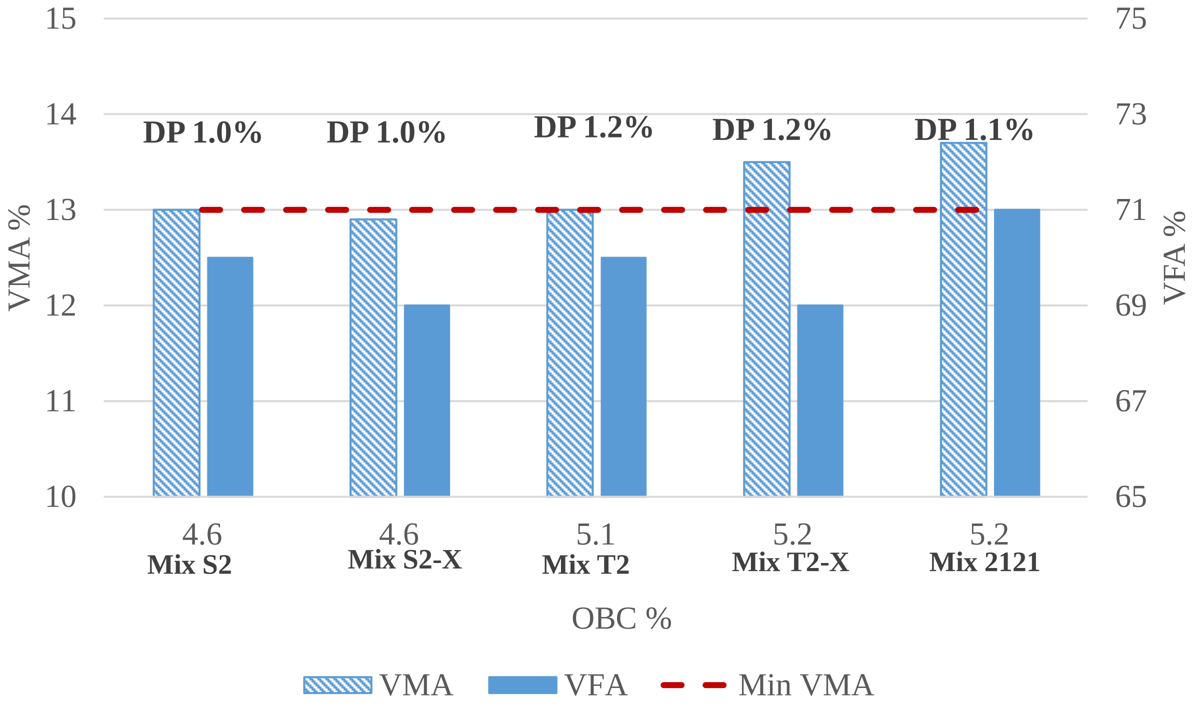


Figure 14: Volumetric Properties for Category A Mixes

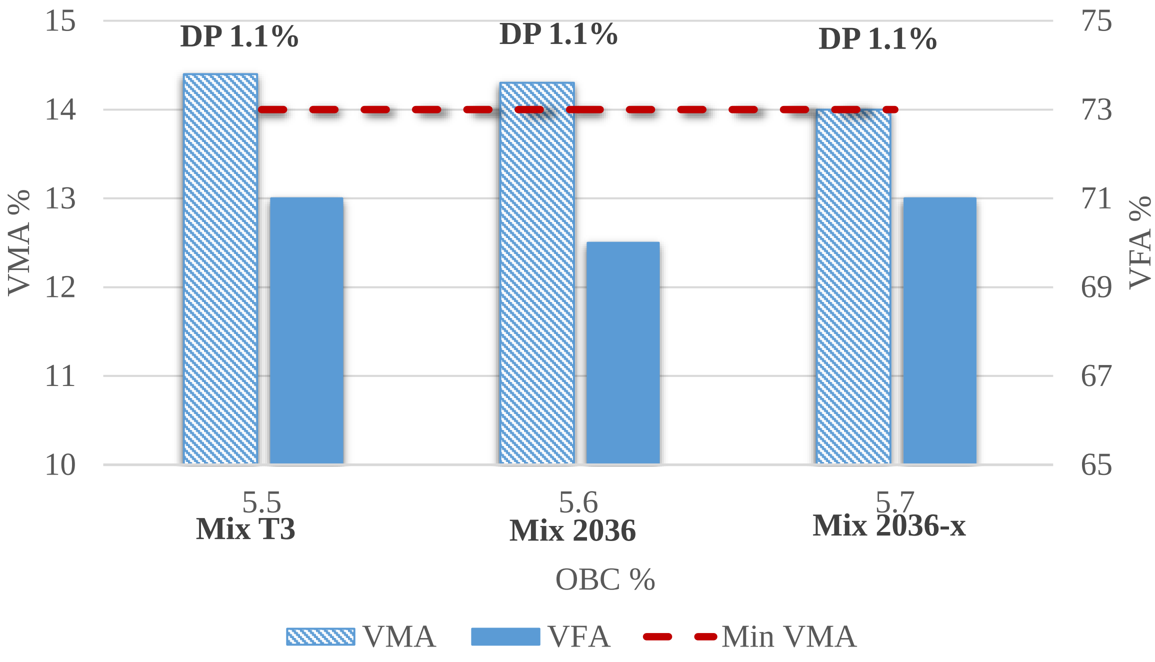


Figure 15: Volumetric Properties for Category B Mixes

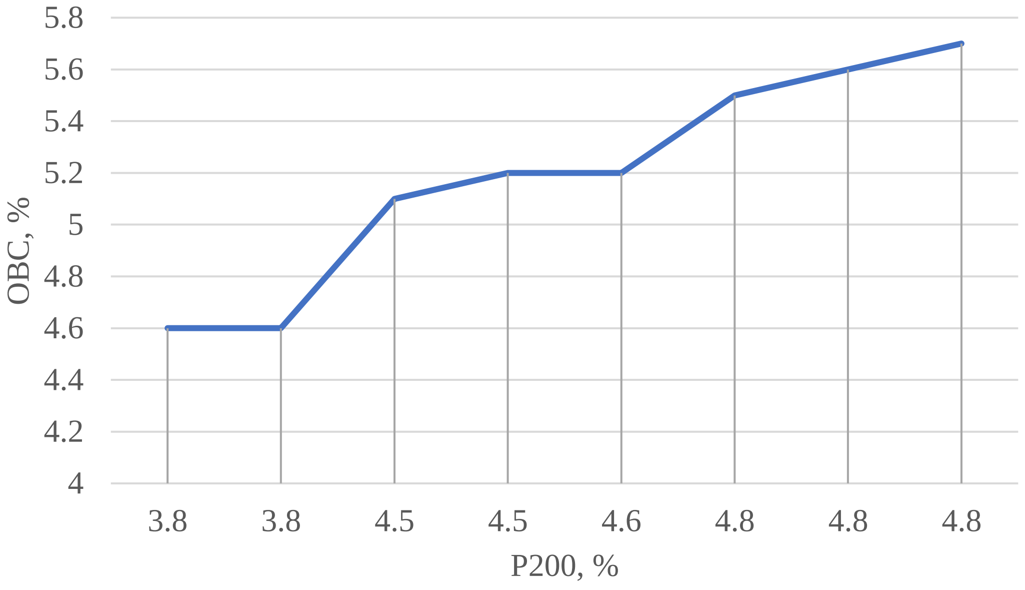


Figure 16: OBC vs p200

5.3 Performance Tests

The intent of this research project is to assist RTC with the transition from Marshall to a BMD methodology founded simultaneously on Superpave volumetric criterion, and performance tests implying stable and durable mixtures. Mixture behavior can be ensured throughout performance testing on short-term and long-term aged specimens for stability and durability verification, respectively. The major refinement to the Superpave methodology suggested in this study, was to improve the long-term mixture durability by decreasing the compaction effort to a single N_{Design} of 50 gyrations. Interestingly, decreasing the design compaction effort N_{Design}, was identified as one of the top alterations to improve Superpave mixes durability through additional asphalt binder, and was implemented by 26 states as per the NCHRP Project 20-07/Task 412 report [27].

It is believed that reducing the design compaction effort will provide a higher optimum binder content for a fixed aggregate gradation. But the observation reported by some SHAs noticed that the contractor can develop cost-effective mixtures by adjusting aggregate gradations to meet all volumetric requirements at a lower N_{Design} without increasing binder content. Despite the fact that contractors can fine-tune the gradations to generate cost-effective mixtures at lower N_{Design} and moderate OBC, this is appropriate as long as performance test requirements are met. Additionally, reducing N_{Design} can ensure higher in-place density due to better field compaction, without significantly affecting volumetric properties of the mix [2]. The detailed performance outcome of all the specimens tested are shown respectively in Appendix B: TSR, Appendix C: HWTT, Appendix D: Ideal-CT, and Appendix E: Marshall Stability and Flow.

5.3.1 Tensile Strength Ratio (TSR)

The Superpave mix design method requires verification of moisture resistance for designed mixtures at OBC once volumetric requirements are met. Specimens are evaluated according to AASHTO T283, *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage* [28]. Additionally, the Tensile Strength Ratio (TSR) test exhibits the effectiveness of marinating the virgin aggregates with hydrated lime to improve overall mixture resistance to moisture damage. The TSR test is conducted on 150 mm diameter Superpave gyratory compactor specimens following these steps:

1. Six samples are mixed at OBC, cured in an oven for 16±1 hour at 60℃, then compacted to 95 mm height within 7±0.5 AV%.
2. Compacted specimens are grouped in two categories with similar AV%: conditioned and unconditioned set.
3. The dry tensile strength of the unconditioned set can be measured after 2 hours at 25℃.
4. The conditioned set should be saturated between 70% and 80%, subjected to one freeze-thaw cycle (16 hours at -18℃ followed by 24 hours at 60℃), then conditioned at 25℃ for 2 hours before running the test and obtain the wet tensile strength.

Consequently, the TSR is the ratio of the average tensile strength of the conditioned and unconditioned set of specimens. The Superpave methodology sets a minimum TSR of 80% in AASHTO M323, while the RTC Orange Book defines a minimum TSR of 70%

combined with a minimum dry strength of 65 psi (448 kPa) ([7], [25]). Figure 18 illustrates the specimen loaded in compression mode, subjected to 50 mm/min load rate during the test prior to cracking at the peak load which is recorded. In reference to the dry and the wet strength formulated in

Table 22 below, the TSR values greatly exceeded the minimum requirement of 80% defined by Superpave method as shown in Figure 18 with the 95% confidence interval (CI) bars. Theoretically, the controlled marination process of the virgin aggregates for 48 hours in the laboratory, played a major role in increasing the TSR values and improving the mixtures stripping resistance. None of the mixtures had a dry strength below RTC Orange Book requirement of 65 psi. The influence of binder type was evident in the tensile strength values, given that mixes with unmodified binder PG64-22, experienced the highest dry and wet strength comparing to the PG64-28NV mixtures. The average dry tensile strength among mixes with PG64-22 was 147 psi, which it was 112 psi for mixtures containing PG64-28NV. The reason mixtures containing PG64-22 have greater strengths is because this neat binder has higher stiffness at the specified test temperature, as illustrated in Figure 19 for dry and wet tensile strengths with the 95%CI bars.

Table 22: Summary of TSR Results

Mix ID	2036	2036-X	2121	T3	T2	T2-X	S2	S2-X
PM/Neat Binder (1)	PM	Neat	PM	PM	PM	Neat	PM	Neat
Dry Strength, psi	113	142	118	109	106	154	112	146
Wet Strength, psi	102	125	103	101	99	136	103	122
TSR, %	90	88	87	93	93	88	92	84

1.PM: Polymer modified binder PG64-28NV.
Neat Binder: PG64-22

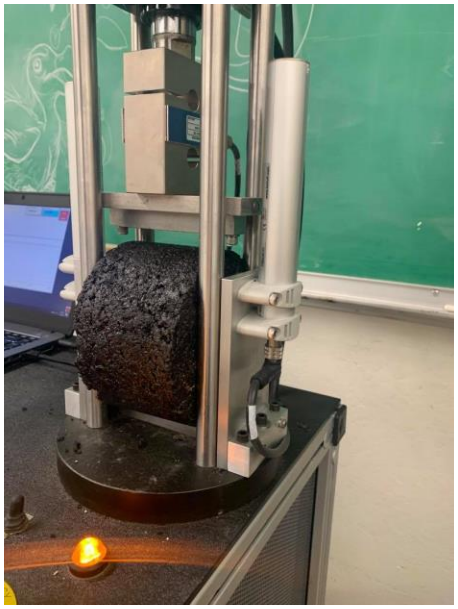


Figure 17: Indirect Tension Test Fixture

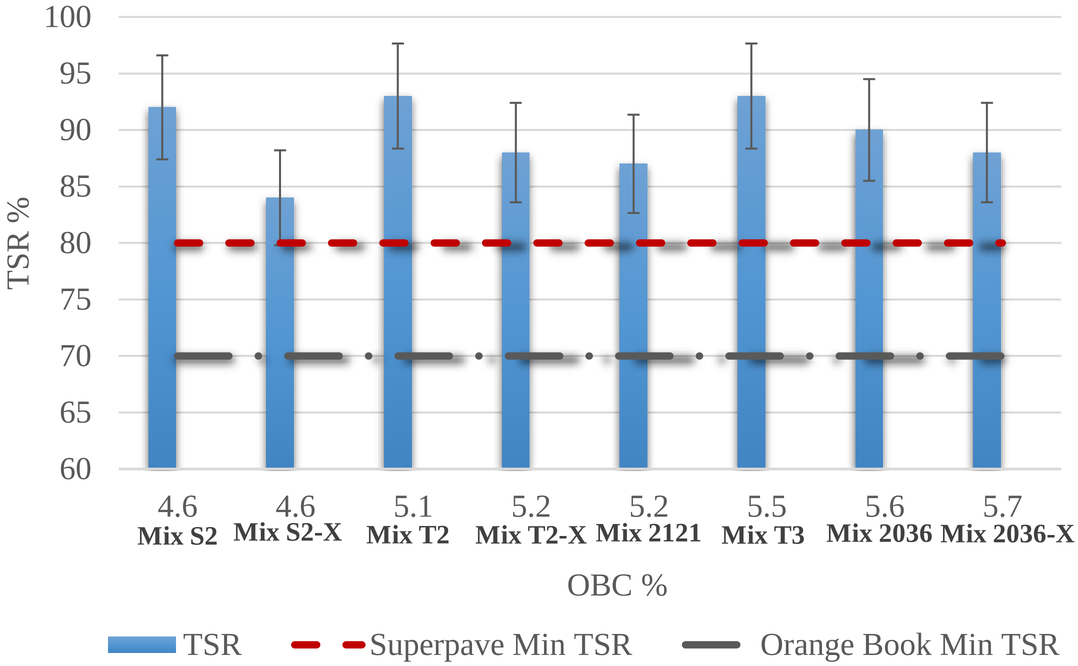


Figure 18: TSR Results

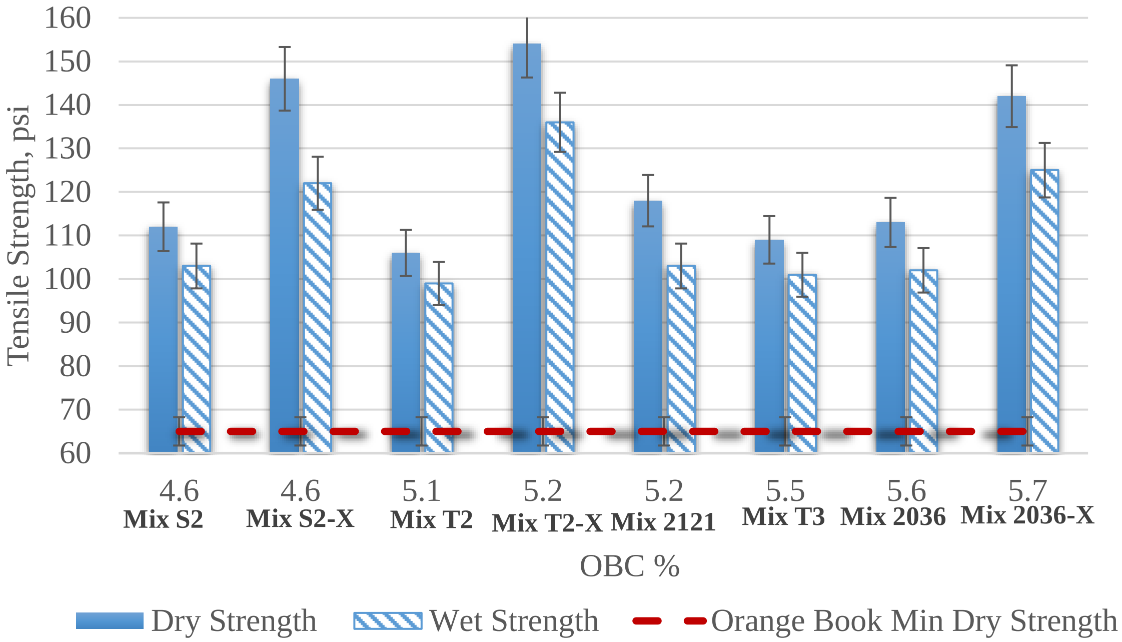


Figure 19: Wet and Dry Tensile Strengths

5.3.2 Hamburg Wheel Track Test (HWTT)

The stability verification is a fundamental step while evaluating mixture performance in terms of rutting resistance. Therefore, the HWTT which is widely used across the United States and many other parts of the world was adopted to evaluate both rutting and moisture susceptibility of mixtures. As well, this test exhibited sensitivity to binder stiffness, aggregate skeleton, and test specimen air void level. This test method involves running a weighted steel wheel repeatedly over two cut samples joined inside the Hamburg mold and conditioned in a water bath, at a defined temperature inside the testing machine presented in Figure 20. The HWTT is conducted on 150 mm Superpave gyratory specimens as per AASHTO T324, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures* [17]. For every mix, four samples were mixed at OBC, short-term aged as per AASHTO R30 for 4 hours at 135℃, compacted to 60 mm height then cut at the edge within 7±0.5 AV%[18]. The HWTT specimens were not subjected to long-term aging since rutting distress occurs early in pavement life. The test is run after submerging the specimens in water at the set test temperature and defining the failure criteria such as allowable rut depth or maximum number of cycles.

The HWTT was performed at 50℃ because the high temperature grade of the binders used was PG 64, and the failure criteria was set to 12.5 mm maximum rut depth and 20,000 cycles to failure, based on current DOT thresholds. The rut depth is recorded as a function of wheel passes to determine the Stripping Inflection Point (SIP) representing a stripping failure, whereas the number of passes corresponding to 12.5mm rut depth denotes a rutting failure.

Figure 20: Samples in the HWTT Fixture

The generated test data Table 23, reveal that none of the Superpave mixtures were susceptible to rutting failure or stripping failure. Interestingly, the mixtures exhibited a high resistance to rutting at 50℃, with the greatest rut depth observed being 3.7 mm for Mix

T3, which is well below the maximum allowable deformation of 12.5 mm. Figure 21 with the 95% CI bars, denotes the efficiency of the polymer modified binder PG 64-28NV in a slight drop of the rut depth for mixes T2 and S2, comparing respectively to T2-X and S2-X with PG64-22. Figure 22 illustrates the three curves plotted for Mix 2036 corresponding to: right wheel, left wheel, and average wheel along with the failure criteria limit at 12.5mm rut depth.

Table 23:Summary of HWTT Results

Mix ID	2036	2036-X	2121	T3	T2	T2-X	S2	S2-X
PM/Neat Binder (1)	PM	Neat	PM	PM	PM	Neat	PM	Neat
Max Rut Depth, mm	2.4	2.2	2.4	3.7	3.0	3.2	2.4	2.8
Stripping Inflection Point	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

1. PM: Polymer modified binder PG64-28NV.
   Neat Binder: PG64-22

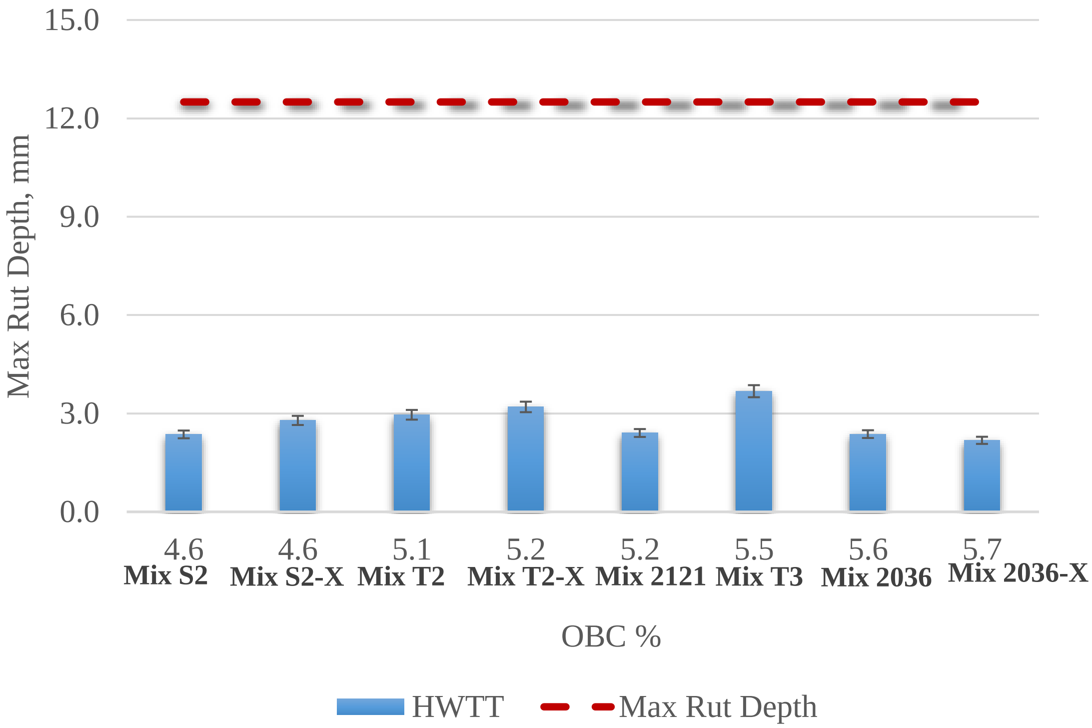


Figure 21: HWTT Maximum Rut Depth

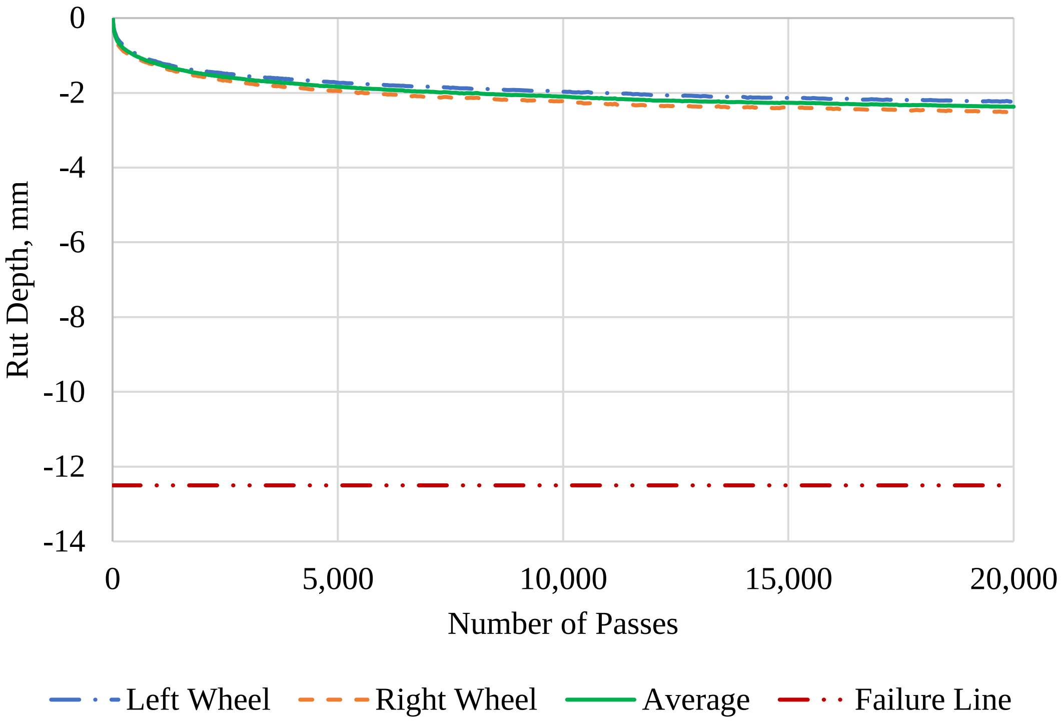


Figure 22: HWTT Output for Mix 2036

5.3.3 Ideal-CT (Short-term conditioned, Short-term Unconditioned, Long-term)

The primary form of asphalt concrete pavement distress in Northern Nevada is related to poor durability (cracking and raveling distress) amid several aging factors and load levels. Therefore, the durability of mixtures in this study was assessed with the Ideal-CT, which has been used to evaluate the relative cracking resistance of mixtures containing RAP and can be practically implemented for mix design, QC, and acceptance purposes. The tests were performed on 150 mm diameter Superpave gyratory compacted samples, as per ASTM standard D8225-19 [19]. Based on the principle of fracture energy obtained from a load-displacement curve like the example plotted in Figure 23, this indirect tensile strength test determines the cracking tolerance index of mixture at intermediate temperature. Even though cracking resistance is most critical at later pavement life as aging occurs, the Ideal-CT was verified for mixtures in this study under three conditions:

- Short-term specimens conditioned with 1 freeze-thaw cycle, cured as loose mixtures for 16 hours at 60°C: Ideal-CT_{Cond}.
- Short-term unconditioned specimens cured as loose mixtures for 16 hours at 60°C: Ideal-$\text{CT}_{\text{Uncond}}$.
- Long-term aged specimens, cured as loose mixtures for 4 hours at 135°C, then aged after compaction for 5 days at 85°C: Ideal-CT_{Long}.

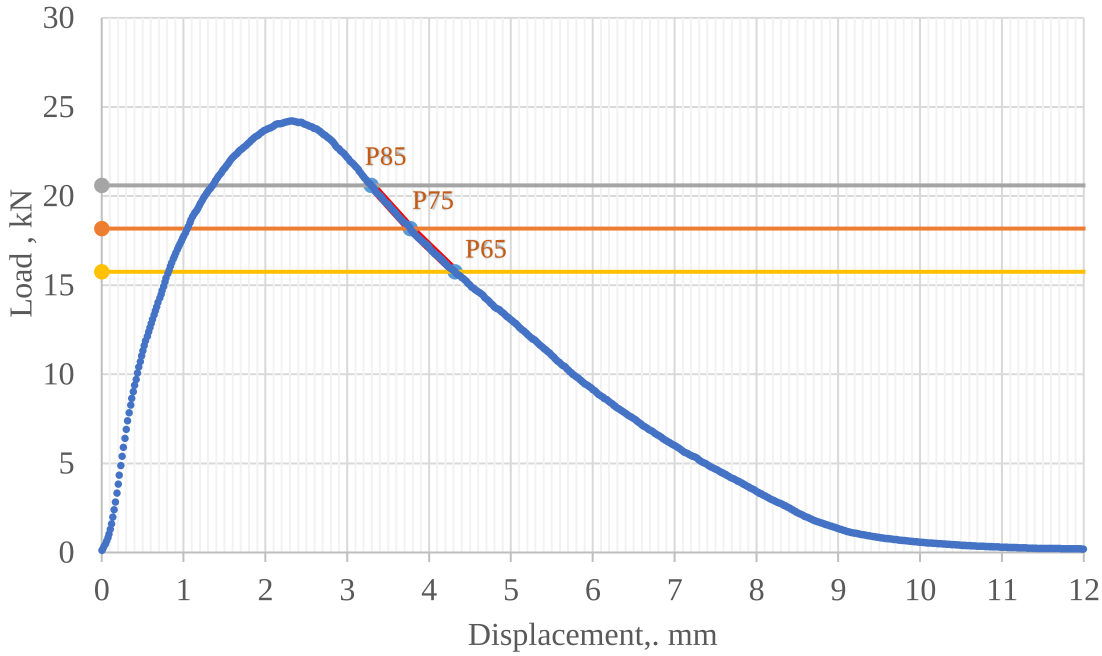


Figure 23: Ideal-CT Output for long-term aged Specimen of Mix 2121

For each level, three replicate specimens per mixture were prepared at the OBC, conditioned appropriately, then tested at 25°C. The Ideal-CT is being evaluated for implementation in balanced mix design methods, and for QC as well as acceptance testing by several agencies. It is favored because the test equipment is inexpensive, sample preparation is simple, and test can be performed in a matter of minutes once samples are appropriately conditioned. Additionally, the publication of ASTM D8255-19 is a newly available standard published for this test[19]. However, a challenge associated with it is establishing a criterion under defined aging level(s), particularly after long-term aging when mixture behaves more brittle as is less crack resistant. Some preliminary criteria have been developed for a minimum short-term Ideal-CT. For example Minnesota DOT research suggests 80,while NCAT and Virginia DOT work suggest 70. ([11], [29], [30]). Texas DOT is evaluating a minimum Ideal-CT of 65 for dense-graded mixes and 105 for Superpave mixes [29].

The sensitivity analysis presented in the original standard for the development of this test by Texas A&M Transportation Institute, examined the Ideal-CT sensitivity at 3 different aging levels: 4, 12, and 24 hours at 135℃. It was observed that Ideal-CT after 12 hours of aging was about 23% lower than it was after 4 hours of aging [31]. Some studies suggested using 4 and 12 hours to represent short-term and long-term aging conditions. Accordingly, to estimate an approximative criteria, if the short-term Ideal-CT threshold was set to a minimum limit of 70, the associated long-term value subjected to 23% reduction will be 54. Asphalt mixture durability and fatigue resistance are known to decline as pavements age, which makes using a form of long-term aging rational with Ideal-CT testing. However, the Ideal-CT$_{cond}$ and Ideal-CT$_{uncond}$ on short-term aged specimens are also of interest for comparison analysis and reflective cracking assessment.

Table 24 and Figure 24 with the 95% CI bars, summarize the Ideal-CT values observed under the three different conditions investigated, along with the minimum criterion of 54.

All PG64-28NV mixtures exceeded the minimum long-term Ideal-CT of 54, regardless of conditioning level. The long-term aged 2036-X, T2-X and S2-X mixtures with PG64-22 dropped significantly below this minimum of criteria of 54 illustrating the superior cracking performance of mixes with polymer modified binder. Despite the damage that is induced with a freeze-thaw cycle, all of the mixes exceeded the minimum criteria of 54. This is because the mixtures are highly resistant to moisture damage regardless of binder type, as indicated by the prominent TSR results analyzed in

Table 22. Even with a lower peak strength than Ideal-$\mathrm{CT}_{\mathrm{uncond}}$, the post-peak load-displacement curve of the Ideal-$\mathrm{CT}_{\mathrm{cond}}$ specimens had a flatter slope, consequently greater fracture energy and less brittle mixes. Similarly, this phenomenon has been observed in the Project Phase I analysis [22].A comprehensive examination of the data presented in Figure 25 and Figure 26 for category A and category B mixes, designates the major role of the effective binder content (P_{be}) in improving long-term durability: the higher the P_{be}, the greater the Ideal-CT. With PG64-28NV binder, the short-term Ideal-CT (conditioned and unconditioned) of category B mixes notably exceeded the category A mixes. However, this significant difference between both categories was not observed on the long-term aged specimens.

Table 24: Summary of Ideal-CT Results

Mix ID	2036	2036-X	2121	T3	T2	T2-X	S2	S2-X
PM/Neat Binder (1)	PM	Neat	PM	PM	PM	Neat	PM	Neat
Ideal-CT Conditioned	240	166	211	234	210	95	182	86
Ideal-CT Unconditioned	141	71	93	106	105	48	101	49
Ideal-CT Long-term Aged	75	43	72	55	59	18	58	30

1. PM: Polymer modified binder PG64-28NV.
   Neat Binder: PG64-22.

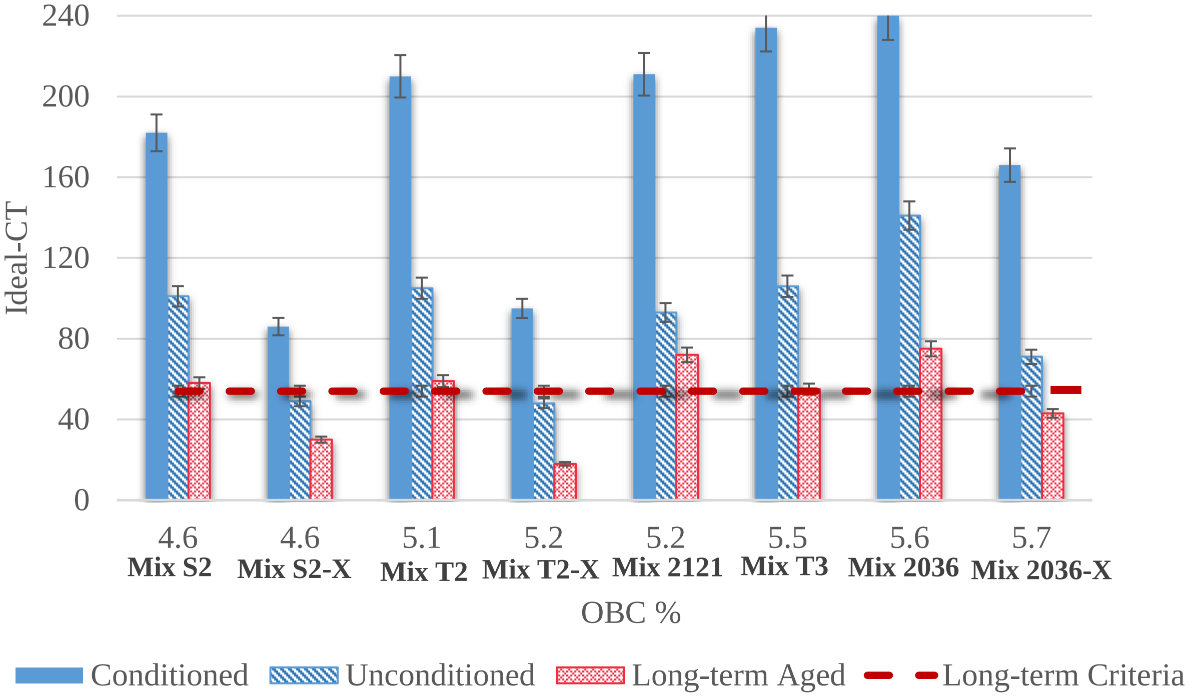


Figure 24: Ideal-CT Results

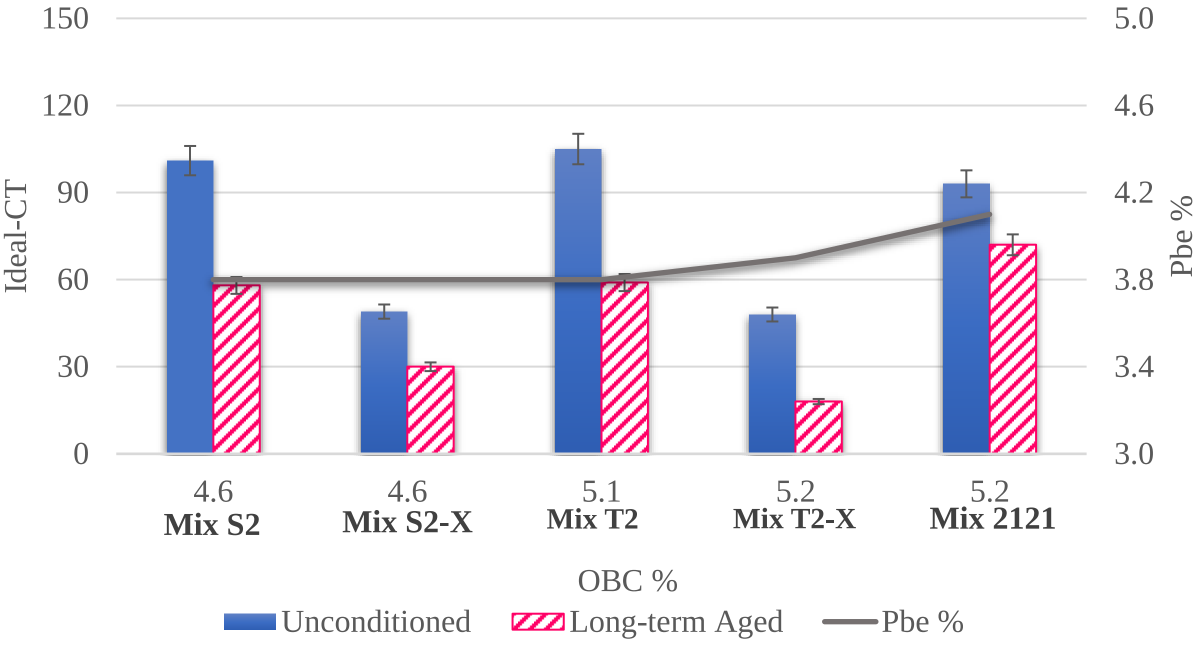


Figure 25: Ideal-CT Results for Category A Mixes

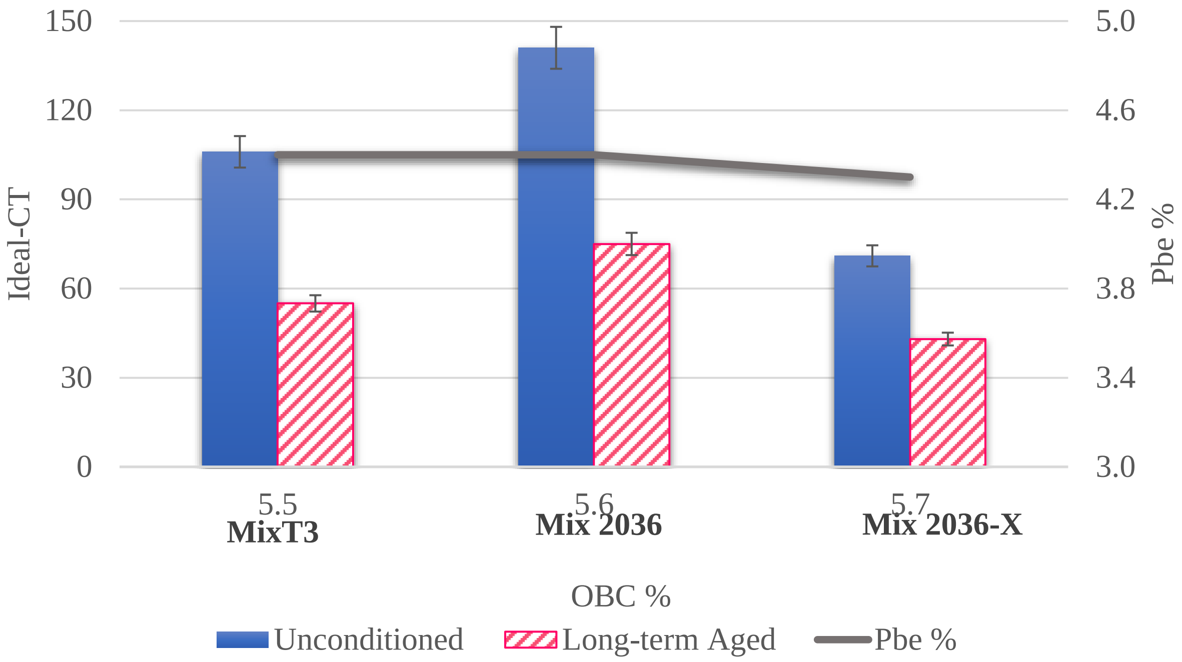


Figure 26: Ideal-CT Results for Category B Mixes

5.3.4 Marshall Stability and Flow

The Marshall stability and flow test produces important properties in the Marshall mix design method. They are suggested to relate to rutting resistance and there is a long history of use, and thus data generated for mixtures used in Northern Nevada. To provide a tie between these historically used mixture properties and the BMD approach, Marshall stability and flow was performed on all Superpave mixtures as well. Three specimens per mix were prepared at the Superpave OBC while compacted with a manual Marshall Hammer to 75 blows. Specimens were then conditioned for 30-40 min in a 60℃-water bath prior to testing. During this test, the applied load increases while a constant rate of displace of 2 inches/minute is applied, until a maximum load carried by the sample defined as the stability. Displacement is measured during the test and reported as the flow value at the peak load. Flow corresponds to the deformation in units of 0.25 mm (0.01 inch) at the maximum load recorded during the test.

ASTM D6927, *Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures*, was followed to evaluate the Marshall stability and flow of the various mixtures [32]. The RTC Orange Book requires a minimum stability of 1800 lbf and a range of 8-20 (0.01 inch) for the Marshall flow. However, the Marshall flow range limit does not apply for the mixtures with polymer modified asphalt binders [25].

The Marshall stability values observed are summarized in Table 25, and confirm that stability for all the mixtures exceeded the minimum criteria of 1800 lbf significantly. This is typical of asphalt mixtures historically designed per the RTC Orange Book requirements. Mixtures with PG64-22 binder all exhibited flow values in the allowable range of 8-20 (0.01 inch) as per RTC Orange Book. Figure 28 shows the minimum stability observed was 4606 lbf for mix S2-X, which illustrates considerable stability of the Superpave designed mixtures. Mix S2 with PG64-28NV revealed a higher stability at 60°C relatively to mix S2-X at the same OBC, but with PG 64-22 asphalt binder.

Table 25:Summary of Marshall Stability and Flow Results

Mix ID	2036	2036-X	2121	T3	T2	T2-X	S2	S2-X
PM/Neat Binder (1)	PM	Neat	PM	PM	PM	Neat	PM	Neat
Corrected Marshall Stability, lbf	4666	4724	4917	5511	5954	6269	5229	4606
Marshall Flow, 0.01 in	N/A	14	N/A	N/A	N/A	13	N/A	18

1. PM: Polymer modified binder PG64-28NV.
   Neat Binder: PG64-22

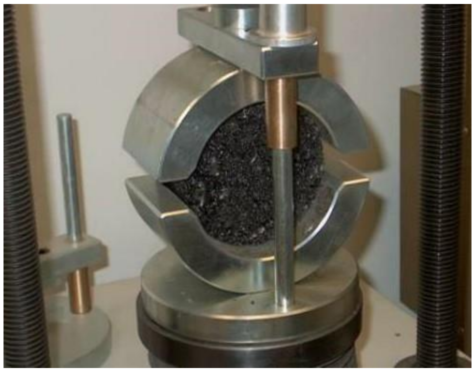


Figure 27: Marshall Stability Fixture

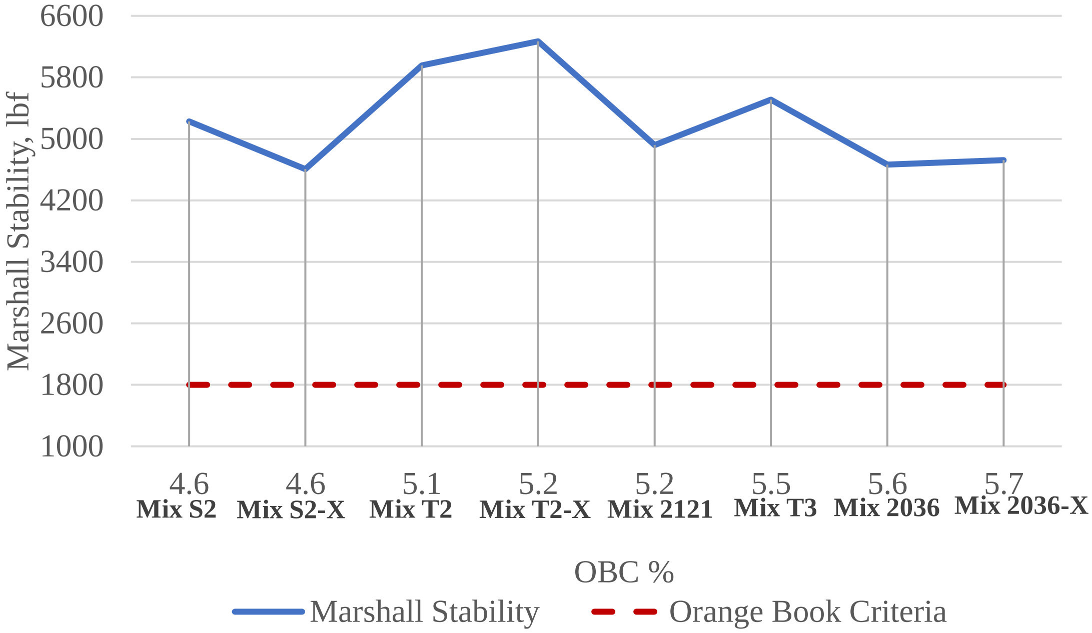


Figure 28: Marshall Stability Results

5.4 Cost Analysis

With the purpose of estimating mixture unit prices, a cost analysis was conducted on some of the asphalt mixtures evaluated in this report. The unit prices of several Superpave mixtures generated in Phase II, were compared to the unit prices of their relative Marshall mixtures using the producer JMFs. The unit prices adopted are based on local supplier raw material costs, including virgin aggregates, RAP, virgin binder, and hydrated lime. In terms of binder amount, the recycled binder was subtracted from the total binder content and just the cost of virgin binder was considered. This is appropriate since the cost of the recycled RAP binder is included in the RAP cost. It is worth mentioning that Superpave (UNR) and Marshall mixtures were compared with respect to the same binder type, thus same unit price was allocated for both binder types in this analysis. A comparison between the producer JMF and the Superpave mixtures unit prices is shown in Figure 29 with the 95% CI bars. The Superpave mixtures designed per the proposed BMD have costs about 5 % higher than the historical Marshall designed mixtures. According to the price breakdown in Table 26 and Table 27, this additional cost is mainly associated with the higher OBC within the Superpave mixtures and due to the need to use higher percentages of some washed aggregate stockpiles. However, based on the data generated in this effort the durability of the Superpave BMD mixtures should be significantly better than the historical Marshall mixtures.

Table 26: Unit Price Breakdown for Mixes S2, 2121, and T2-X

Material	$/Ton	Mix S2		Mix 2121		Mix T2-X	
		UNR	JMF	UNR	JMF	UNR	JMF
3/4" Stockpile	16.0	0.0	10.0	19.0	10.0	17.0	20.0
1/2" Stockpile	17.0	29.7	17.0	10.0	15.0	0.0	10.0
3/8" Stockpile	15.0	9.0	8.0	13.0	19.0	18.7	10.0
Washed Sand Stockpile	18.0	14.0	10.0	36.0	13.0	20.0	35.0
Fines Stockpile	15.0	31.0	40.0	6.0	26.7	28.0	10.0
RAP Stockpile	10.0	15.0	15.0	15.0	15.0	15.0	15.0
Hydrated Lime	155.0	1.3	1.3	1.3	1.3	1.3	1.3
Virgin Binder @OBC	550.0	4.2	4.5	4.7	4.3	4.8	4.3
Washing Stockpile	3.0	45.0	0.0	0.0	0.0	20.0	0.0
Total Mix Unit Price ($/Ton)		$41.5	$41.8	$43.4	$40.5	$43.8	$41.4

Table 27: Unit Price Breakdown for Mixes T3 and 2036

Material	$/Ton	Mix T3		Mix 2036	
		UNR	JMF	UNR	JMF
3/4" Stockpile	16.0	0.0	0.0	0.0	0.0
1/2" Stockpile	17.0	30.5	35.0	28.7	18.0
3/8" Stockpile	15.0	5.0	5.0	11.0	26.0
Washed Sand Stockpile	18.0	8.0	35.0	37.0	13.0
Fines Stockpile	15.0	40.2	10.0	7.0	26.7
RAP Stockpile	10.0	15.0	15.0	15.0	15.0
Hydrated Lime	155.0	1.3	1.3	1.3	1.3
Virgin Binder @OBC	550.0	5.2	4.6	5.1	4.9
Washing Stockpile	3.0	8.0	0.0	0.0	0.0
Total Mix Unit Price ($/Ton)		$45.8	$43.3	$45.8	$43.8

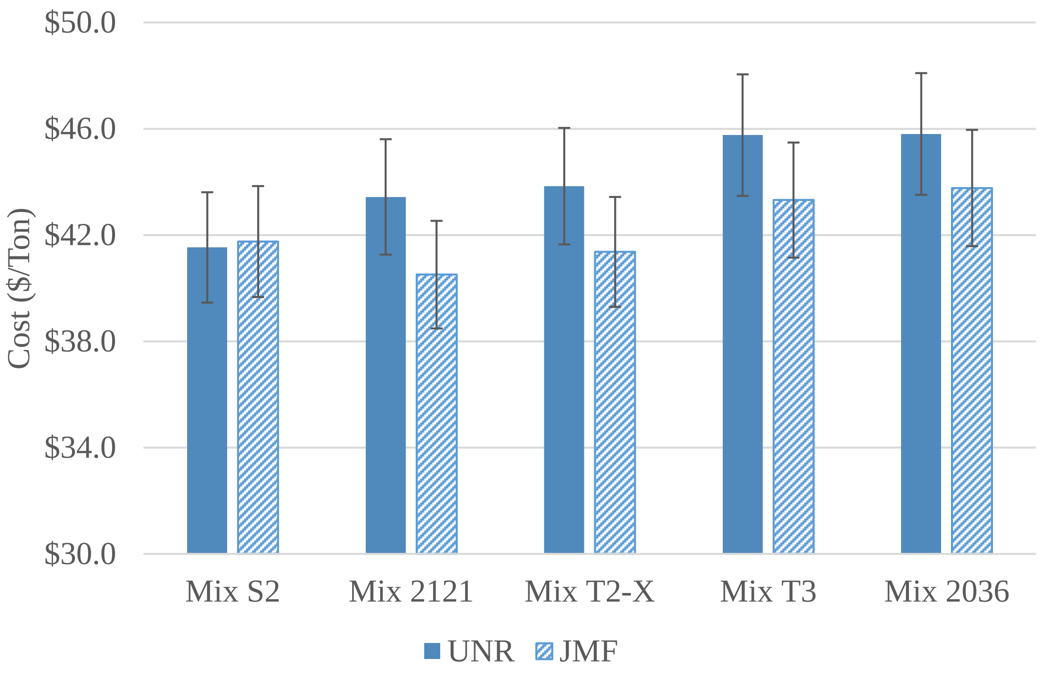


Figure 29: Unit Price Comparison

Chapter 6. Findings and Implementation

6.1 Summary of Findings

The intent of this research study was to assist the RTC of Washoe County, with the transition from Marshall method to the BMD, the latest methodology for designing asphalt concrete mixtures, using the Superpave gyratory compactor and mixture performance tests. Shifting toward to a BMD approach, based just on performance testing, could be a precarious move for any agency considering new concepts in designing asphalt mixtures.

Therefore, the new mixtures generated in this study were designed to meet the Superpave volumetric criteria, and subsequently verified with performance testing intended to be related to the most prevalent distresses in Northern Nevada including long-term durability (cracking and stripping resistance) while maintaining a rutting resistance test (HWTT) that also provides additional moisture resistance data. The research experiments for this project involved evaluating the mixtures through the TSR, the HWTT, the Ideal-CT and the Marshall stability, along with volumetric properties.

The flowchart presented previously in Figure 12, elaborates on the sequence of steps adopted in this study, to design and verify Superpave mixtures with less likelihood of premature failures. Eight new mixtures including 15% RAP and 1.5% hydrated lime, were designed from local materials used in Northern Nevada, while the aggregate blends complied with Superpave broadband specifications and RTC Orange book limits.

Based on the data generated in the execution of the experimental plan and the reported performance analysis, the following findings and conclusions are made:

- All the mixtures except mix S2, when redesigned in the Project Phase II as per Superpave, had higher OBC compared to the producer JMF, which denotes a major improvement for long-term durability considered as most common form of distress in Northern Nevada.
- Altering the gradation and the mixture components represents the key effort to design conventional mixtures meeting the required volumetric properties.
- The Superpave mixtures of Phase II, exhibited greater stripping resistance according to higher TSR values, increased by 6% relative to Phase I mixtures which is likely due to the reduced amount of material passing the #200 sieve in the Superpave mixes conforming to DP requirement.
- Based on HWTT data, Superpave mixtures exhibited approximately 60% less rutting than Phase I mixtures, and higher stability without any indications of stripping failure. This is a large difference, though it should be noted that both the Phase I and Phase II mixtures all possessed very low deformations in the HWTT.
- The marination of virgin aggregates per the Nevada DOT Silver Book for 48 hours, showed high effectiveness in stripping resistance.
- The Ideal-CT values observed on long-term aged specimens with PG64-22 binder, were significantly less than the mixes with PG64-28NV. None of the mixes with PG64-22 met the proposed minimum criteria when long-term aged. Conversely, all of the mixes with PG64-28NV significantly exceed the proposed

criteria and clearly demonstrated the relative improvement in durability performance provided by the modified binder.

- Aggregate stockpiles had to be washed in order to develop mixes meeting the Superpave requirements for two of the three local sources, specifically the VMA and DP criteria. Therefore, it was necessary to reduce the amount of material passing the #200 sieve.
- The Superpave mix unit price increased on average by 2.5$/ton compared to the historical producer JMF prices, due to more binder in the mixes and cost of washing stockpile aggregates. However, it is important to recognize that the producer JMFs used effective specific gravities of RAP and some used bulk SSD aggregate specific gravities for virgin aggregate. Both of these lead to higher VMA values than actual VMA which results in lower asphalt contents. Had correct specific gravity been used in developing historical Marshall mix designs, the asphalt contents would have been higher increasing cost or in other words resulting in less difference in Marshall and Superpave mix costs. Additionally, based on the BMD performance tests, the Superpave mixtures should provide better durability performance than the Marshall mixes have.

6.2 BMD Implementation Plan for RTC Washoe

Construction techniques and mix design methods are subjected to continuous development along with new inventions, new technologies and related implementation strategies. Asphalt concrete mix design methods for flexible pavements have evolved significantly in the last 20 years and the Superpave mix design method has become the industry standard. Due to recent materials introduced into asphalt mixtures such as polymer-modified asphalt binders, high percentages of recycled materials, rubber tire modified asphalt binder, warm mix technologies, rejuvenators and others, the industry is rapidly moving toward the "Balanced Mix Design" (BMD). This is because conventional mix design methods do not ensure good performance of mixtures integrating these new materials. The BMD methodology is a promising approach that can include volumetrics, but also includes rutting and durability tests.

The main goal of this effort was to assist the Regional Transportation Commission (RTC) with the transition from Marshall mix design to a BMD method with the Superpave method as a foundation. However, moving toward a new approach will have impacts on the industry (agencies, contractors, and engineering firms). Agencies have to adopt new methodologies that require new specifications, testing requirements, staff training, acceptance provisions, etc. Contractors and engineer firms have to be prepared to respond to the new specifications successfully as well. Despite the advantages of the BMD methodology, the lack of a well-defined implementation plan could increase the risk during implementation for all of industry. A proposed implementation plan is presented in the flowchart of Figure 30.

The proposed implementation plan is a multi-year plan to create the best opportunity for success. The research study provides the basis for drafting specifications with references to some existing and some new tests and well as mix design criteria. The next phase comprises to set a provisional draft standard including new design procedures, recommended specifications, with QC and acceptance provisions. The draft should be shared with the industry, in order to get constructive feedback and improve the draft guidelines suggested. Industry feedback should be used to make revisions, then wide-spread industry training will take place on the new specifications and test methods.

Training should start as early as the new specifications have been revised and improved. The training should include industry personnel involved in specifying, designing mixtures, and accepting asphalt concrete pavements. The certification of technicians on new sampling and testing procedures including hands-on demonstrations would be needed. The training should extend to the Nevada Alliance Quality Transportation Construction (NAQTC) also such that technicians can be certified for any new test methods added.

The subsequent step is to kick off a limited number of pilot projects, constructed per the new specifications. The construction process should be monitored during all phases to identify any challenges that need to be addressed or deviations from them in the field, if any. The goal of pilot projects is to collect samples during construction, evaluate it with laboratory testing and check the consistency with the anticipated quality level of the new specifications. The pilot project analysis includes collecting feedback from contractor's on observations throughout the projects. If the overall feedback is unsatisfactory either for the agency or for the contractor, then improvement for the proposed guidelines need to be made. Additionally, if unforeseen issues arise during construction, the new specifications should be fine-tuned, followed by extra training and new pilot projects, as necessary.

A safe way to do this is for the pilot projects to be accepted on the old specifications and at the same time be compared to the new specification to see what the impacts would be. This would identify training needs, create awareness around changes, identify specification items that need to be revised and allow the industry to determine how the specification changes will impact it. Based on assessment of the analysis and feedback from the pilot projects the specifications would be further revised, and in the following year the specifications could be implemented. The implementation should start with higher risk projects, for example arterials in the first year of implementation, then expanded to all classifications in the second year. This would allow the industry to adopt to the new specifications, acquire new equipment and get technicians and engineers up to speed on the new specification for successful implementation.

The iteration loop of the proposed flowchart suggests frequent adjustments to improve new guidelines for implementation, until reaching a satisfactory outcome. It is important to keep bear in mind that BMD projects should be monitored for a higher quality level and to consider future contractor concerns after implementation. As with any specification, once fully implemented, it should be reviewed on a reasonable frequency to continually improve the processes associated and the products quality provided by it.

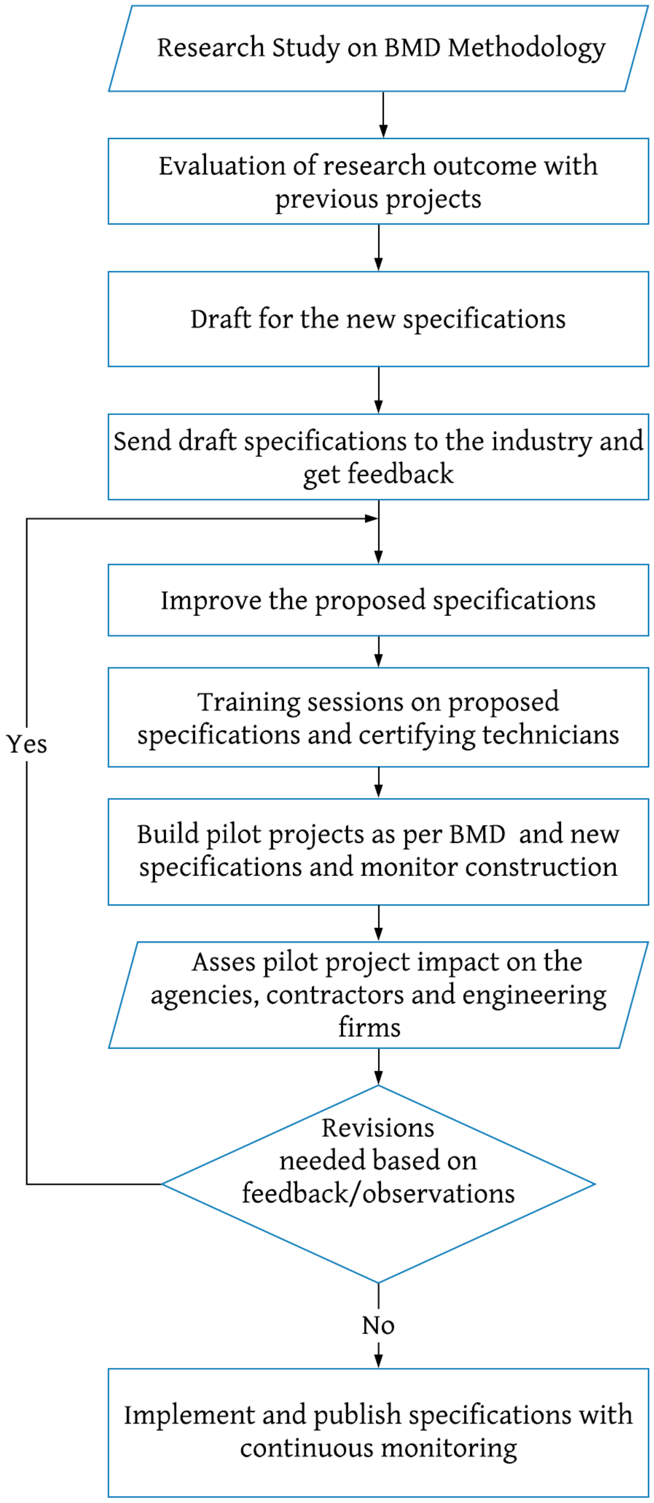


Figure 30: BMD Implementation Flowchart

6.3 Recommendations

Based on the data analysis of the mixture properties and the comprehensive evaluation of performance observations presented in this report, below are the main recommendations to expedite the implementation of the BMD methodology by RTC:

- The BMD methodology can help RTC to enhance sustainability and design high RAP mixtures while monitoring the pavement performance and conserving virgin materials.
- Similar to many recent SHAs implementations, reducing N_{Design} can enrich the mixture with more asphalt binder, and provide better field compaction.
- The BMD and the implementation flowcharts presented in Figure 12 and Figure 30 respectively, are highly recommended for future applications by RTC, while limiting the agency and contractor risk.
- The p200 shall be tightly controlled during mix design process and plant production for accurate volumetric properties and superior performance.
- The binder PG64-28NV is highly recommended alternatively to the binder PG64-22 for long-term durability improvement.
- Including the hydrated lime within the mix gradation is fundamental for better assessment of the mix properties and film thickness.
- The Superpave mix design method specifies using bulk dry specific gravities of virgin and RAP aggregates. This is important because the alternative is to use effective specific gravity for RAP aggregates as an estimate of RAP aggregate bulk specific gravity, which inaccurately over-estimates VMA.

- A well-defined criterion should be established for the Ideal-CT after properly long-term aging the specimens, simulating the long-term durability.
- Based on their practicality and field correlation, the HWTT and the Ideal-CT tests are recommended to evaluate the stability and durability of the mixtures in the BMD methodology.
- A life cycle cost analysis shall evaluate the performance benefit in terms of fatigue and rutting life, relative to the added cost with the Superpave mixtures.

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Chapter 7. Appendices

7.1 Appendix A: Volumetric Properties

Table 28: Summary of Volumetric Properties

Mix	AC	Gmb	Gmm	AV %	VMA %	VFA %	DP %
2036	5.2	2.305	2.450	5.9	14.9	60	1.2
	5.6	2.333	2.436	4.2	14.3	70	1.1
	5.7	2.339	2.434	3.9	14.1	72	1.1
2036-X	5.6	2.340	2.443	4.2	14.0	70	1.2
	5.7	2.342	2.440	4.0	14.0	71	1.1
	5.8	2.343	2.436	3.8	14.1	73	1.1
2121	4.9	2.306	2.461	6.3	15.0	58	1.2
	5.2	2.351	2.450	4.0	13.7	70	1.1
	5.4	2.374	2.442	2.8	13.0	78	1.1
T3	5.4	2.317	2.436	4.9	14.7	67	1.1
	5.5	2.332	2.432	4.1	14.4	71	1.1
	5.7	2.352	2.425	3.0	13.7	78	1.1
T2	4.8	2.345	2.474	5.2	13.6	62	1.3
	5.1	2.367	2.463	3.9	13.0	70	1.2
	5.3	2.375	2.456	3.3	12.9	74	1.1
T2 -X	5.1	2.352	2.463	4.5	13.6	67	1.2
	5.2	2.358	2.460	4.1	13.5	69	1.2
	5.3	2.363	2.456	3.8	13.4	72	1.2
S2	4.6	2.421	2.519	3.9	13.0	70	1.0
	4.8	2.430	2.516	3.4	12.9	74	0.9
	5.3	2.447	2.497	2.0	12.7	84	0.9
S2-X	4.6	2.423	2.524	4.0	12.9	69	1.0
	4.8	2.457	2.517	2.4	11.9	80	1.0

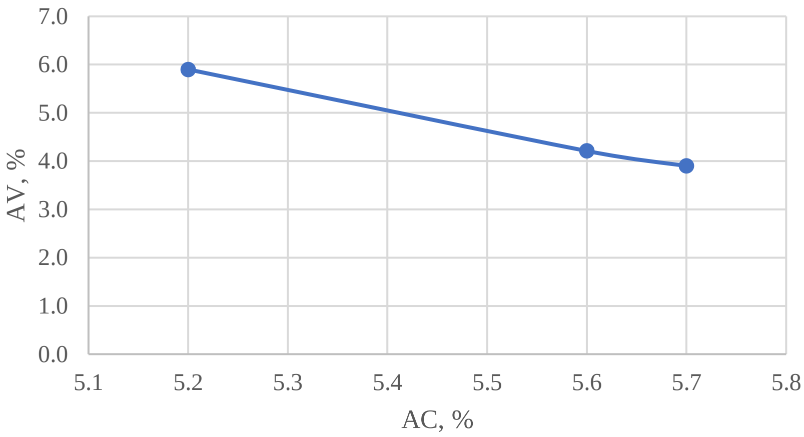


Figure 31: Mix 2036 AV vs AC

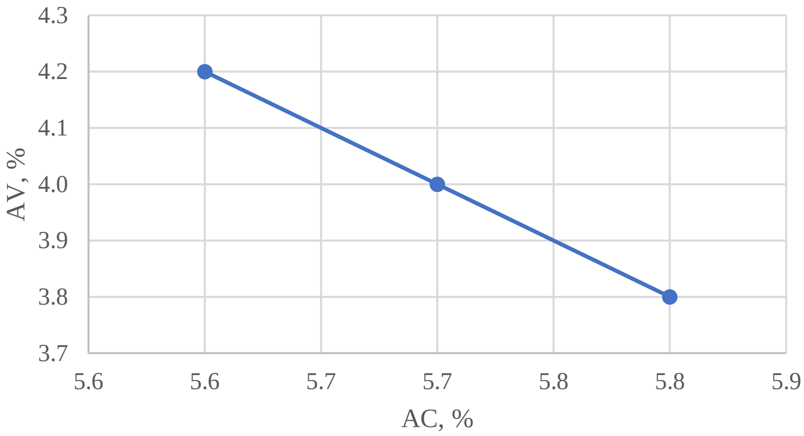


Figure 32: Mix 2036-X AV vs AC

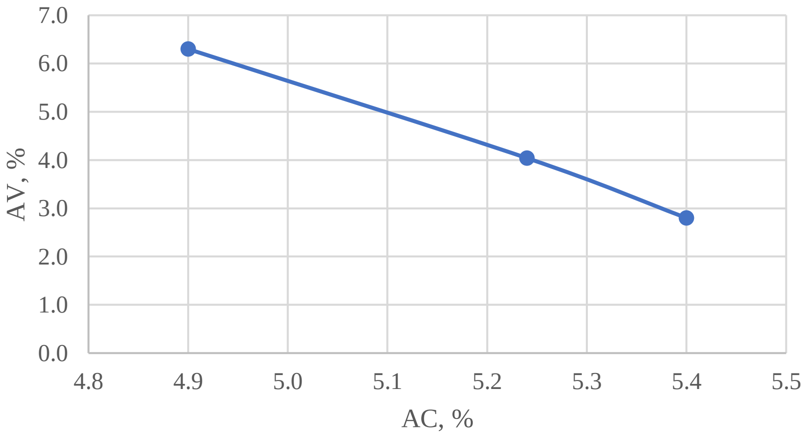


Figure 33:Mix 2121 AV vs AC

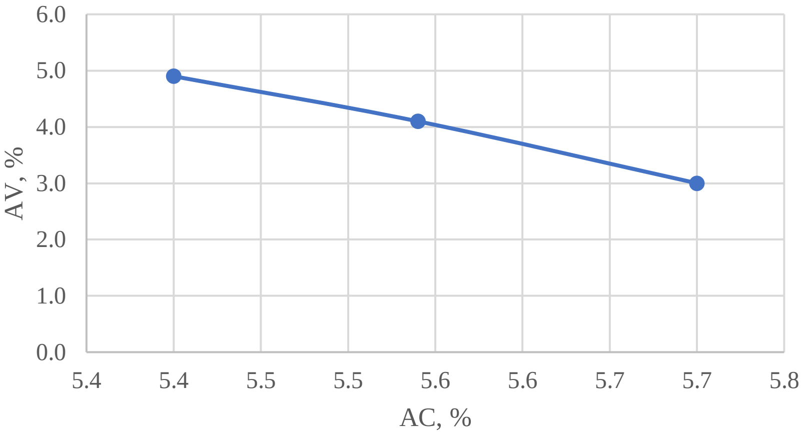


Figure 34: Mix T3 AV vs AC

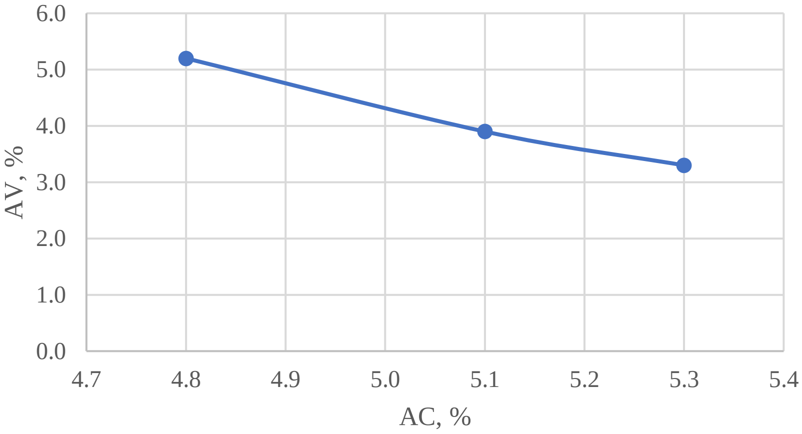


Figure 35: Mix T2 AV vs AC

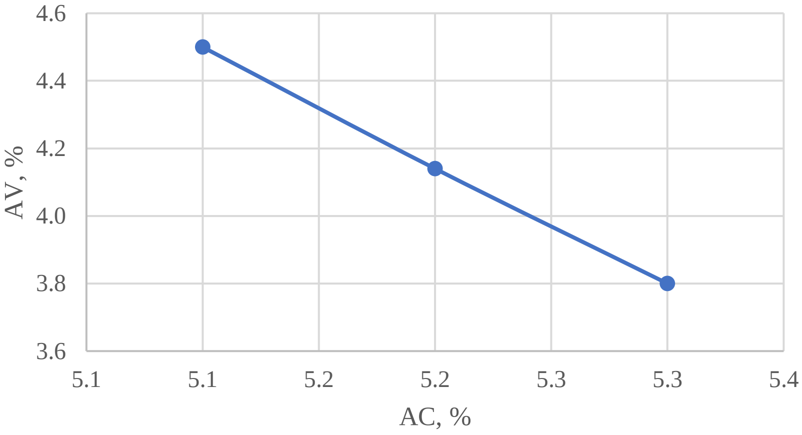


Figure 36: Mix T2-X AV vs AC

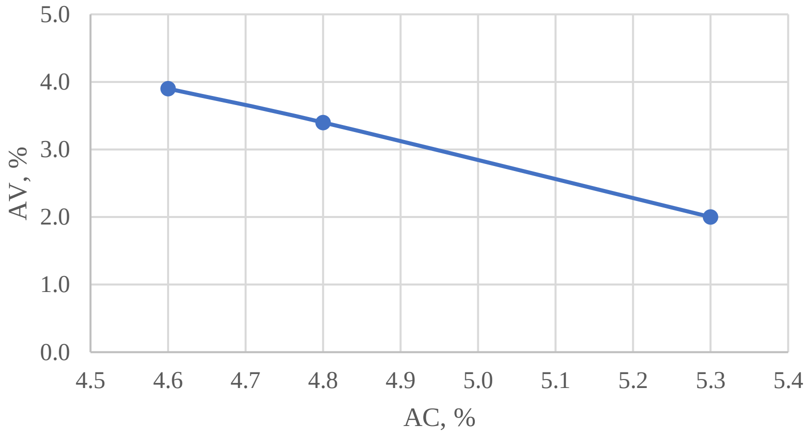


Figure 37: Mix S2 AV vs AC

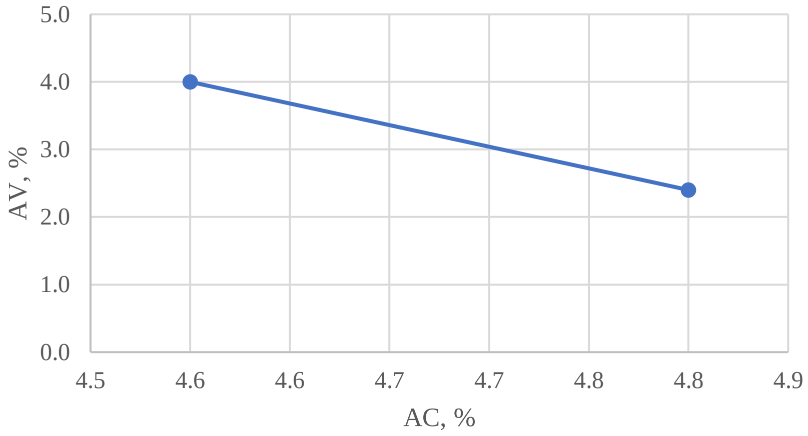


Figure 38: Mix S2-X AV vs AC

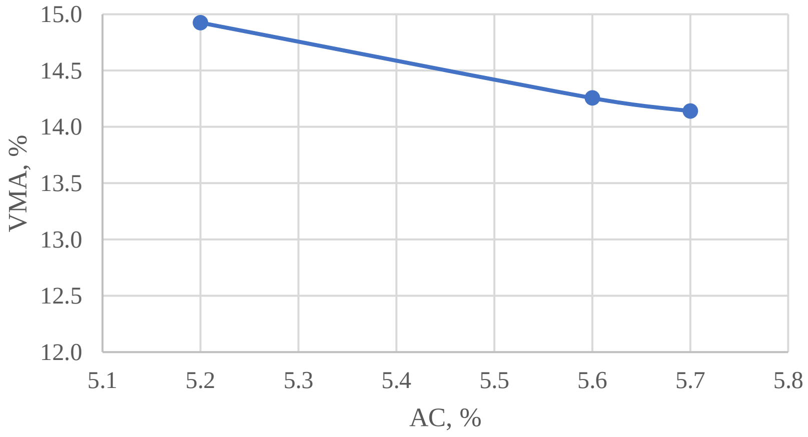


Figure 39: Mix 2036 VMA vs AC

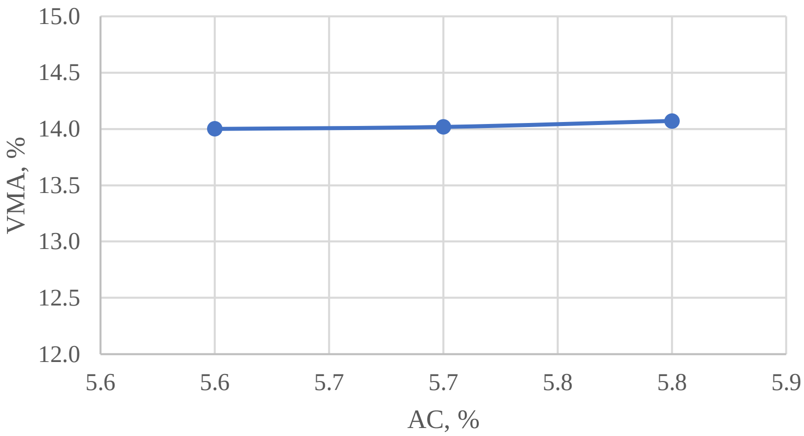


Figure 40: Mix 2036-X VMA vs AC

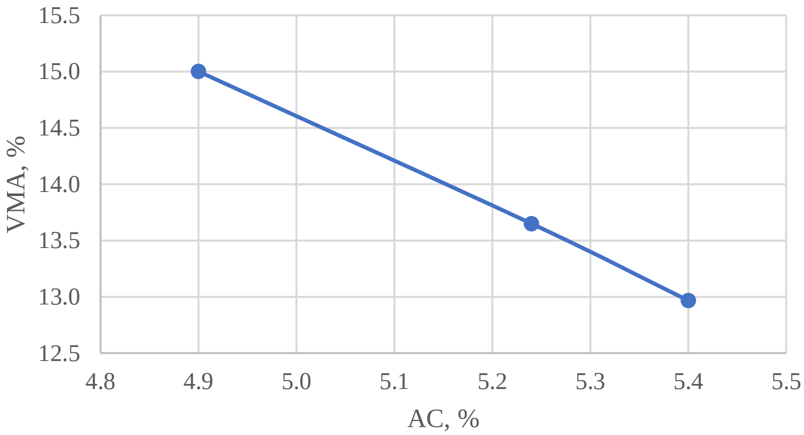


Figure 41: Mix 2121 VMA vs AC

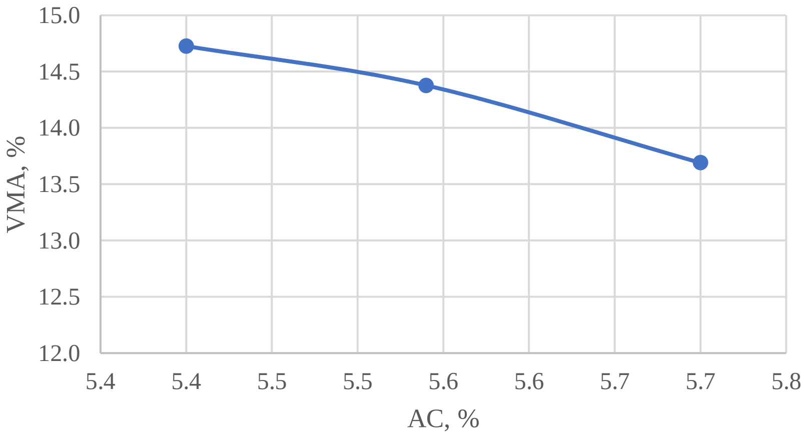


Figure 42: Mix T3 VMA vs AC

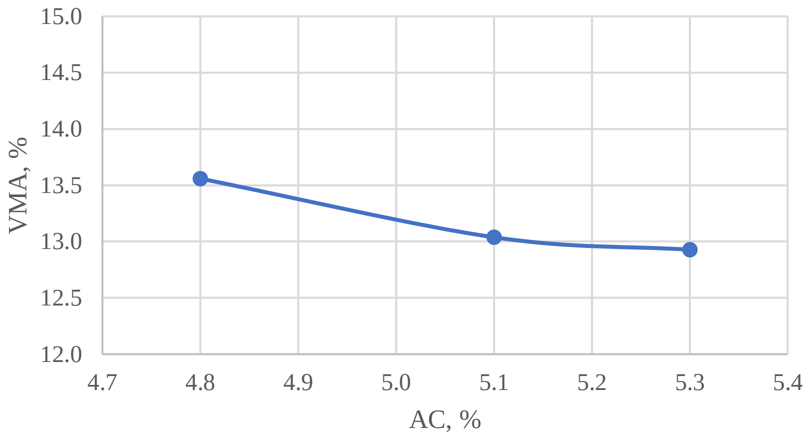


Figure 43: Mix T2 VMA vs AC

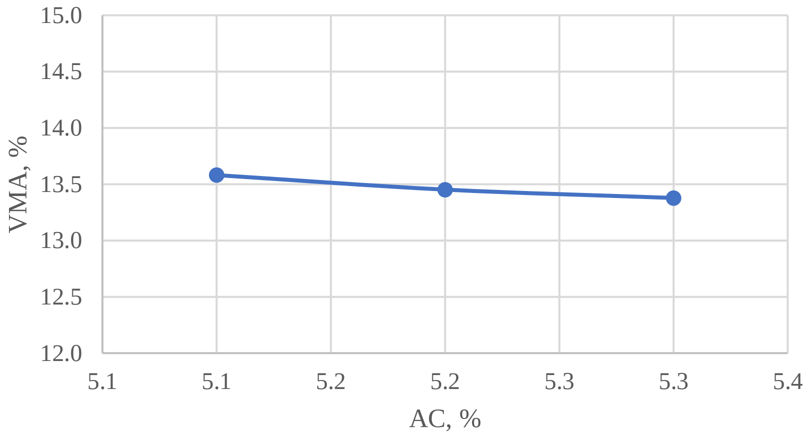


Figure 44: Mix T2-X VMA vs AC

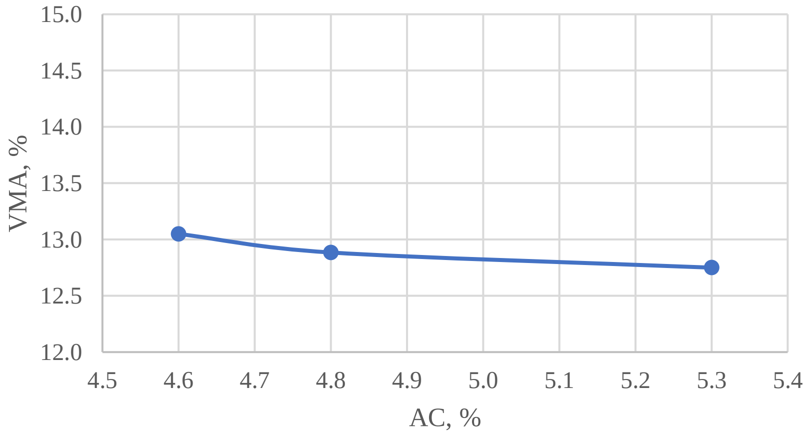


Figure 45: Mix S2 VMA vs AC

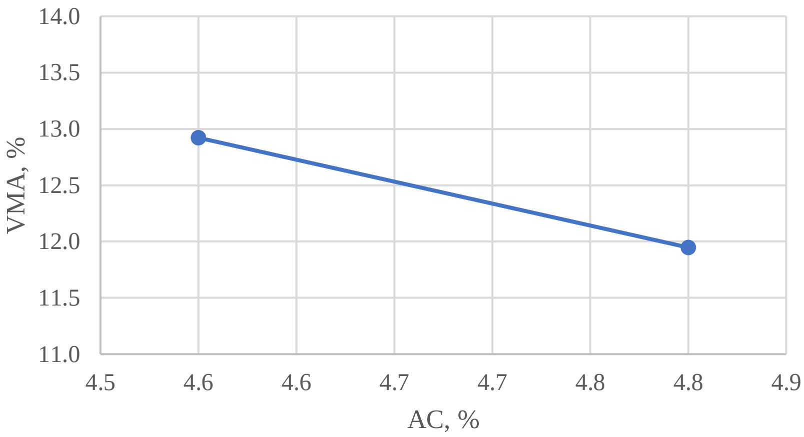


Figure 46: Mix S2-X VMA vs AC

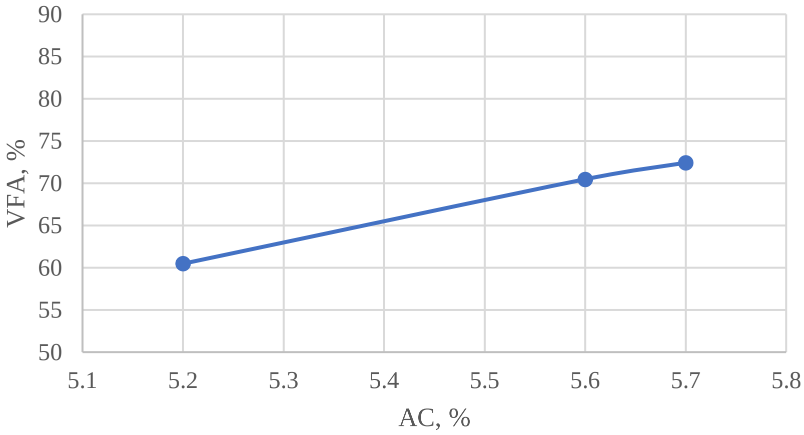


Figure 47: Mix 2036 VFA vs AC

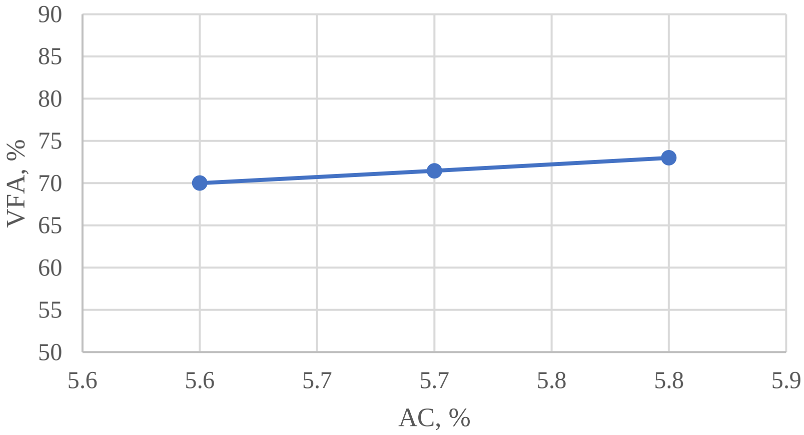


Figure 48: Mix 2036-X VFA vs AC

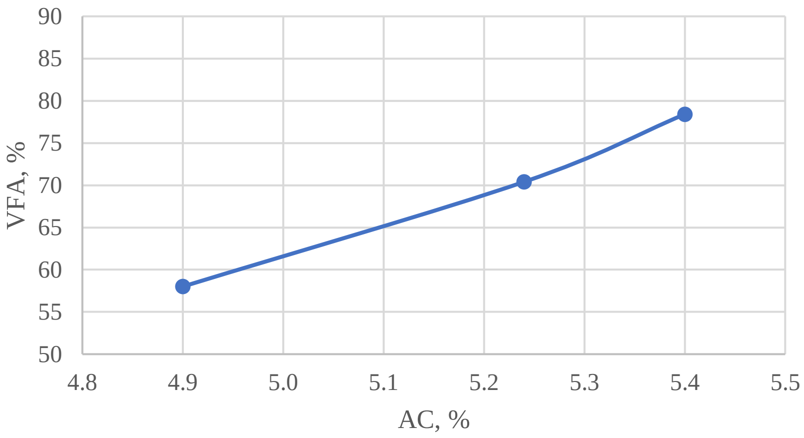


Figure 49: Mix 2121 VFA vs AC

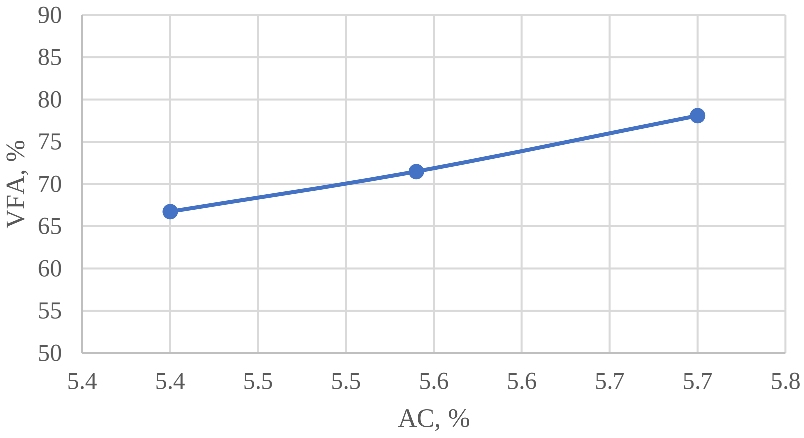


Figure 50: Mix T3 VFA vs AC

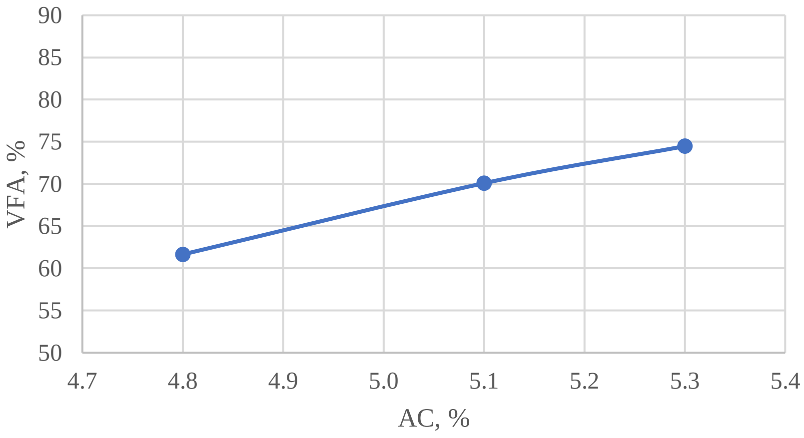


Figure 51: Mix T2 VFA vs AC

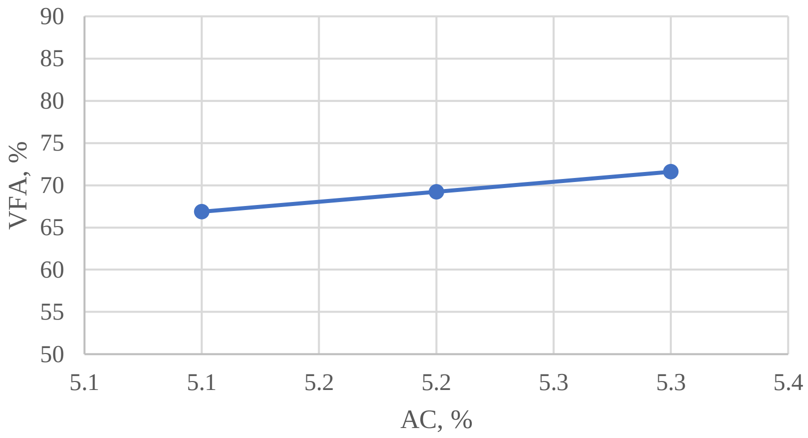
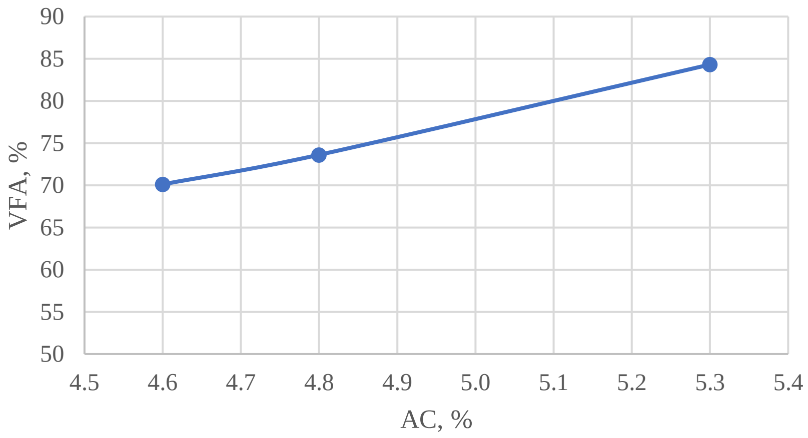


Figure 52: Mix T2-X VFA vs AC



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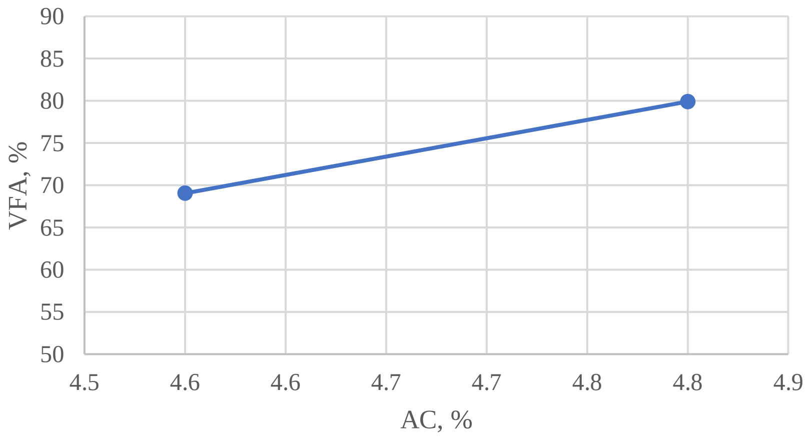

Figure 54: Mix S2-X VFA vs AC

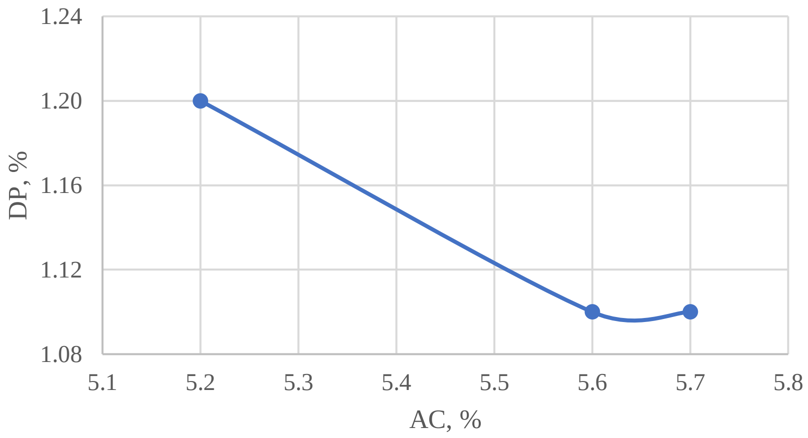

Figure 55: Mix 2036 DP vs AC

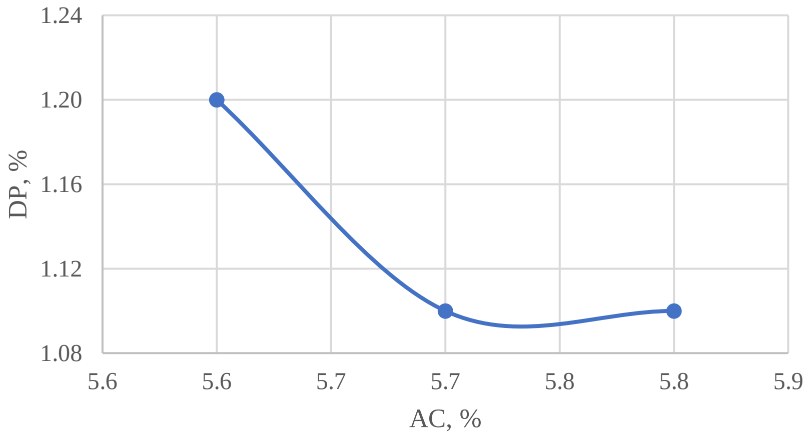

Figure 56: Mix 2036-X DP vs

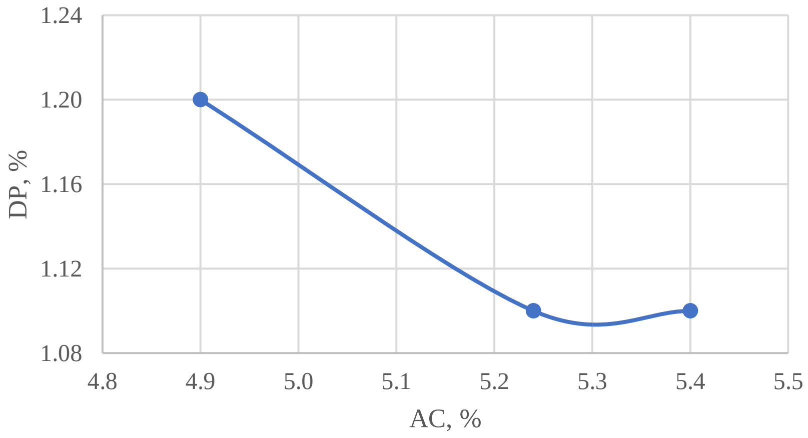

Figure 57: Mix 2121 DP vs AC

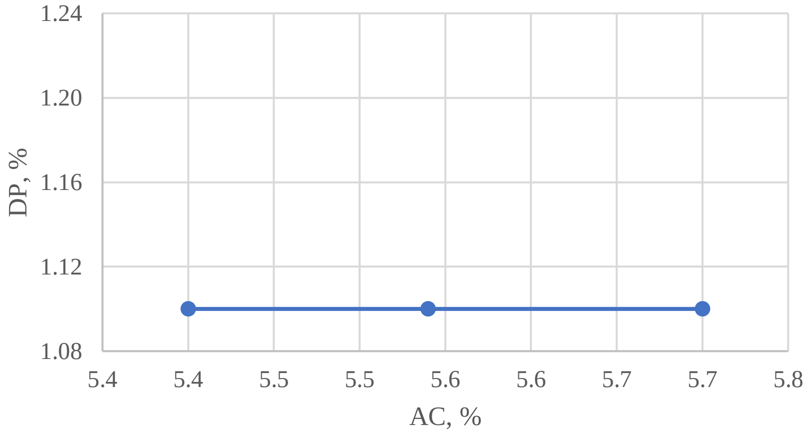

Figure 58: Mix T3 DP vs AC

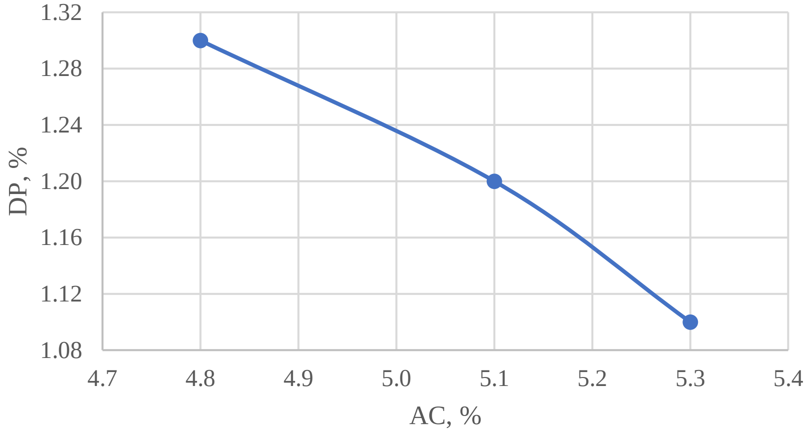

Figure 59: Mix T2 DP vs AC

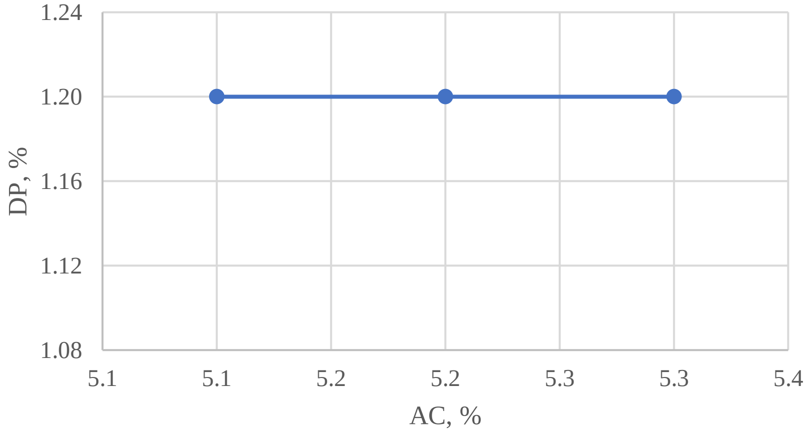

Figure 60:Mix T2-X DP vs AC

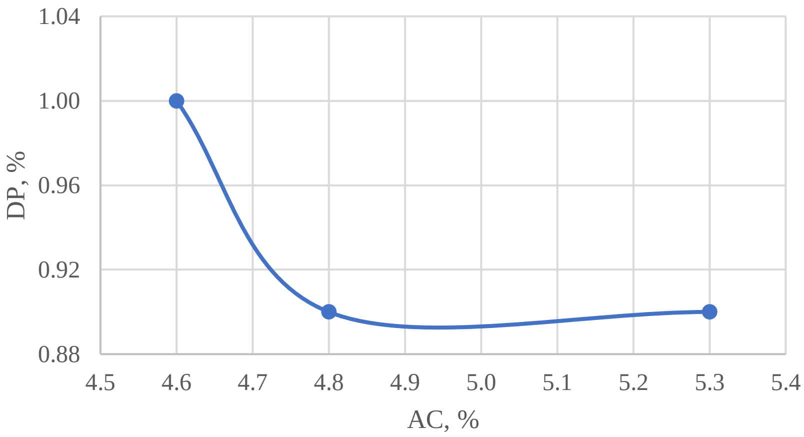

Figure 61: Mix S2 DP vs AC

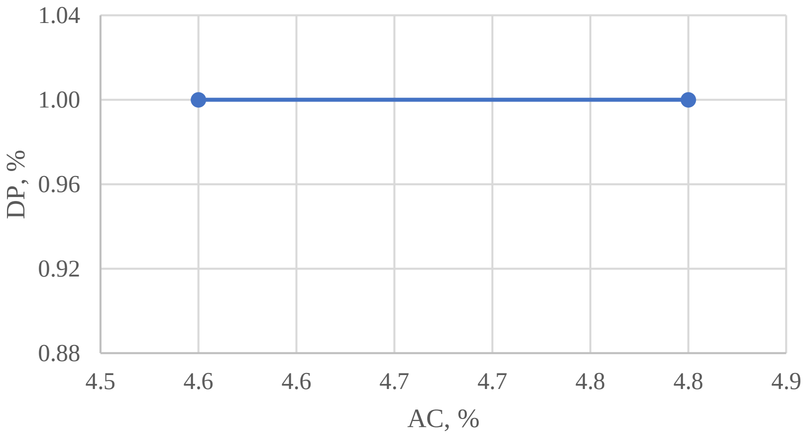

Figure 62: Mix S2-X DP vs AC

7.2 Appendix B: TSR

Table 29: Mix 2036 TSR Samples

Mix ID	Wet			Dry		
	TSR 1	TSR 2	TSR 3	TSR 4	TSR 5	TSR 6
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3714.9	3711.9	3706.7	3722.9	3704.9	3722.9
SSD mass, g	3728.0	3727.0	3722.5	3738.1	3720.6	3733.4
Mass in water, g	2082.0	2085.5	2082.6	2091.2	2077.0	2092.0
Bulk specific gravity	2.257	2.261	2.260	2.261	2.254	2.268
Maximum specific gravity	2.436	2.436	2.436	2.436	2.436	2.436
AV, %	7.3	7.2	7.2	7.2	7.5	6.9
Average AV % subset	7.2			7.2		
Saturation %	74	72	73	N/A	N/A	N/A
Strength, psi@77F	97	98	110	110	113	117
COV, %	6%			2%		
Average Strength, psi	102			113		
TSR (%) Dry/Wet @77F	90%					

Table 30: Mix 2036-X TSR Samples

Mix ID	Wet			Dry		
	TSR 1	TSR 2	TSR 3	TSR 4	TSR 5	TSR 6
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3724.1	3723.6	3723.3	3724.8	3721.3	3724.3
SSD mass, g	3737.2	3735.9	3735.6	3738.5	3735.7	3739.2
Mass in water, g	2094.4	2092.6	2092.1	2095.5	2092.1	2103.2
Bulk specific gravity	2.267	2.266	2.265	2.267	2.264	2.276
Maximum specific gravity	2.440	2.440	2.440	2.440	2.440	2.440
AV, %	7.1	7.1	7.1	7.1	7.2	6.7
Average AV % subset	7.1			7.0		
Saturation %	70	79	78	N/A	N/A	N/A
Strength, psi@77F	126	121	127	145	142	138
COV, %	2%			2%		
Average Strength, psi	125			142		
TSR (%) Dry/Wet @77F	88%					

Table 31: Mix 2121 TSR Samples

Mix ID	Wet			Dry		
	TSR 1	TSR 2	TSR 3	TSR 4	TSR 5	TSR 6
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3738.6	3734.4	3743.7	3738.3	3743.0	3742.6
SSD mass, g	3760.4	3758.4	3762.0	3757.0	3764.0	3761.5
Mass in water, g	2117.5	2115.8	2125.3	2110.1	2126.2	2119.2
Bulk specific gravity	2.276	2.273	2.287	2.270	2.285	2.279
Maximum specific gravity	2.450	2.450	2.450	2.450	2.450	2.450
AV, %	7.1	7.2	6.6	7.3	6.7	7.0
Average AV % subset	7.0			7.0		
Saturation %	74	78	70	N/A	N/A	N/A
Strength, psi@77F	111	95	104	110	120	125
COV, %	6%			5%		
Average Strength, psi	103			118		
TSR (%) Dry/Wet @77F	87%					

Table 32: Mix T3 TSR Samples

Mix ID	Wet			Dry		
	TSR 1	TSR 2	TSR 3	TSR 4	TSR 5	TSR 6
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3716.4	3716.7	3719.6	3719.2	3719.3	3713.5
SSD mass, g	3730.2	3739.1	3733.0	3732.0	3733.2	3728.1
Mass in water, g	2084.1	2094.7	2082.6	2093.1	2091.7	2081.3
Bulk specific gravity	2.258	2.260	2.254	2.269	2.266	2.255
Maximum specific gravity	2.432	2.432	2.432	2.432	2.432	2.432
AV, %	7.2	7.1	7.3	6.7	6.8	7.3
Average AV % subset	7.2			6.9		
Saturation %	72	79	76	N/A	N/A	N/A
Strength, psi@77F	104	100	100	111	111	106
COV, %	2%			2%		
Average Strength, psi	101			109		
TSR (%) Dry/Wet @77F	93%					

Table 33: Mix T2 TSR Samples

Mix ID	Wet			Dry		
	TSR 1	TSR 2	TSR 3	TSR 4	TSR 5	TSR 6
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3769.2	3759.2	3766.1	3766.2	3764.7	3772.2
SSD mass, g	3784.8	3777.1	3783.6	3780.3	3782.1	3787.6
Mass in water, g	2140.3	2132.0	2140.7	2132.9	2136.1	2145.2
Bulk specific gravity	2.292	2.285	2.292	2.286	2.287	2.297
Maximum specific gravity	2.464	2.464	2.464	2.464	2.464	2.464
AV, %	7.0	7.3	7.0	7.2	7.2	6.8
Average AV % subset	7.1			7.1		
Saturation %	77	74	71	N/A	N/A	N/A
Strength, psi@77F	100	97	99	102	101	116
COV, %	1%			7%		
Average Strength, psi	99			106		
TSR (%) Dry/Wet @77F	93%					

Table 34: Mix T2-X TSR Samples

Mix ID	Wet			Dry		
	TSR 1	TSR 2	TSR 3	TSR 4	TSR 5	TSR 6
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3765.9	3766.0	3769.9	3761.3	3767.3	3763.6
SSD mass, g	3787.6	3788.2	3789.1	3777.9	3786.5	3781.5
Mass in water, g	2135.7	2137.5	2144.5	2130.2	2138.0	2137.1
Bulk specific gravity	2.280	2.281	2.292	2.283	2.285	2.289
Maximum specific gravity	2.460	2.460	2.460	2.460	2.460	2.460
AV, %	7.3	7.2	6.8	7.2	7.1	7.0
Average AV % subset	7.1			7.1		
Saturation %	72	74	73	N/A	N/A	N/A
Strength, psi@77F	128	139	141	150	163	150
COV, %	4%			4%		
Average Strength, psi	136			154		
TSR (%) Dry/Wet @77F	88%					

Table 35: Mix S2 TSR Samples

Mix ID	Wet			Dry		
	TSR 1	TSR 2	TSR 3	TSR 4	TSR 5	TSR 6
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3799.0	3801.1	3800.5	3798.5	3800.8	3801.2
SSD mass, g	3825.7	3823.5	3832.7	3824.7	3830.9	3832.0
Mass in water, g	2198.8	2206.2	2207.6	2211.0	2207.7	2208.0
Bulk specific gravity	2.335	2.350	2.339	2.354	2.342	2.341
Maximum specific gravity	2.519	2.519	2.519	2.519	2.519	2.519
AV, %	7.3	6.7	7.2	6.6	7.1	7.1
Average AV % subset	7.1			6.9		
Saturation %	71	70	72	N/A	N/A	N/A
Strength, psi@77F	98	110	101	112	113	112
COV, %	5%			0%		
Average Strength, psi	103			112		
TSR (%) Dry/Wet @77F	92%					

Table 36: Mix S2-X TSR Samples

Mix ID	Wet			Dry		
	TSR 1	TSR 2	TSR 3	TSR 4	TSR 5	TSR 6
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3806.2	3806.4	3805.2	3808.4	3809.0	3810.0
SSD mass, g	3833.0	3837.5	3835.0	3835.7	3833.5	3834.0
Mass in water, g	2212.0	2209.2	2209.0	2213.3	2210.6	2203.0
Bulk specific gravity	2.348	2.338	2.340	2.347	2.347	2.336
Maximum specific gravity	2.524	2.524	2.524	2.524	2.524	2.524
AV, %	7.0	7.4	7.3	7.0	7.0	7.5
Average AV % subset	7.2			7.2		
Saturation %	70	70	71	N/A	N/A	N/A
Strength, psi@77F	126	118	121	154	138	145
COV, %	3%			4%		
Average Strength, psi	122			146		
TSR (%) Dry/Wet @77F	84%					

7.3 Appendix C: HWTT

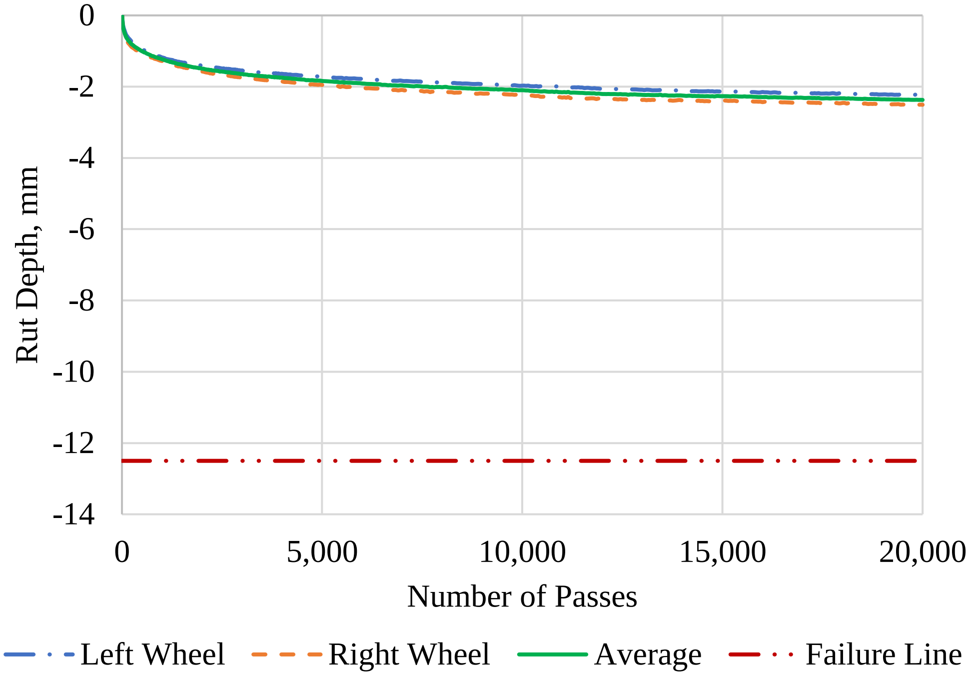

Figure 63:Mix 2036 HWTT

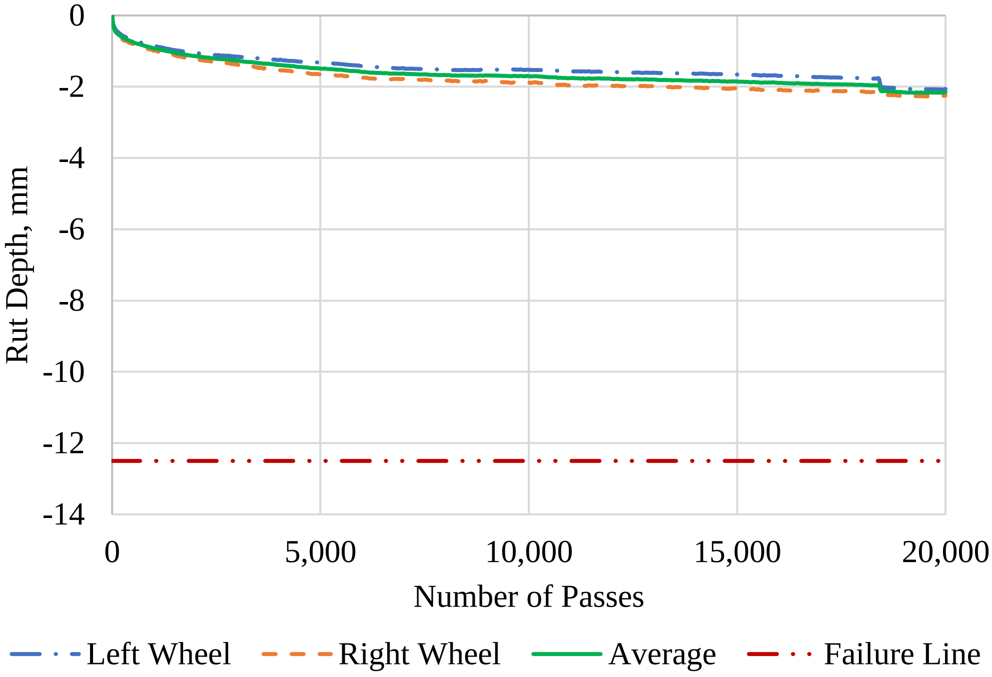

Figure 64: Mix 2036-X HWTT

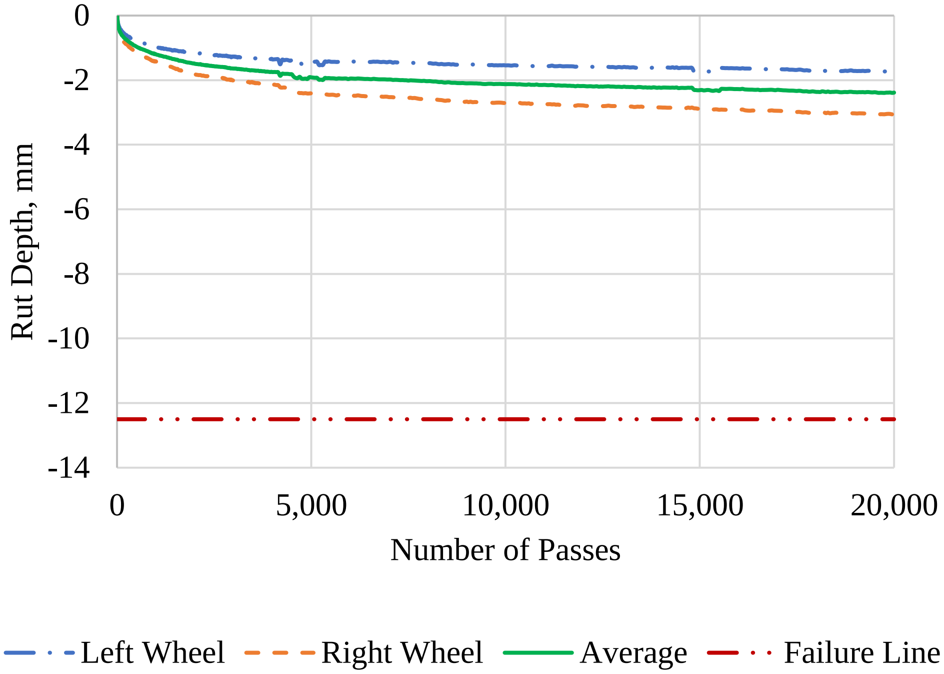

Figure 65:Mix 2121 HWTT

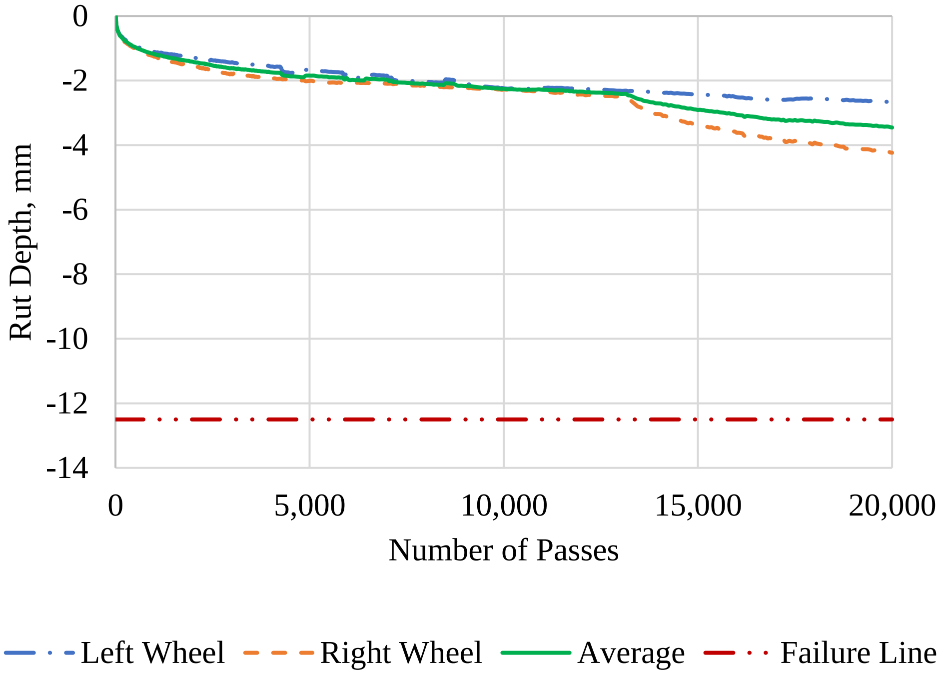

Figure 66:Mix T3 HWTT

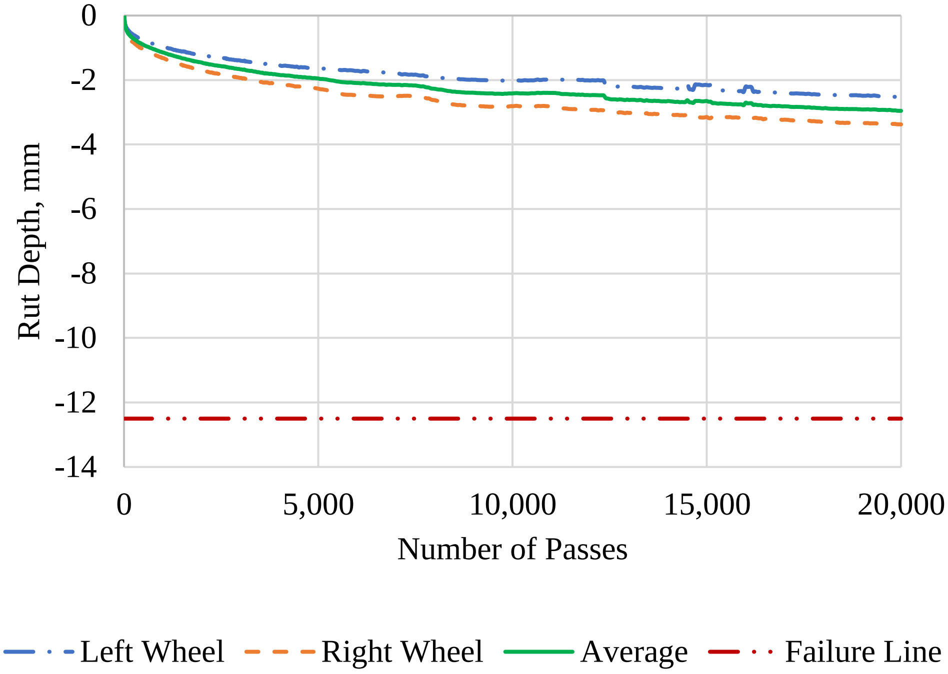

Figure 67:Mix T2 HWTT

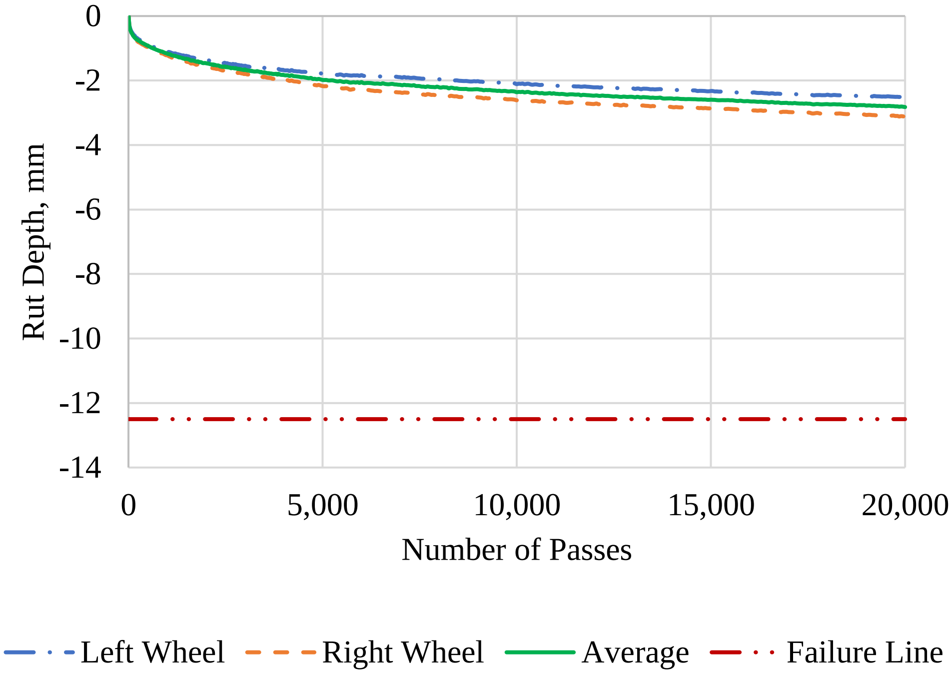

Figure 68: Mix T2-X HWTT

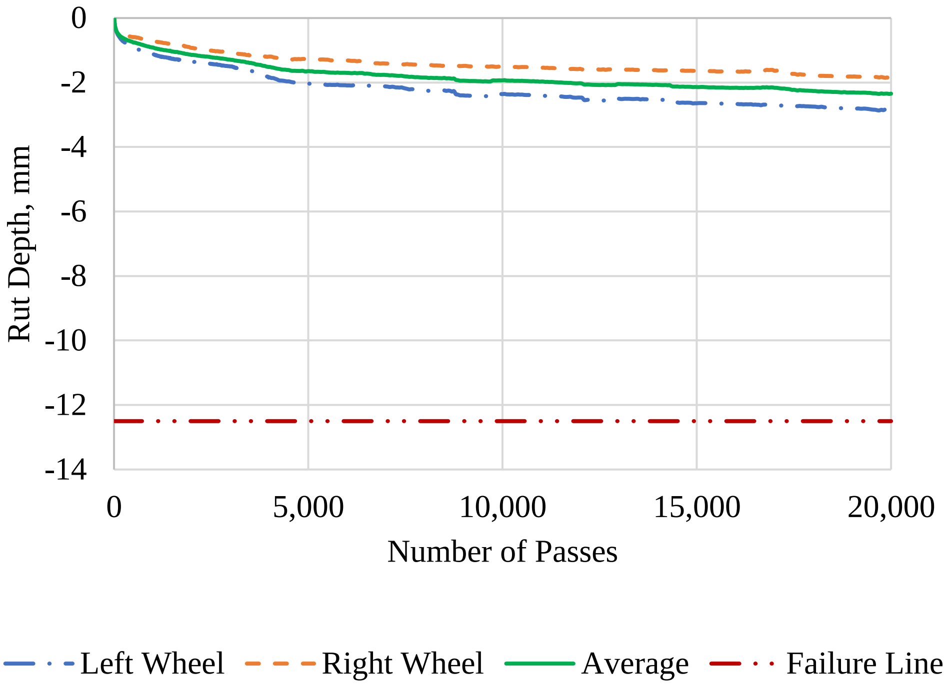

Figure 69:Mix S2 HWTT

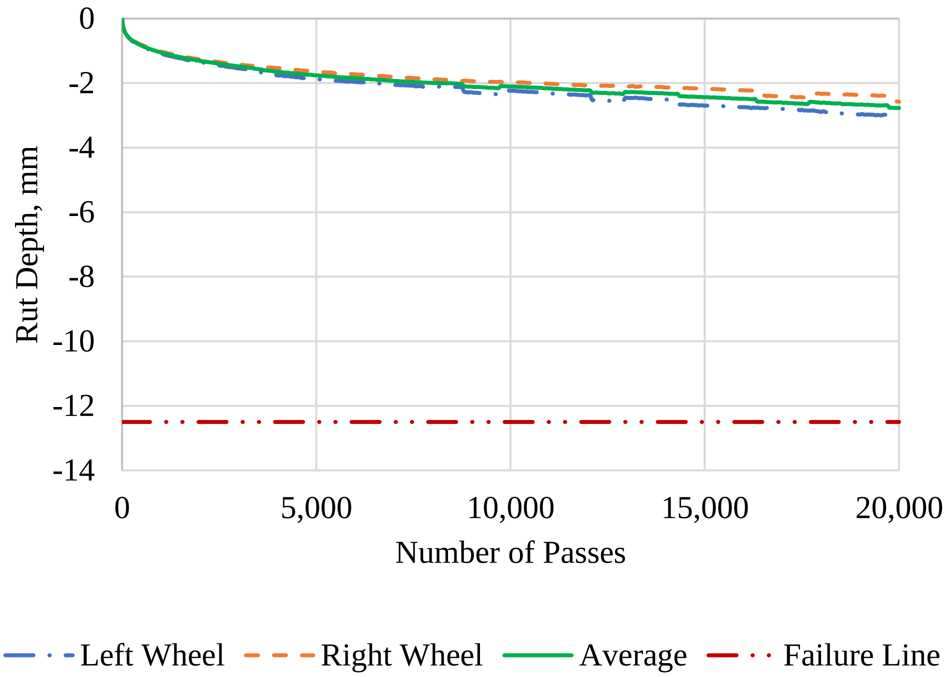

Figure 70: Mix S2-X HWTT

7.4 Appendix D: Ideal-CT

Table 37: Mix 2036 Ideal-CT Samples

Mix ID	Ideal-CT Cond			Ideal-CT Uncond			Ideal-CT Long		
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3714.9	3711.9	3706.7	3722.9	3704.9	3722.9	3721.7	3722.8	3722.9
SSD mass, g	3728.0	3727.0	3722.5	3738.1	3720.6	3733.4	3739.1	3741.4	3739.5
Mass in water, g	2082.0	2085.5	2082.6	2091.2	2077.0	2092.0	2098.9	2103.4	2098.6
Bulk specific gravity	2.257	2.261	2.260	2.261	2.254	2.268	2.269	2.273	2.269
Maximum specific gravity	2.436	2.436	2.436	2.436	2.436	2.436	2.436	2.436	2.436
AV, %	7.4	7.2	7.2	7.2	7.5	6.9	6.9	6.7	6.9
Ideal-CT @77F	222	243	255	142	145	136	89	65	72
d1s (≤13.5)	13.4			3.7			10.5		
Average Ideal-CT	240			141			75		

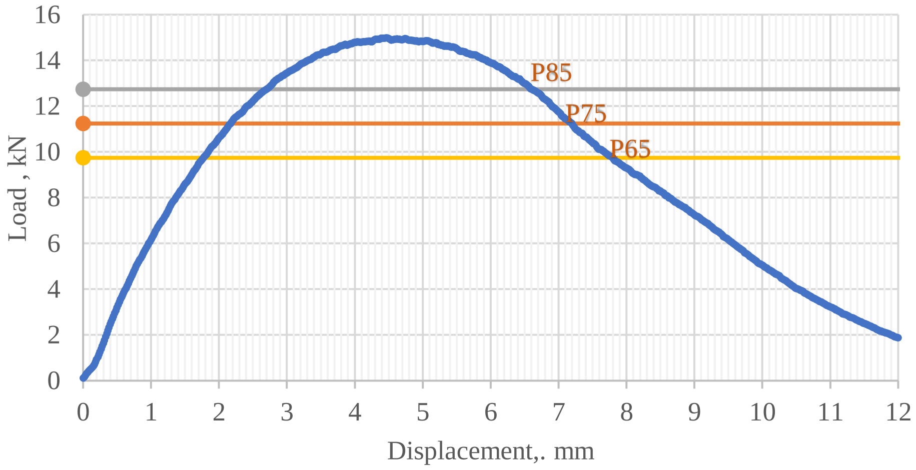

Figure 71:Mix 2036 Ideal-CT Conditioned 1

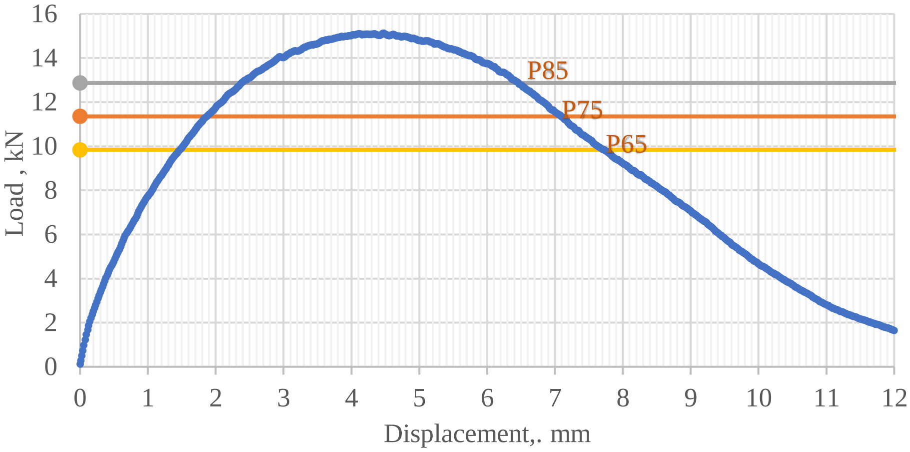

Figure 72:Mix 2036 Ideal-CT Conditioned 2

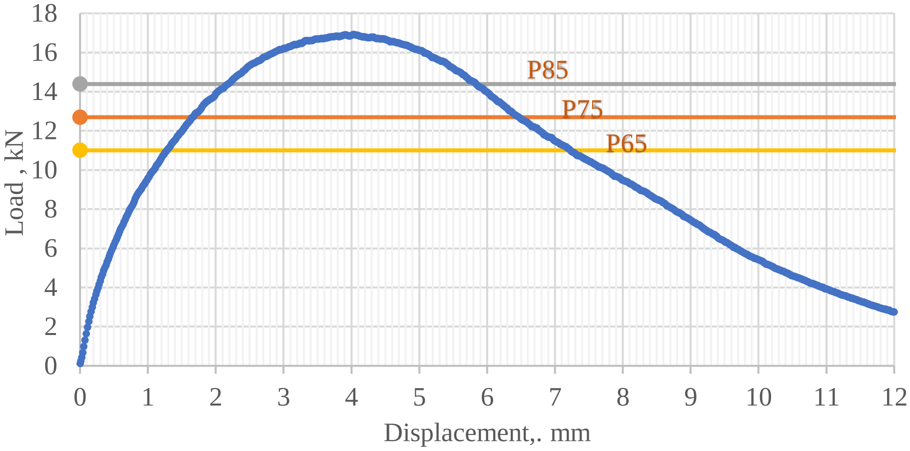

Figure 73:Mix 2036 Ideal-CT Conditioned 3

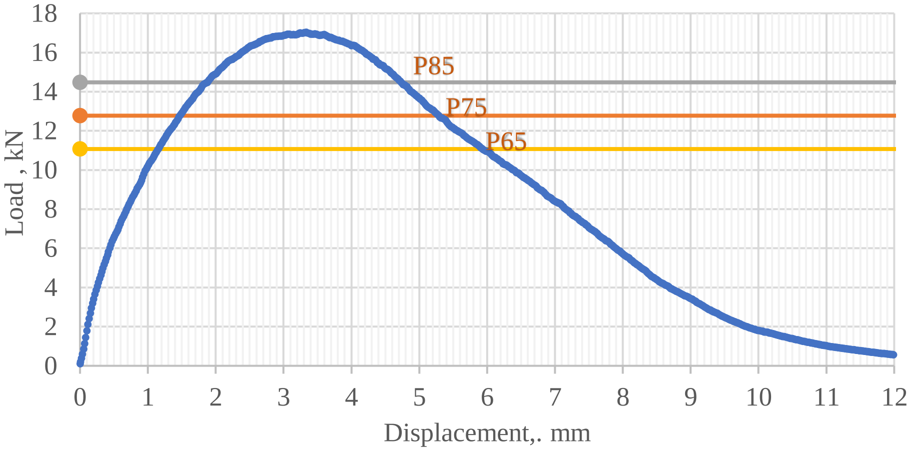

Figure 74:Mix 2036 Ideal-CT Unconditioned 1

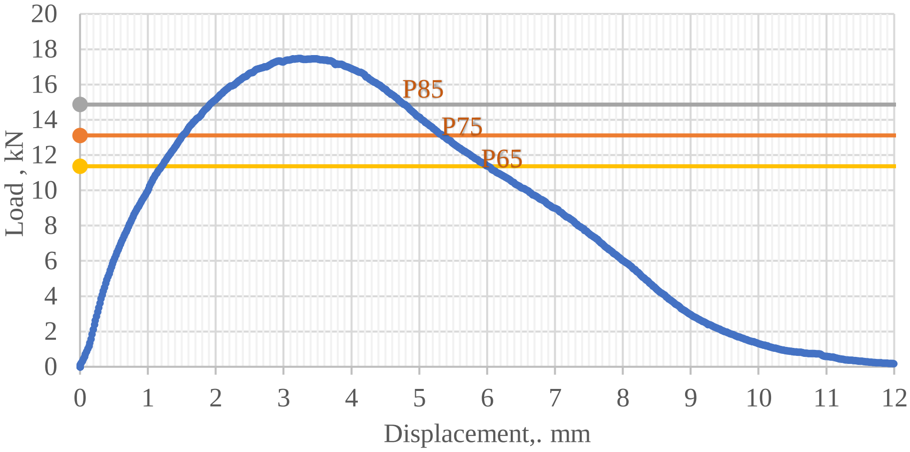

Figure 75:Mix 2036 Ideal-CT Unconditioned 2

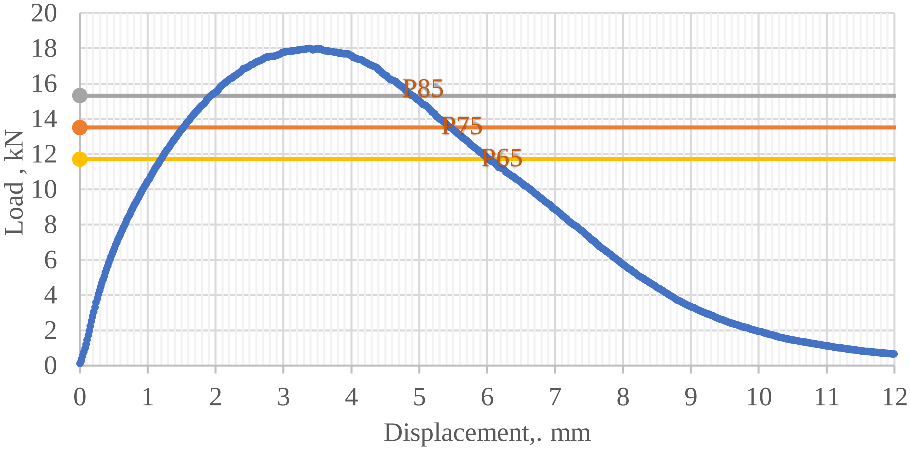

Figure 76:Mix 2036 Ideal-CT Unconditioned 3

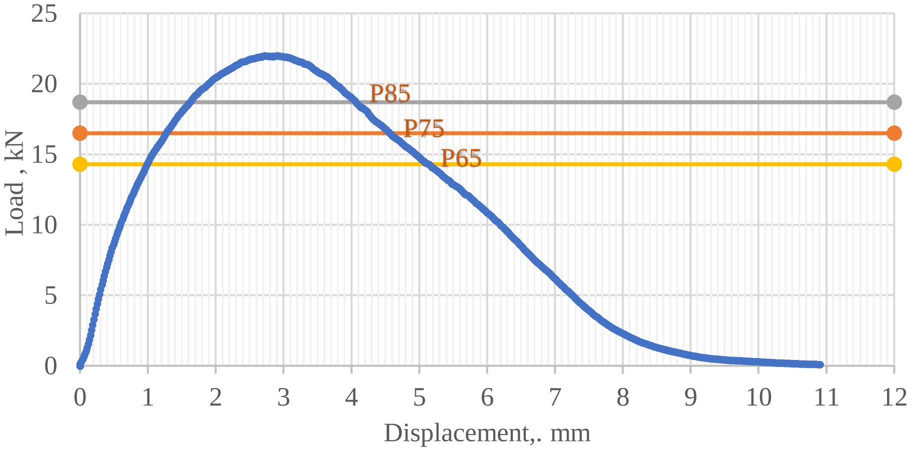

Figure 77:Mix 2036 Ideal-CT Long 1

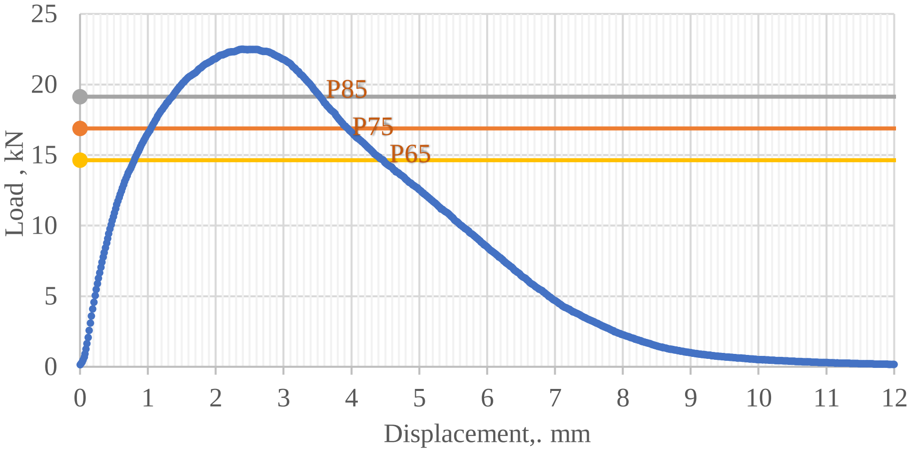

Figure 78:Mix 2036 Ideal-CT Long 2

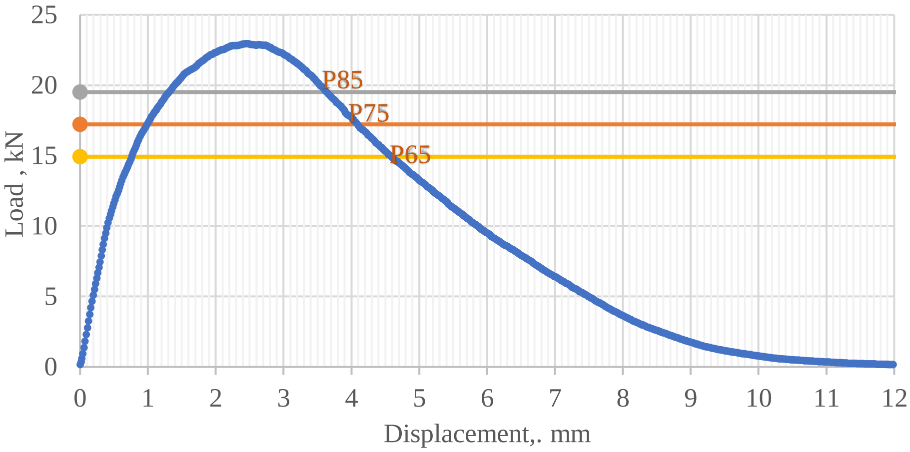

Figure 79:Mix 2036 Ideal-CT Long 3

Table 38:Mix 2036-X Ideal-CT Samples

Mix ID	Ideal-CT Cond			Ideal-CT Uncond			Ideal-CT Long		
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3724.1	3723.6	3723.3	3724.8	3721.3	3724.3	3724.2	3725.9	3730.5
SSD mass, g	3737.2	3735.9	3735.6	3738.5	3735.7	3739.2	3736.9	3740.9	3748.5
Mass in water, g	2094.4	2092.6	2092.1	2095.5	2092.1	2103.2	2096.3	2100.5	2108.2
Bulk specific gravity	2.267	2.266	2.265	2.267	2.264	2.276	2.270	2.271	2.274
Maximum specific gravity	2.440	2.440	2.440	2.440	2.440	2.440	2.440	2.440	2.440
AV, %	7.1	7.1	7.2	7.1	7.2	6.7	7.0	6.9	6.8
Ideal-CT @77F	170	173	155	70	85	59	32	46	52
d1s (≤13.5)	7.7			10.5			8.5		
Average Ideal-CT	166			71			43		

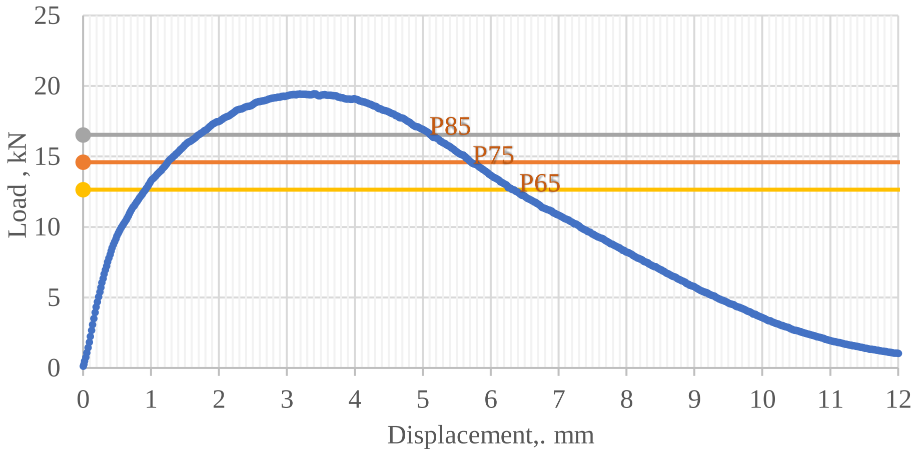

Figure 80:Mix 2036-X Ideal-CT Conditioned 1

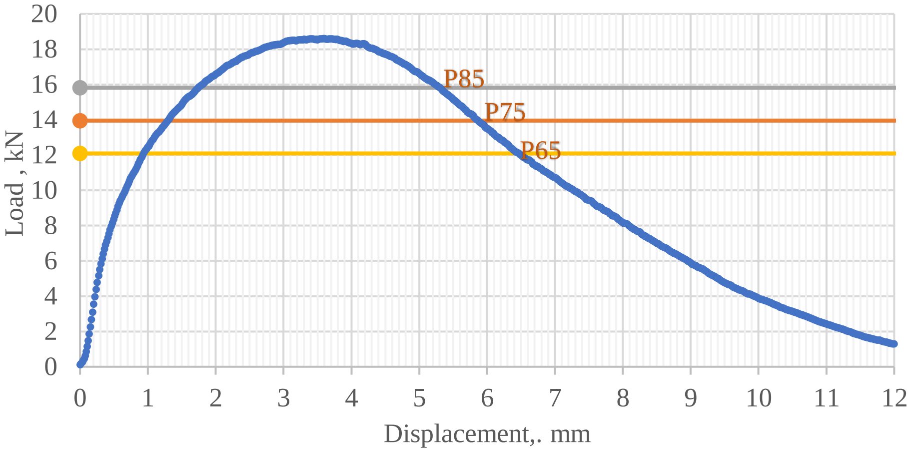

Figure 81:Mix 2036-X Ideal-CT Conditioned 2

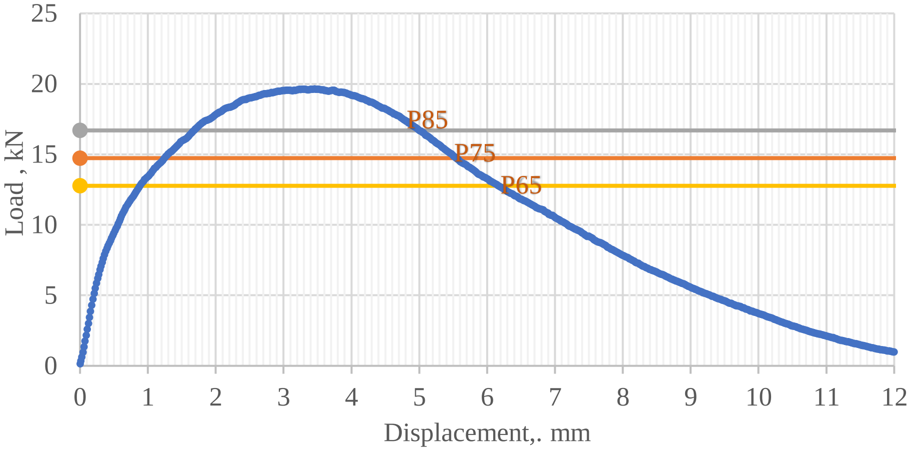

Figure 82:Mix 2036-X Ideal-CT Conditioned 3

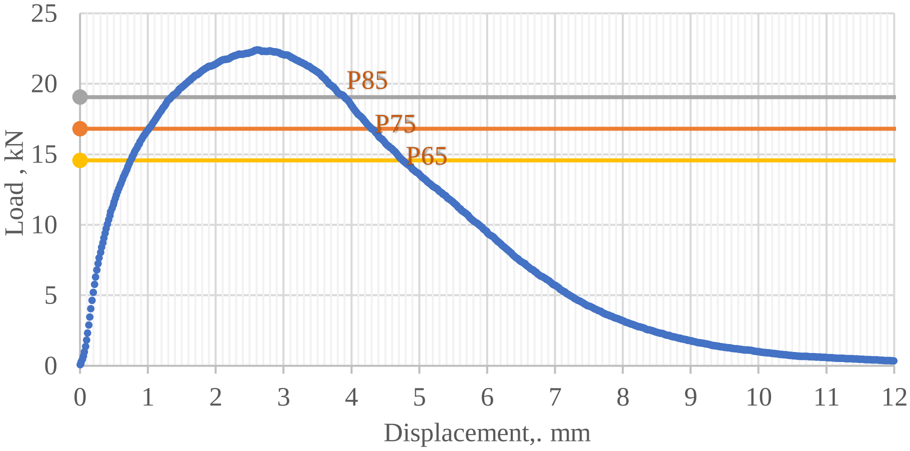

Figure 83:Mix 2036-X Ideal-CT Unconditioned 1

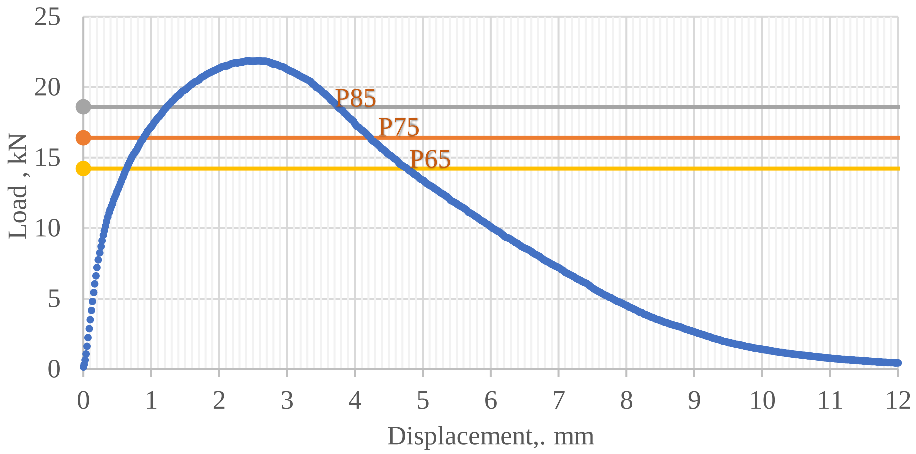

Figure 84:Mix 2036-X Ideal-CT Unconditioned 2

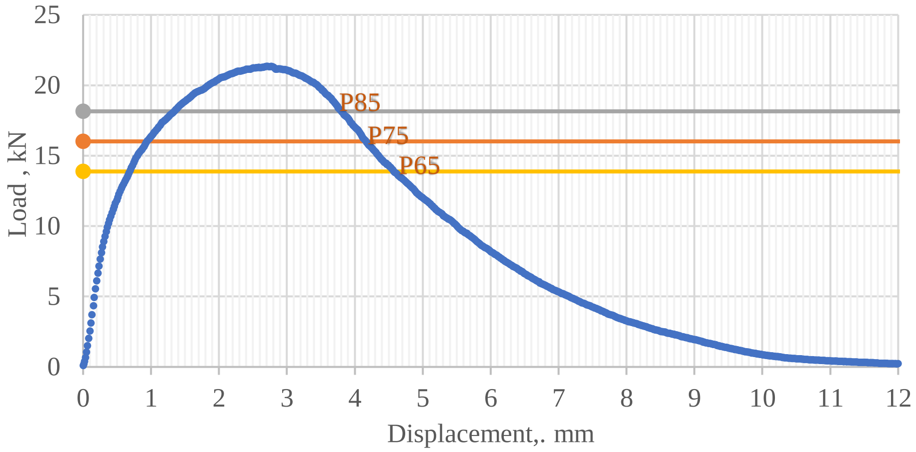

Figure 85:Mix 2036-X Ideal-CT Unconditioned 3

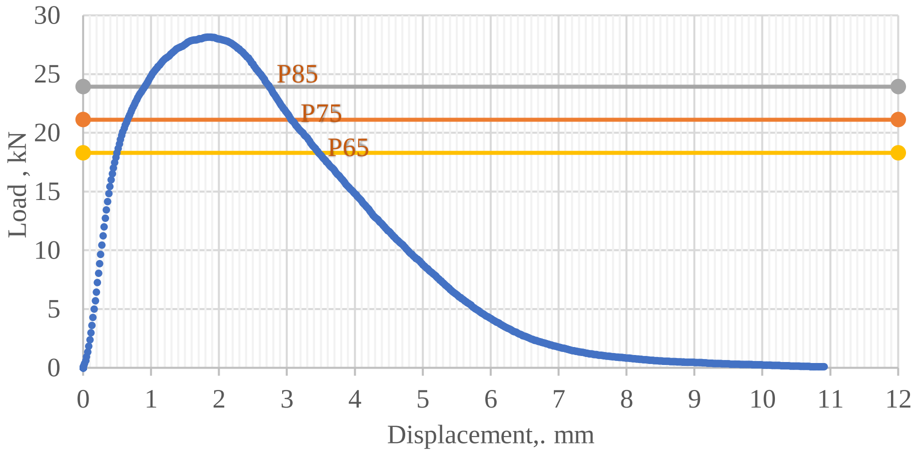

Figure 86:Mix 2036-X Ideal-CT Long 1

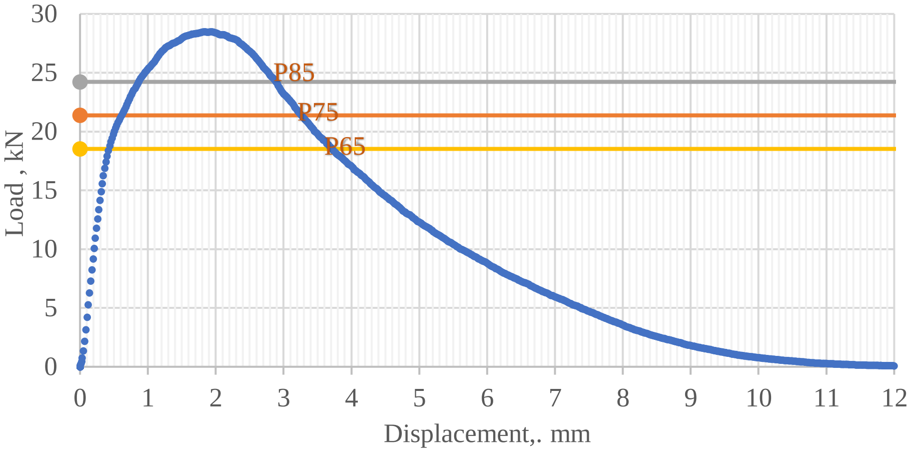

Figure 87:Mix 2036-X Ideal-CT Long 2

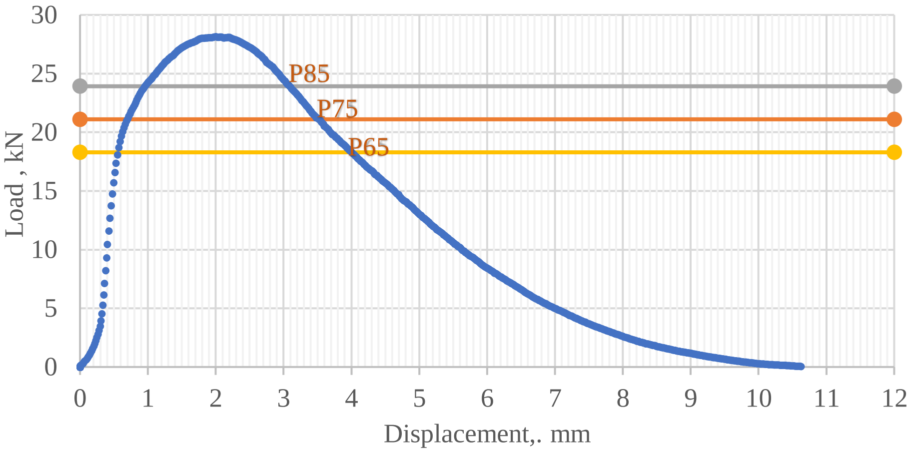

Figure 88: Mix 2036-X Ideal-CT Long 3

Table 39:Mix 2121 Ideal-CT Samples

Mix ID	Ideal-CT Cond			Ideal-CT Uncond			Ideal-CT Long		
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3738.6	3734.4	3743.7	3738.3	3743.0	3742.6	3744.2	3743.5	3742.5
SSD mass, g	3760.4	3758.4	3762	3757.0	3764.0	3761.5	3763.5	3761.1	3761.0
Mass in water, g	2117.5	2115.8	2125.3	2110.1	2126.2	2119.2	2129.3	2124.7	2123.2
Bulk specific gravity	2.276	2.273	2.287	2.270	2.285	2.279	2.291	2.288	2.285
Maximum specific gravity	2.450	2.450	2.450	2.450	2.450	2.450	2.450	2.450	2.450
AV, %	7.1	7.2	6.6	7.4	6.7	7.0	6.5	6.6	6.7
Ideal-CT @77F	217	205	210	98	100	81	67	88	60
d1s (≤13.5)	4.9			8.6			12.0		
Average Ideal-CT	211			93			72		

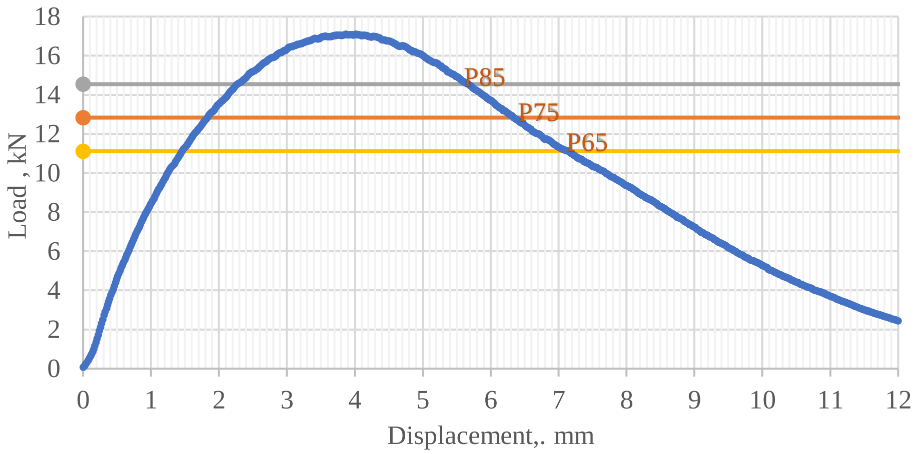

Figure 89: Mix 2121 Ideal-CT Conditioned 1

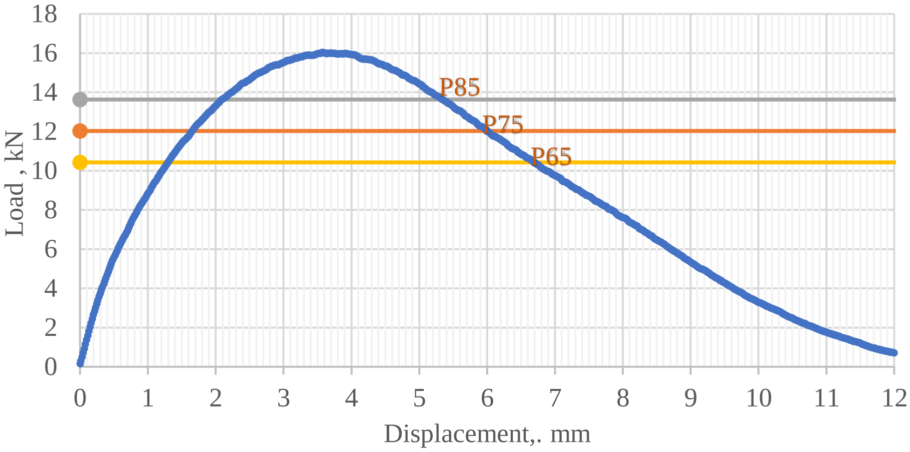

Figure 90: Mix 2121 Ideal-CT Conditioned 2

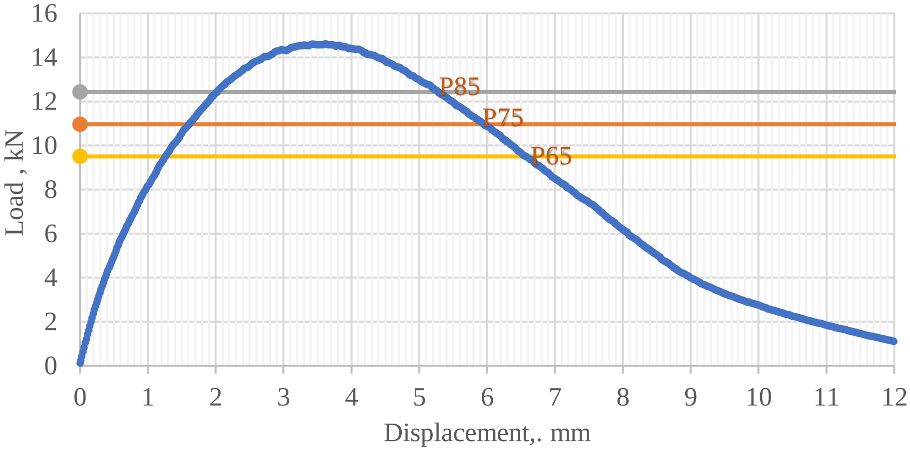

Figure 91: Mix 2121 Ideal-CT Conditioned 3

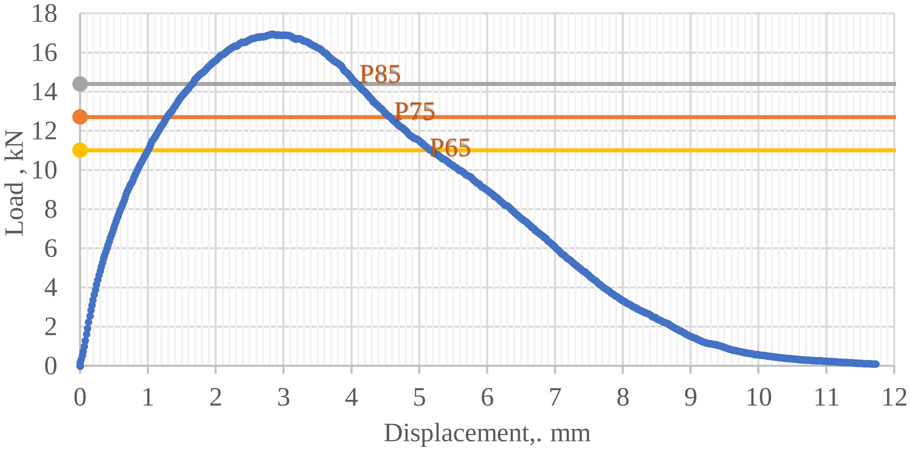

Figure 92: Mix 2121 Ideal-CT Unconditioned 1

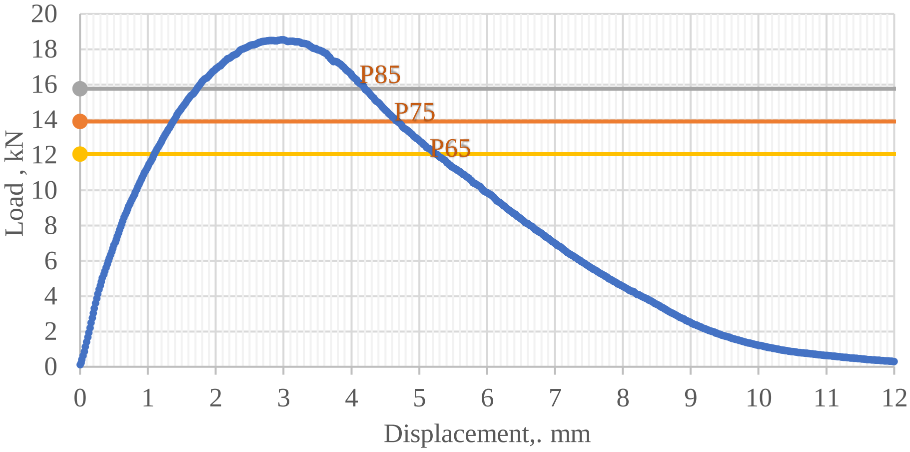

Figure 93: Mix 2121 Ideal-CT Unconditioned 2

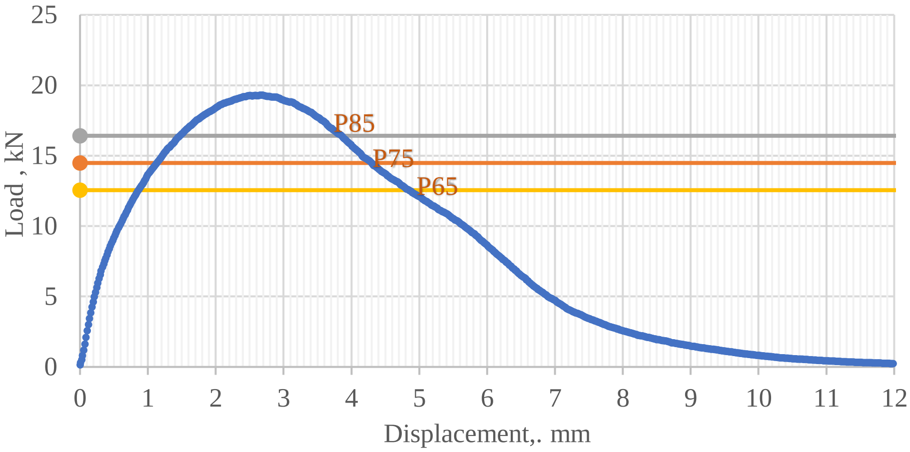

Figure 94: Mix 2121 Ideal-CT Unconditioned 3

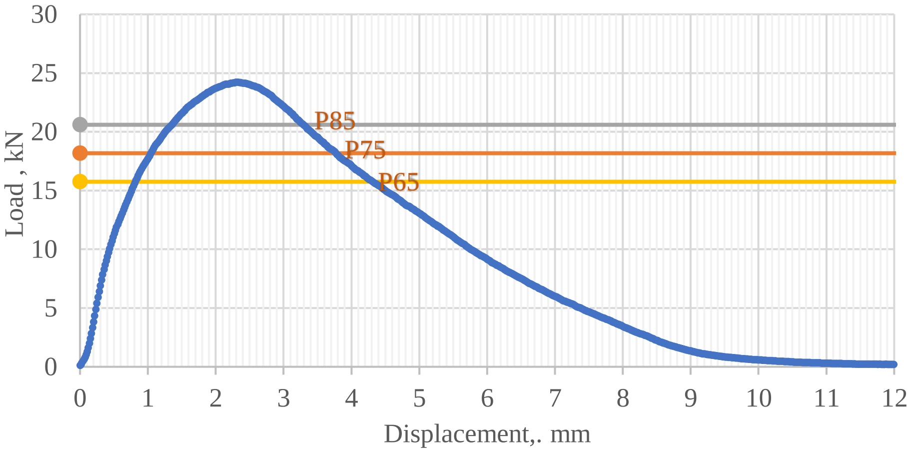

Figure 95: Mix 2121 Ideal-CT Long 1

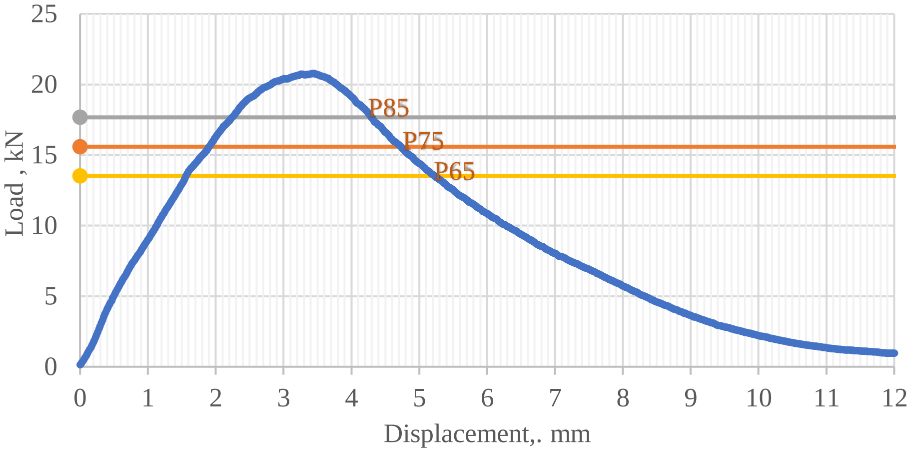

Figure 96: Mix 2121 Ideal-CT Long 2

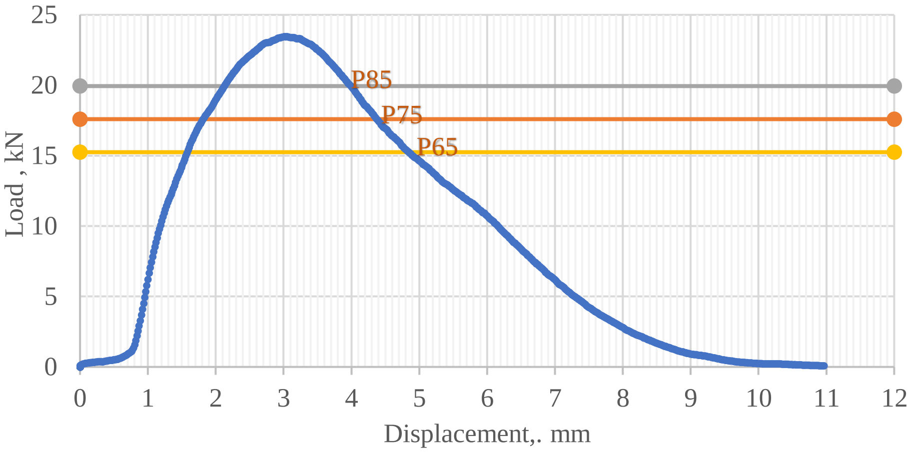

Figure 97: Mix 2121 Ideal-CT Long 3

Table 40: Mix T3 Ideal-CT Samples

Mix ID	Ideal-CT Cond			Ideal-CT Uncond			Ideal-CT Long		
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3716.4	3716.7	3719.6	3719.2	3719.3	3713.5	3715.6	3717.9	3711.9
SSD mass, g	3730.2	3739.1	3733	3732	3733.2	3728.1	3730.0	3736.5	3728.3
Mass in water, g	2084.1	2094.7	2082.6	2093.1	2091.7	2081.3	2084.1	2093.9	2087.1
Bulk specific gravity	2.258	2.260	2.254	2.269	2.266	2.255	2.257	2.263	2.262
Maximum specific gravity	2.432	2.432	2.432	2.432	2.432	2.432	2.432	2.432	2.432
AV, %	7.2	7.1	7.3	6.7	6.8	7.3	7.2	6.9	7.0
Ideal-CT @77F	231	242	230	96	115	106	66	50	49
d1s (≤13.5)	5.4			7.8			7.9		
Average Ideal-CT	234			106			55		

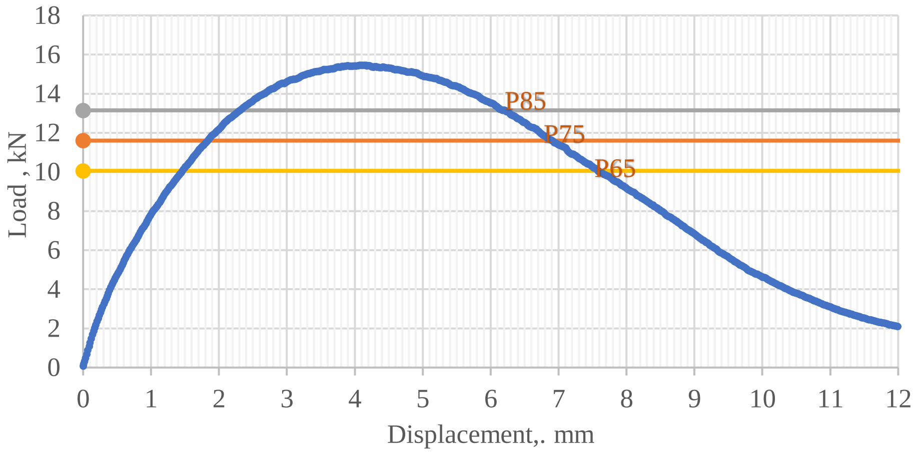

Figure 98: Mix T3 Ideal-CT Conditioned 1

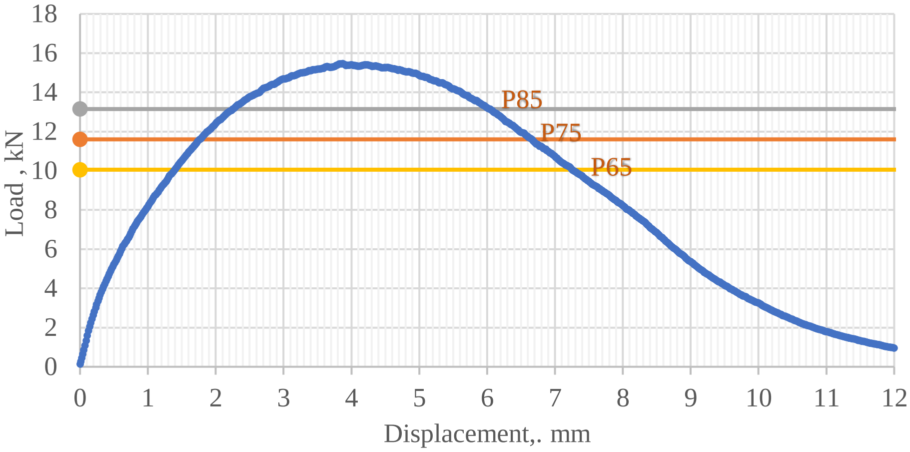

Figure 99: Mix T3 Ideal-CT Conditioned 2

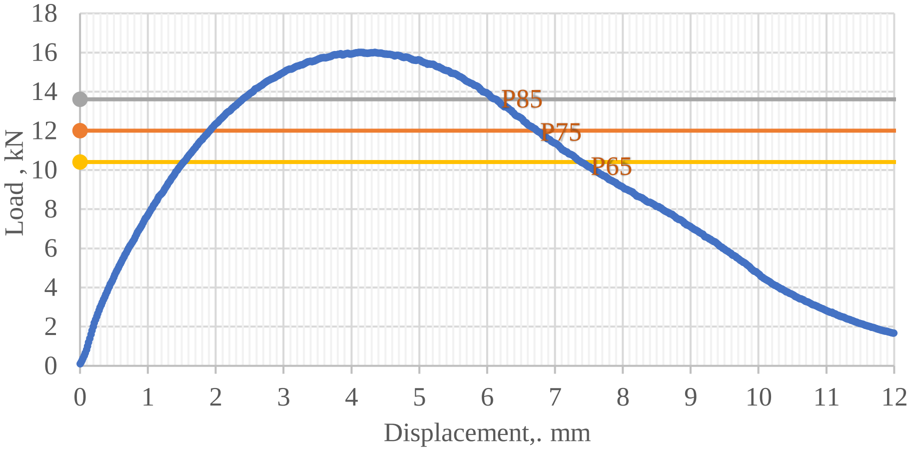

Figure 100: Mix T3 Ideal-CT Conditioned 3

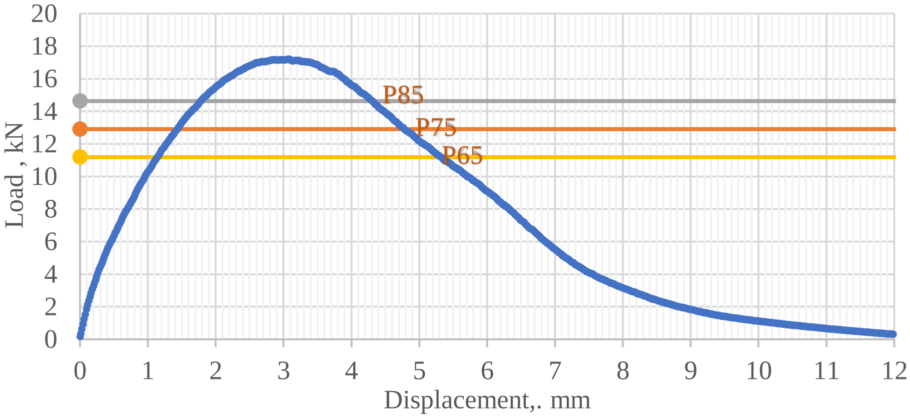

Figure 101: Mix T3 Ideal-CT Unconditioned 1

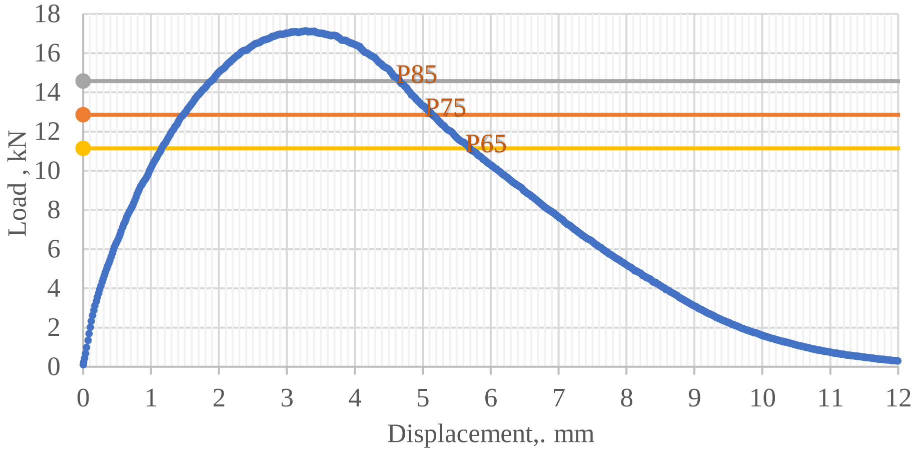

Figure 102: Mix T3 Ideal-CT Unconditioned 2

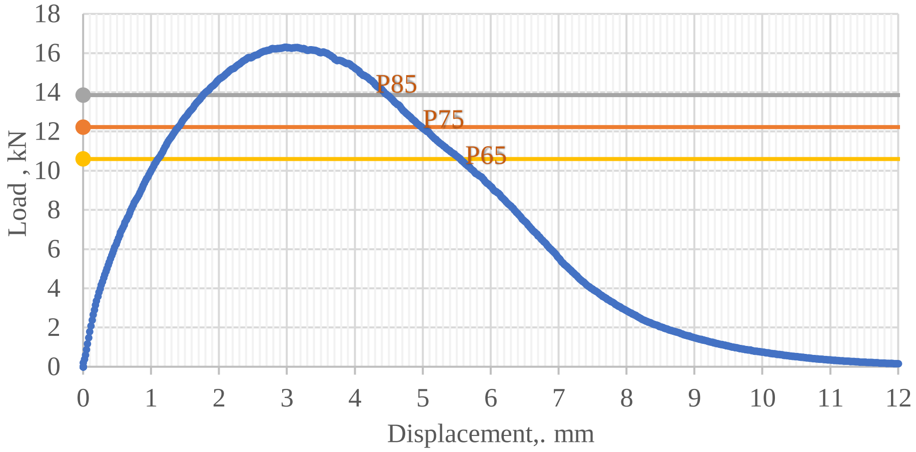

Figure 103: Mix T3- Ideal-CT Unconditioned 3

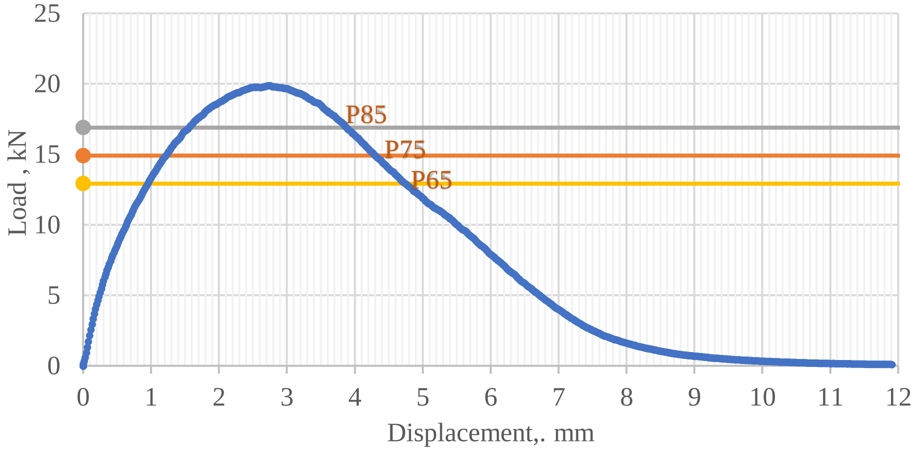

Figure 104: Mix T3 Ideal-CT Long 1

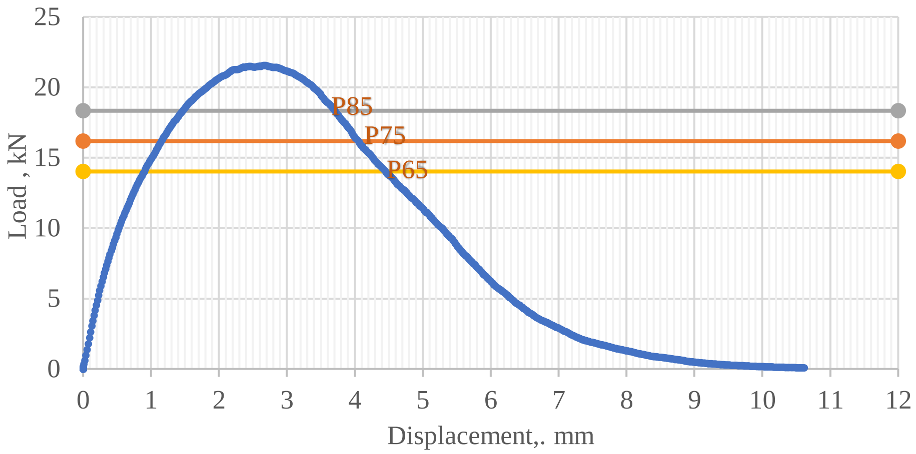

Figure 105:Mix T3 Ideal-CT Long 2

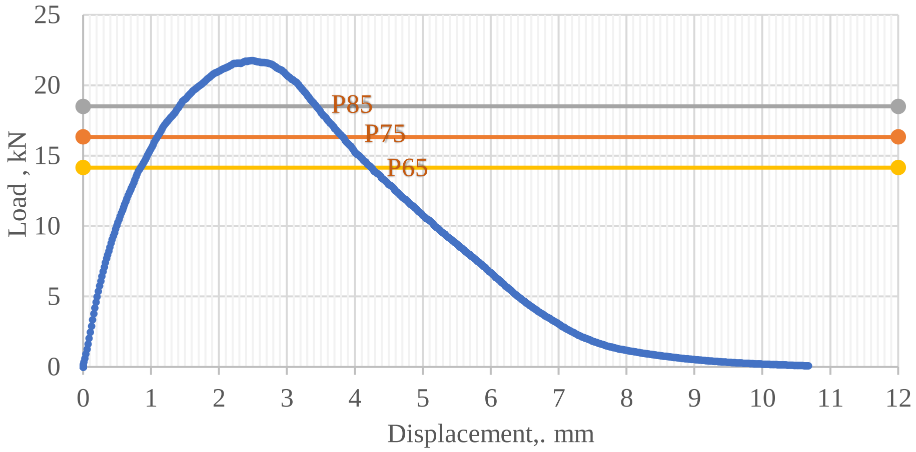

Figure 106: Mix T3 Ideal-CT Long 3

Table 41: Mix T2 Ideal-CT Samples

Mix ID	Ideal-CT Cond			Ideal-CT Uncond			Ideal-CT Long		
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3769.2	3759.2	3766.1	3766.2	3764.7	3767.4	3767.5	3768.1	3766.7
SSD mass, g	3784.8	3777.1	3783.6	3780.3	3782.1	3782.0	3785.4	3784.8	3783.4
Mass in water, g	2140.3	2132.0	2140.7	2132.9	2136.1	2138.4	2139.4	2140.2	2137.5
Bulk specific gravity	2.292	2.285	2.292	2.286	2.287	2.292	2.289	2.291	2.289
Maximum specific gravity	2.464	2.464	2.464	2.464	2.464	2.464	2.464	2.464	2.464
AV, %	7.0	7.3	7.0	7.2	7.2	7.0	7.1	7.0	7.1
Ideal-CT @77F	220	204	207	119	108	89	55	71	51
d1s (≤13.5)	7.1			12.5			9.0		
Average Ideal-CT	210			105			59		

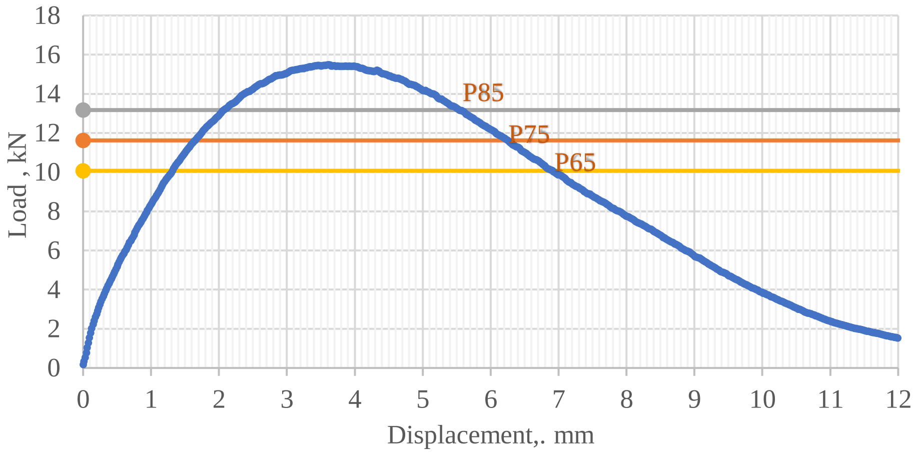

Figure 107: Mix T2 Ideal-CT Conditioned 1

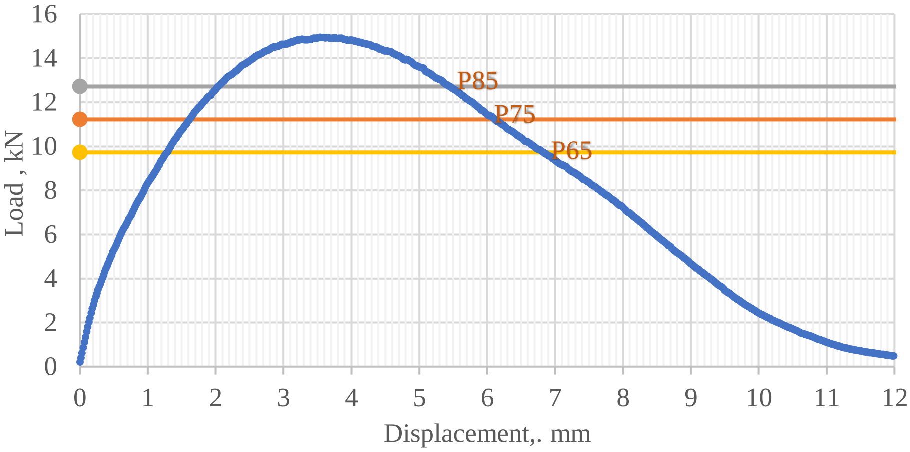

Figure 108: Mix T2 Ideal-CT Conditioned 2

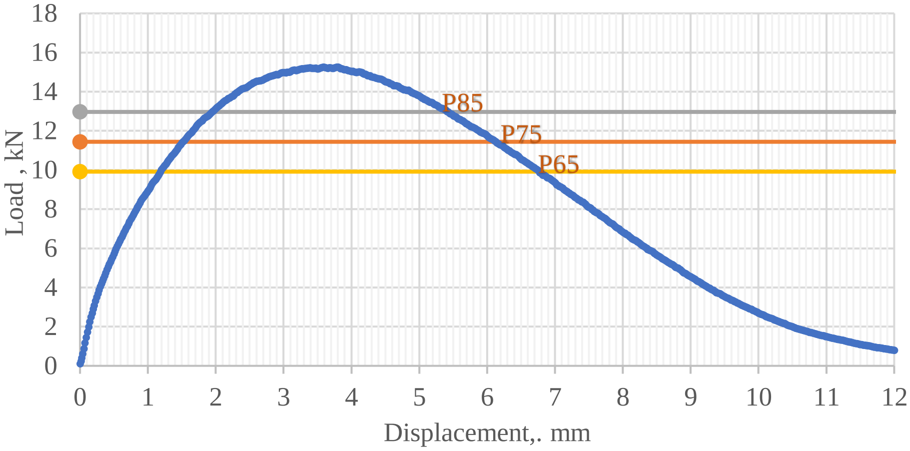

Figure 109: Mix T2 Ideal-CT Conditioned 3

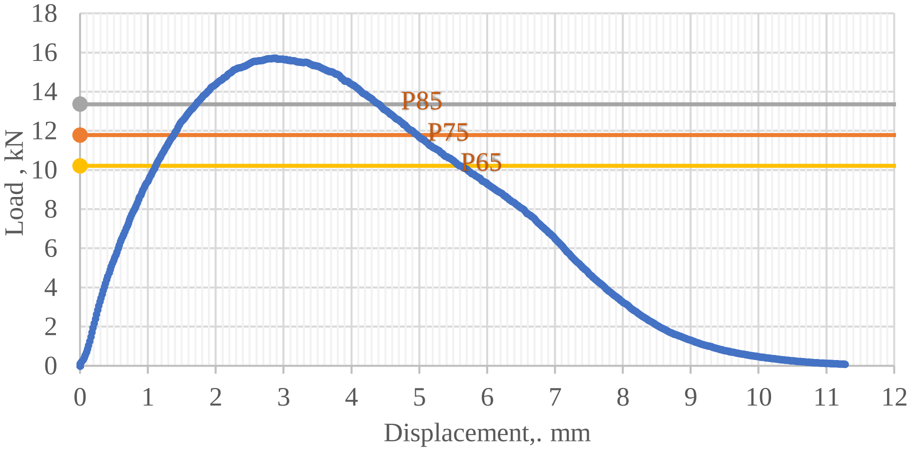

Figure 110: Mix T2 Ideal-CT Unconditioned 1

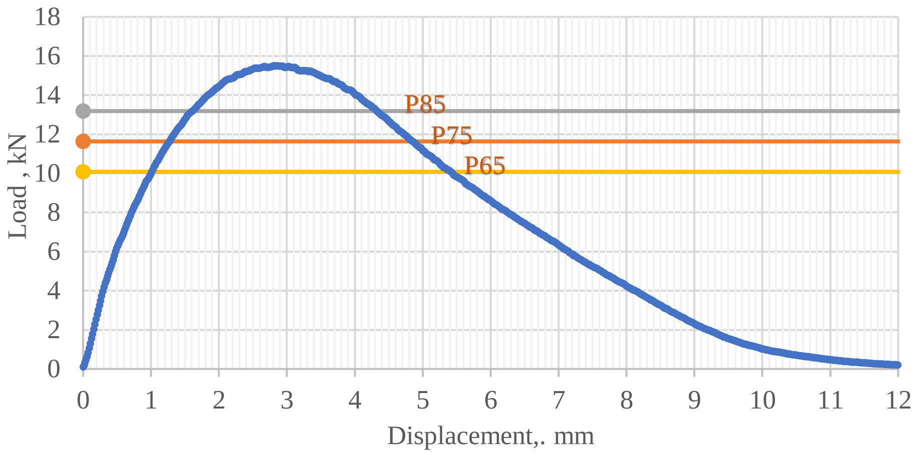

Figure 111: Mix T2- Ideal-CT Unconditioned 2

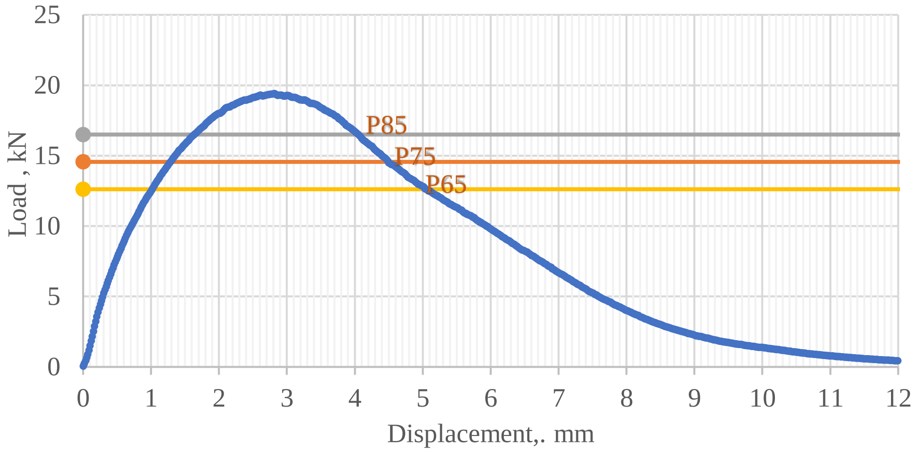

Figure 112: Mix T2 Ideal-CT Unconditioned 3

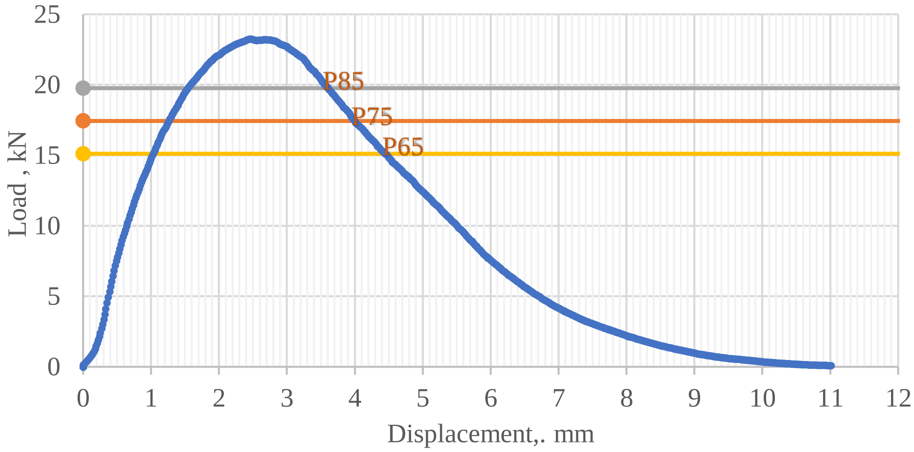

Figure 113: Mix T2 Ideal-CT Long 1

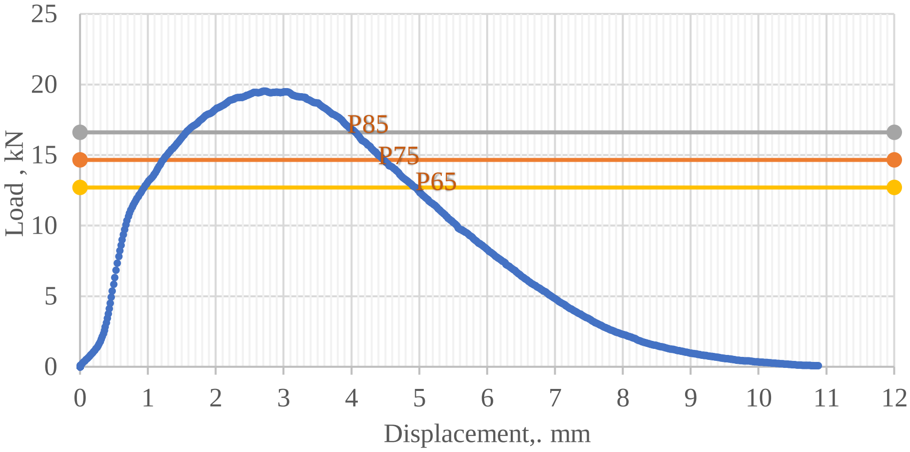

Figure 114: Mix T2 Ideal-CT Long 2

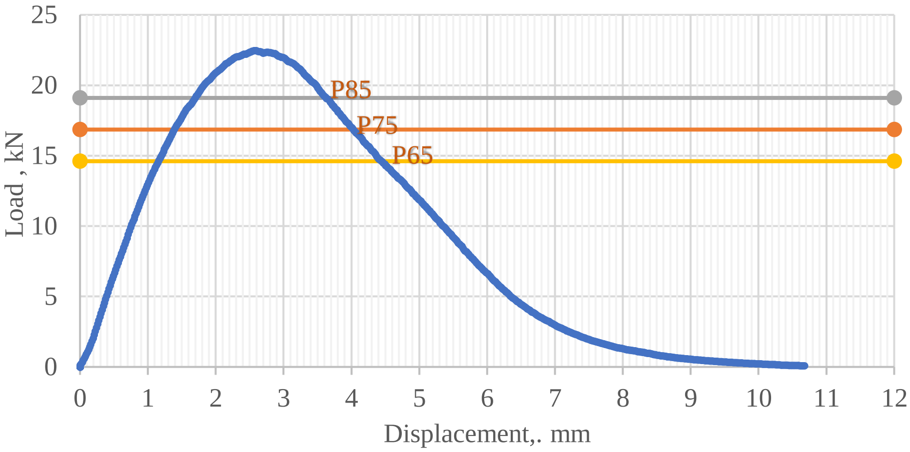

Figure 115: Mix T2 Ideal-CT Long 3

Table 42:Mix T2-X Ideal-CT Samples

Mix ID	Ideal-CT Cond			Ideal-CT Uncond			Ideal-CT Long		
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3765.9	3766.0	3769.9	3761.3	3767.3	3763.6	3767.3	3762.8	3763.8
SSD mass, g	3787.6	3788.2	3789.1	3777.9	3786.5	3781.5	3786.4	3776.6	3779.8
Mass in water, g	2135.7	2137.5	2144.5	2130.2	2138.0	2137.1	2139.8	2125.3	2132.3
Bulk specific gravity	2.280	2.281	2.292	2.283	2.285	2.289	2.288	2.279	2.285
Maximum specific gravity	2.460	2.460	2.460	2.460	2.460	2.460	2.460	2.460	2.460
AV, %	7.3	7.3	6.8	7.2	7.1	7.0	7.0	7.4	7.1
Ideal-CT @77F	83	100	103	54	41	50	15	22	17
d1s (≤13.5)	8.8			5.1			2.9		
Average Ideal-CT	95			48			18		

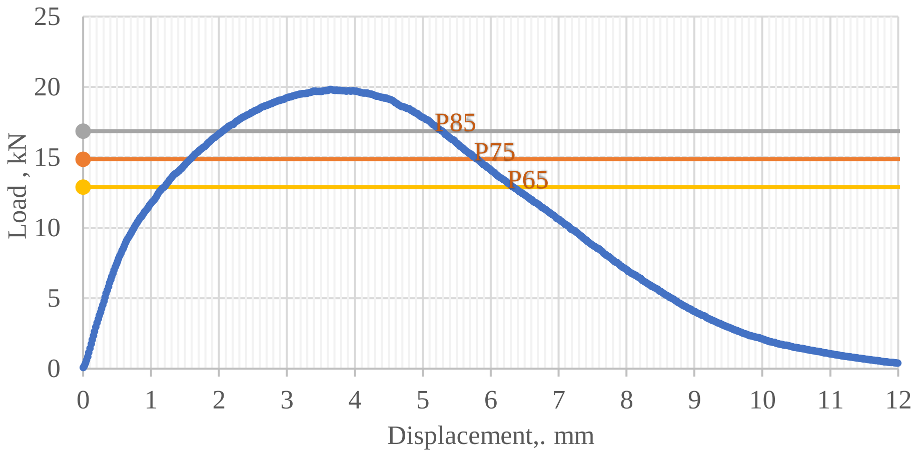

Figure 116: Mix T2-X Ideal-CT Conditioned 1

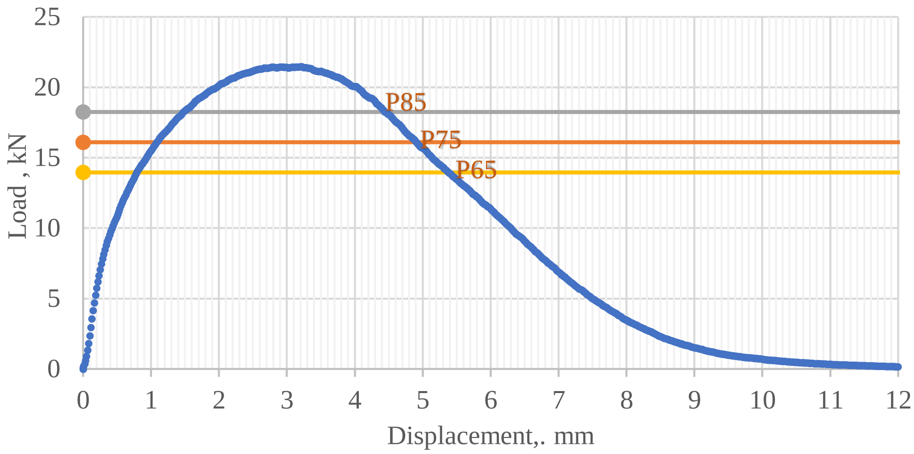

Figure 117: Mix T2-X Ideal-CT Conditioned 2

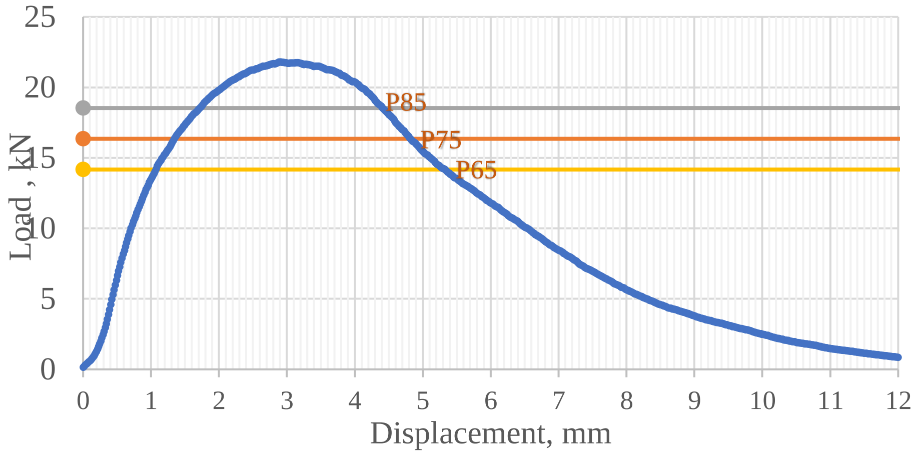

Figure 118: Mix T2-X Ideal-CT Conditioned 3

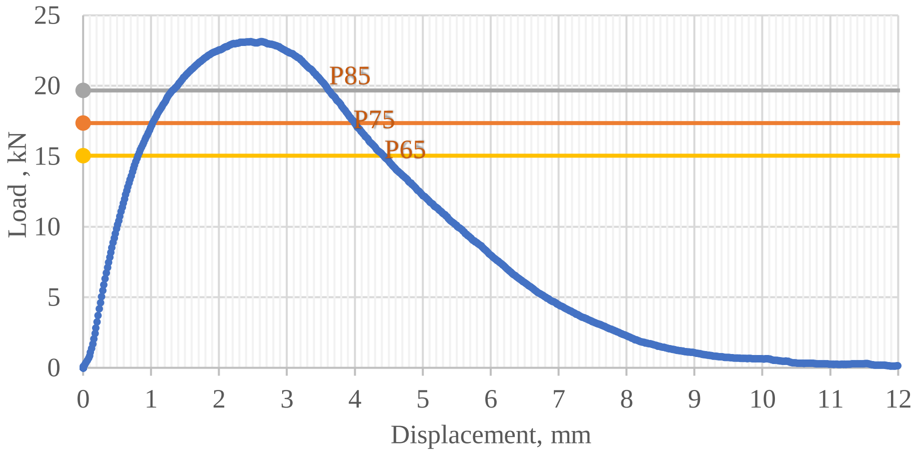

Figure 119: Mix T2-X Ideal-CT Unconditioned 1

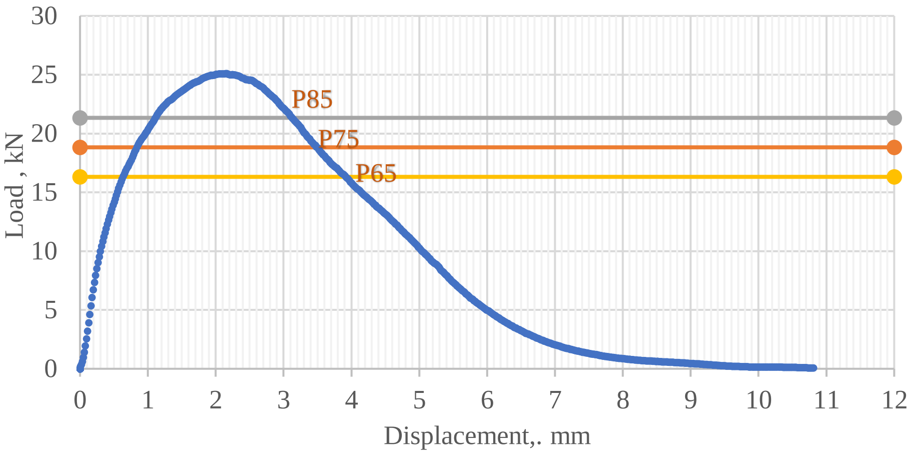

Figure 120: Mix T2-X Ideal-CT Unconditioned 2

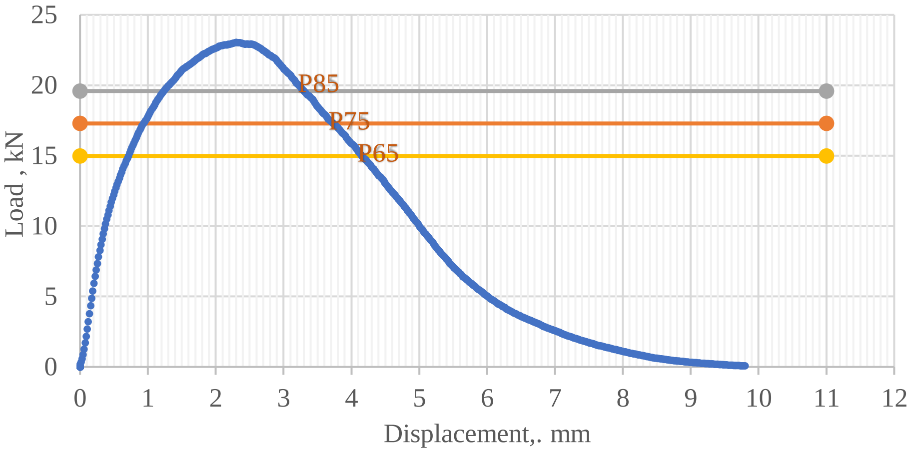

Figure 121: Mix T2-X Ideal-CT Unconditioned 3

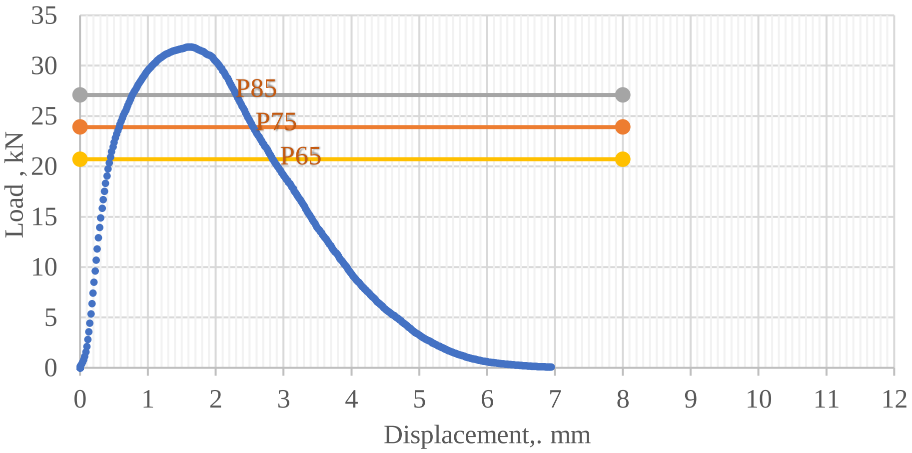

Figure 122: Mix T2-X Ideal-CT Long 1

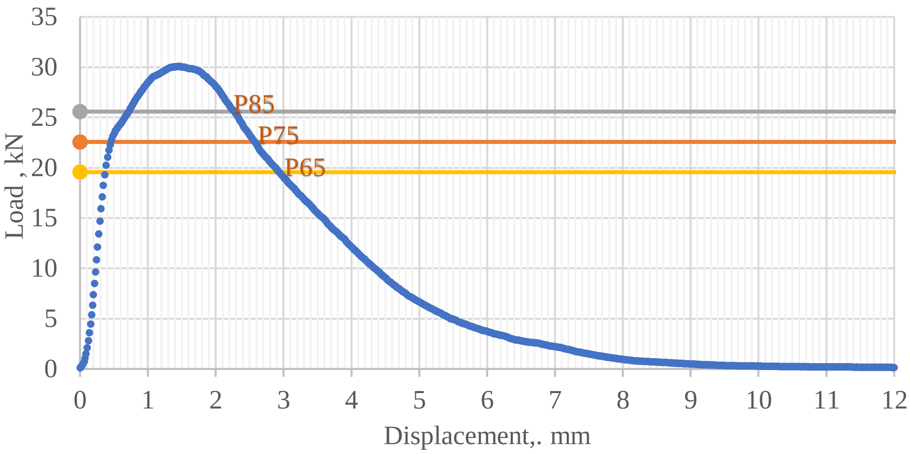

Figure 123: Mix T2-X Ideal-CT Long 2

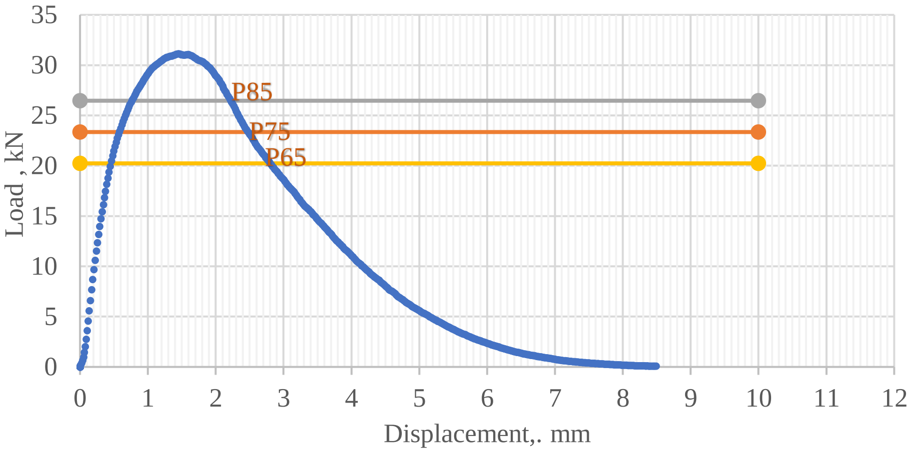

Figure 124: Mix T2-X Ideal-CT Long 3

Table 43:Mix S2 Ideal-CT Samples

Mix ID	Ideal-CT Cond			Ideal-CT Uncond			Ideal-CT Long		
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3799.0	3801.1	3800.5	3798.5	3800.8	3801.2	3802.9	3800.8	3805.0
SSD mass, g	3825.7	3823.5	3832.7	3824.7	3830.9	3833.0	3836.9	3824.5	3827.0
Mass in water, g	2198.8	2206.2	2207.6	2211.0	2207.7	2208.0	2212.5	2198.9	2202.0
Bulk specific gravity	2.335	2.350	2.339	2.354	2.342	2.339	2.341	2.338	2.342
Maximum specific gravity	2.519	2.519	2.519	2.519	2.519	2.519	2.519	2.519	2.519
AV, %	7.3	6.7	7.2	6.6	7.0	7.1	7.1	7.2	7.0
Ideal-CT @77F	170	195	180	112	93	97	57	59	58
d1s (≤13.5)	10.3			8.2			0.8		
Average Ideal-CT	182			101			58		

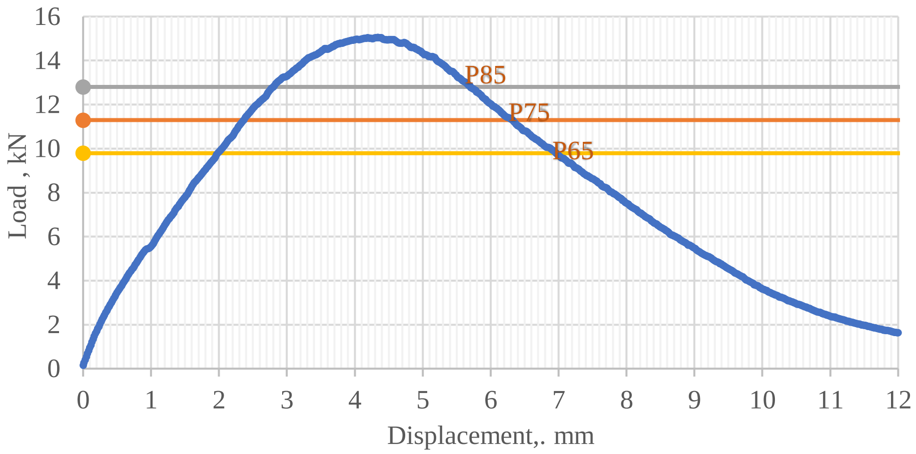

Figure 125: Mix S2 Ideal-CT Conditioned 1

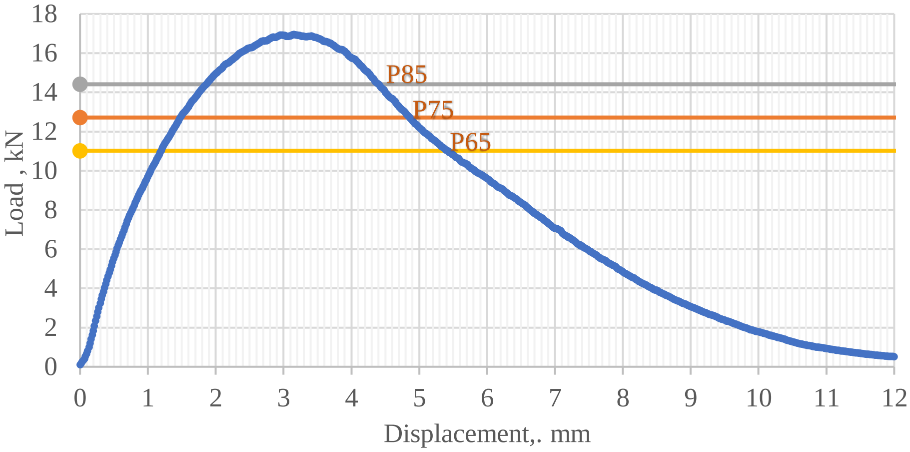

Figure 126: Mix S2 Ideal-CT Conditioned 2

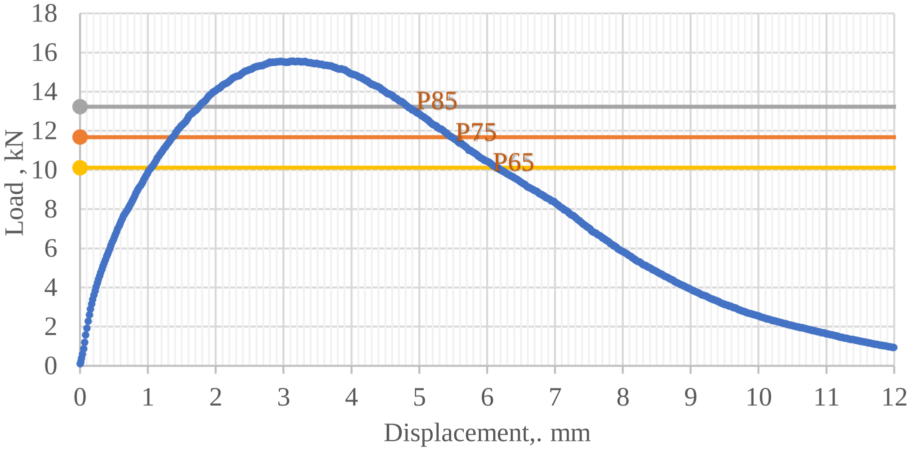

Figure 127: Mix S2 Ideal-CT Conditioned 3

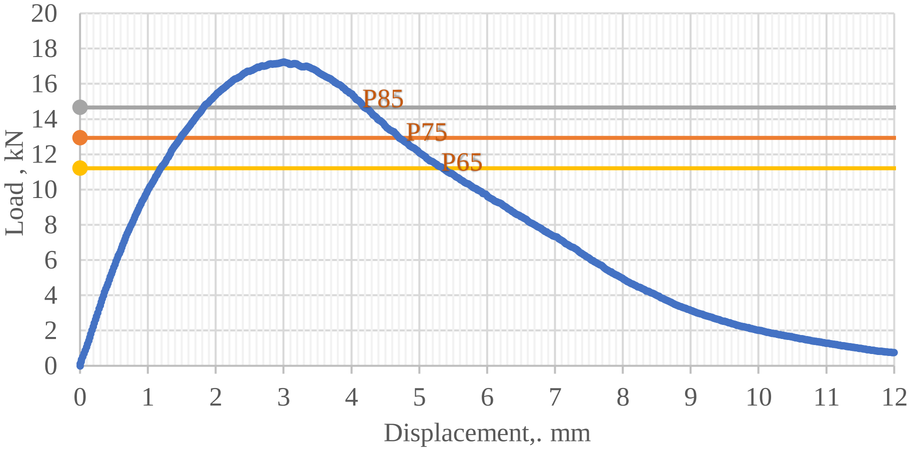

Figure 128: Mix S2 Ideal-CT Unconditioned 1

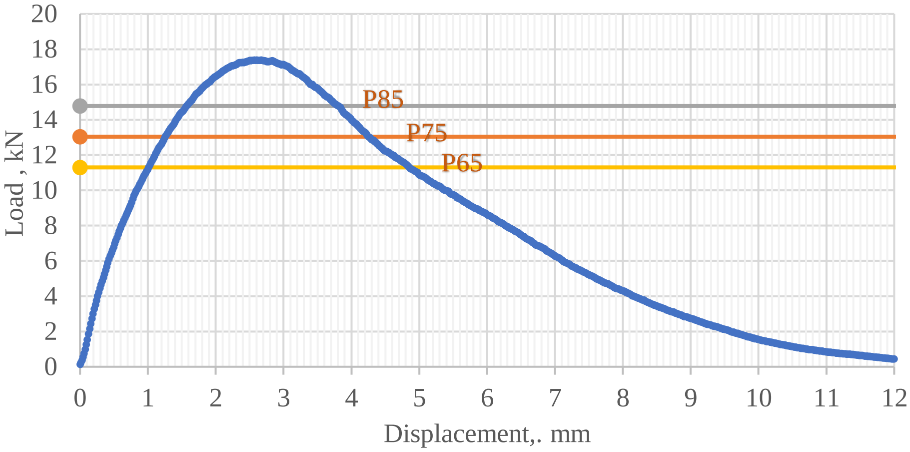

Figure 129: Mix S2- Ideal-CT Unconditioned 2

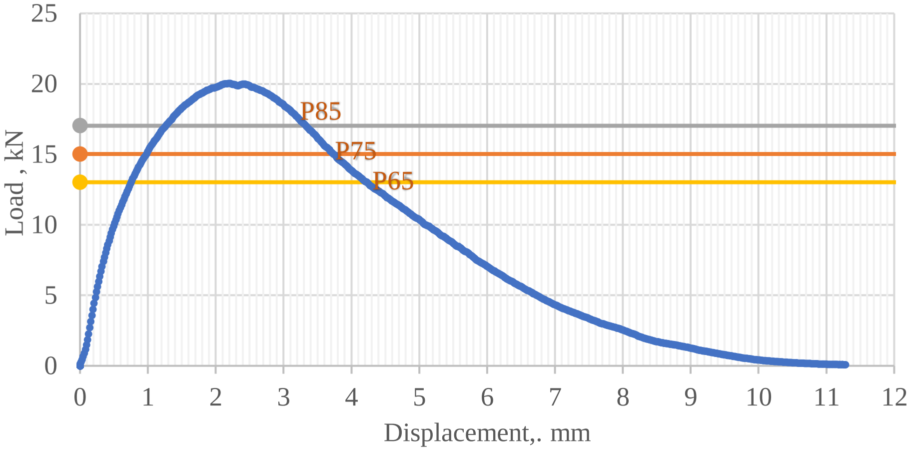

Figure 130: Mix S2 Ideal-CT Long 1

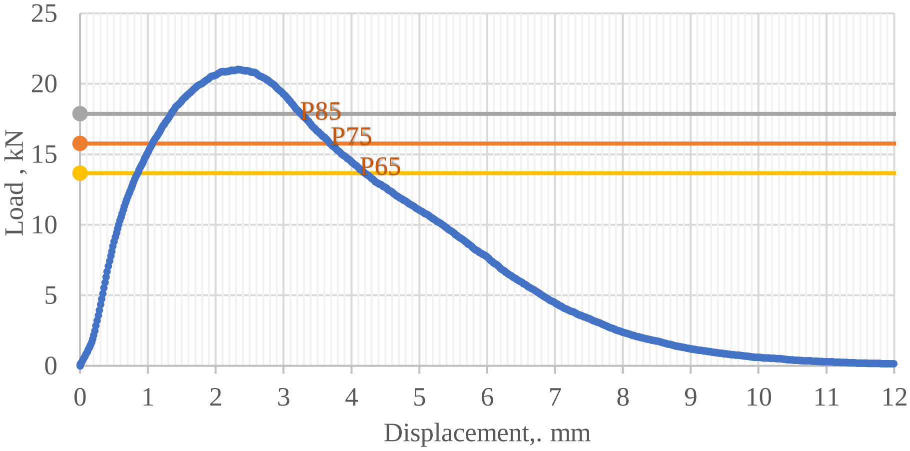

Figure 131: Mix S2 Ideal-CT Long 2

Table 44:Mix S2-X Ideal-CT Samples

Mix ID	Ideal-CT Cond			Ideal-CT Uncond			Ideal-CT Long		
Diameter, in	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thickness, in	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Dry mass in air, g	3806.2	3806.4	3805.0	3808.4	3809.0	3811.0	3809.1	3809.9	3810.0
SSD mass, g	3833.0	3837.5	3839.0	3835.7	3833.5	3834.6	3841.5	3847.4	3852.0
Mass in water, g	2212.0	2209.2	2214.0	2213.3	2210.6	2212.0	2216.9	2226.4	2229.0
Bulk specific gravity	2.348	2.338	2.342	2.347	2.347	2.349	2.345	2.350	2.348
Maximum specific gravity	2.524	2.524	2.524	2.524	2.524	2.524	2.524	2.524	2.524
AV, %	7.0	7.4	7.2	7.0	7.0	6.9	7.1	6.9	7.0
Ideal-CT @77F	86	86	85	40	57	49	24	27	39
d1s (≤13.5)	0.5			6.9			6.5		
Average Ideal-CT	86			49			30		

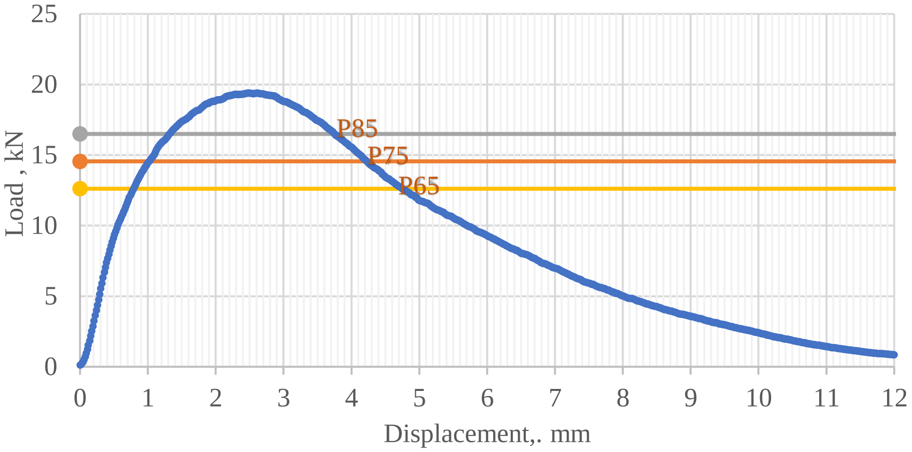

Figure 132: Mix S2-X Ideal-CT Conditioned 1

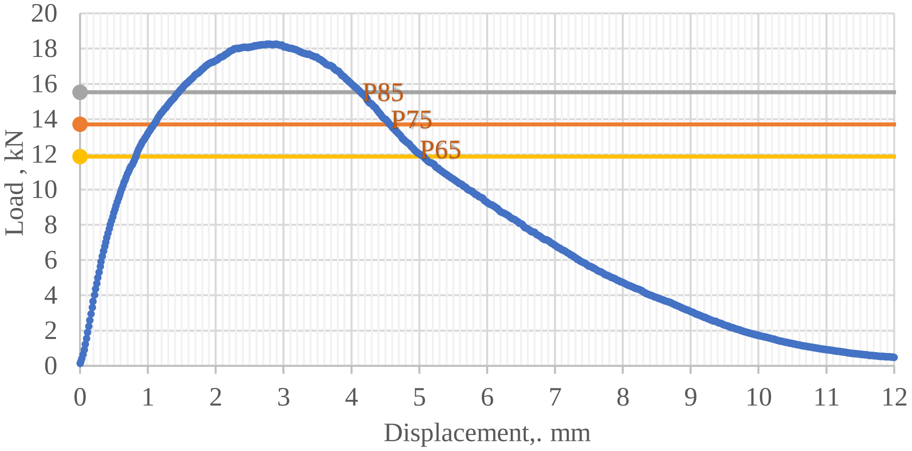

Figure 133: Mix S2-X Ideal-CT Conditioned 2

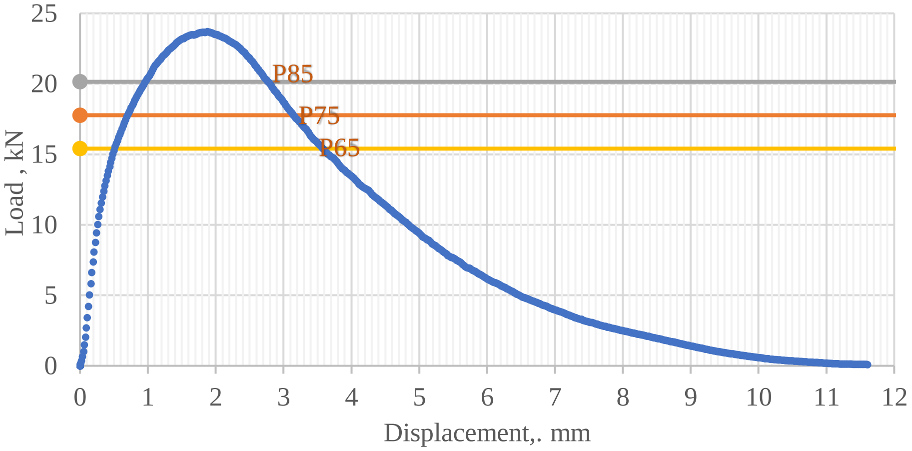

Figure 134: Mix S2-X Ideal-CT Unconditioned 1

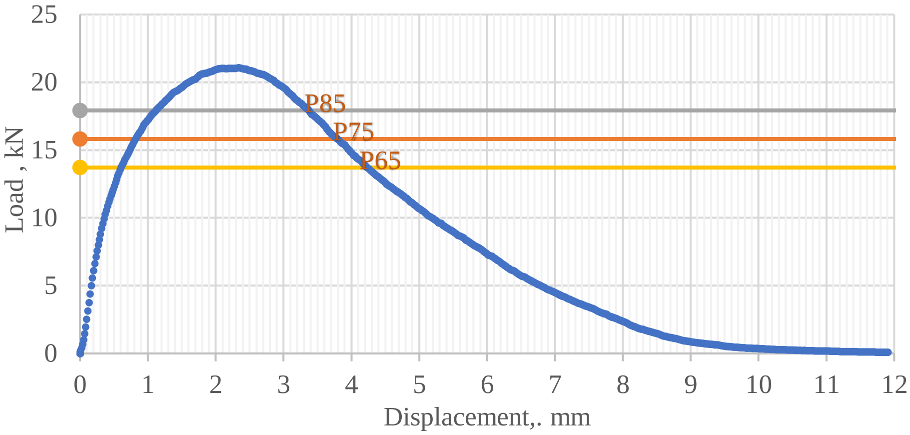

Figure 135: Mix S2-X Ideal-CT Unconditioned 2

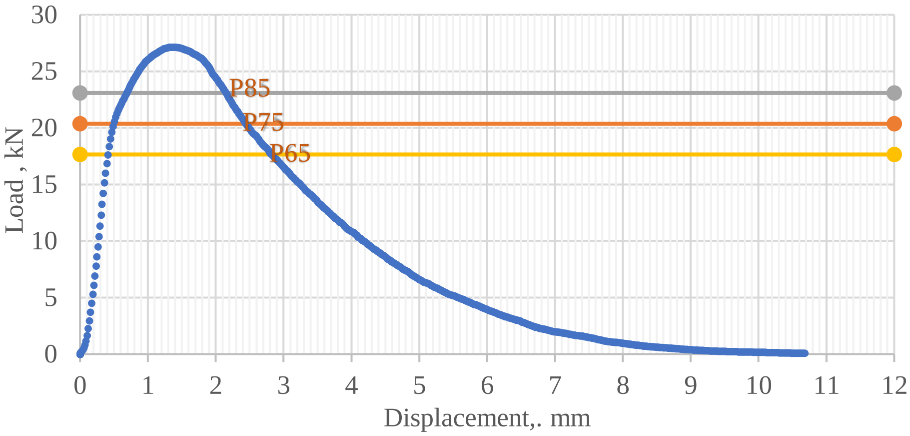

Figure 136: Mix S2-X Ideal-CT Long 1

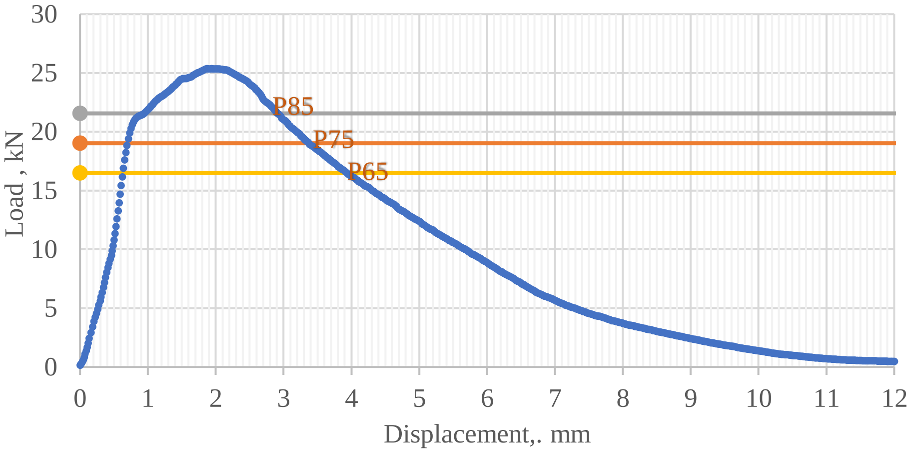

Figure 137: Mix S2-X Ideal-CT Long 2

7.5 Appendix E: Marshall Stability and Flow

Table 45: Mix 2036 Stability Samples

Mix ID	Sample 1	Sample 2	Sample 3
Diameter, in	4.00	4.00	4.00
Thickness, mm	62.29	62.70	61.97
Dry mass in air, g	1157.9	1151.8	1156.2
SSD mass, g	1159.6	1153.3	1157.5
Mass in water, g	663.1	656.9	668.2
Bulk specific gravity	2.332	2.320	2.363
Maximum specific gravity	2.436	2.436	2.436
AV, %	4.3	4.7	3.0
Stability, lbf	4517	4795	4323
Corrected Stability, lbf	4653	4891	4453
Stability COV, % (≤6)	4%		
Stability Acceptable Range, % (≤16)	9%		
Average Corrected Stability, lbf	4666		
Flow, inch	N/A	N/A	N/A

Table 46: Mix 2036-X Stability Samples

Mix ID	Sample 1	Sample 2	Sample 3
Diameter, in	4.00	4.00	4.00
Thickness, mm	61.38	62.78	61.97
Dry mass in air, g	1158.2	1161.8	1159.7
SSD mass, g	1159.8	1163.4	1161.3
Mass in water, g	668.8	663.3	668.2
Bulk specific gravity	2.359	2.323	2.352
Maximum specific gravity	2.440	2.440	2.440
AV, %	3.3	4.8	3.6
Stability, lbf	4581	4613	4434
Corrected Stability, lbf	4856	4705	4611
Stability COV, % (≤6)	2%		
Stability Acceptable Range, % (≤16)	2%		
Average Corrected Stability, lbf	4724		
Flow, inch	0.12	0.15	0.14
Average Flow, inch	0.14		
Flow COV, % (≤9)	9%		
Flow Acceptable Range, % (≤26)	22%		

Table 47: Mix 2121 Stability Samples

Mix ID	Sample 1	Sample 2	Sample 3
Diameter, in	4.00	4.00	4.00
Thickness, mm	61.80	61.70	63.17
Dry mass in air, g	1151.3	1154.6	1171.2
SSD mass, g	1153.3	1156.1	1172.9
Mass in water, g	667.4	665.1	673.8
Bulk specific gravity	2.369	2.352	2.347
Maximum specific gravity	2.450	2.450	2.450
AV, %	3.3	4.0	4.2
Stability, lbf	4668	4836	4784
Corrected Stability, lbf	4869	5059	4822
Stability COV, % (≤6)	2%		
Stability Acceptable Range, % (≤16)	5%		
Average Corrected Stability, lbf	4917		
Flow, inch	N/A	N/A	N/A

Table 48: Mix T3 Stability Samples

Mix ID	Sample 1	Sample 2	Sample 3
Diameter, in	4.00	4.00	4.00
Thickness, mm	62.46	61.70	61.77
Dry mass in air, g	1155.9	1151.3	1163.1
SSD mass, g	1157	1153.2	1163.8
Mass in water, g	661.8	658.5	671.0
Bulk specific gravity	2.334	2.327	2.360
Maximum specific gravity	2.432	2.432	2.432
AV, %	4.0	4.3	3.0
Stability, lbf	4897	5445	5497
Corrected Stability, lbf	5044	5717	5772
Stability COV, % (≤6)	6%		
Stability Acceptable Range, % (≤16)	13%		
Average Corrected Stability, lbf	5511		
Flow, inch	N/A	N/A	N/A

Table 49: Mix T2 Stability Samples

Mix ID	Sample 1	Sample 2	Sample 3
Diameter, in	4.00	4.00	4.00
Thickness, mm	62.67	62.32	62.82
Dry mass in air, g	1171.6	1172.6	1177
SSD mass, g	1172.7	1173.8	1178.3
Mass in water, g	681.5	679.4	682.1
Bulk specific gravity	2.385	2.372	2.372
Maximum specific gravity	2.464	2.464	2.464
AV, %	3.2	3.7	3.7
Stability, lbf	6288	5662	5508
Corrected Stability, lbf	6413	5832	5618
Stability COV, % (≤6)	6%		
Stability Acceptable Range, % (≤16)	13%		
Average Corrected Stability, lbf	5954		
Flow, inch	N/A	N/A	N/A

Table 50: Mix T2-X Stability Samples

Mix ID	Sample 1	Sample 2	Sample 3
Diameter, in	4.00	4.00	4.00
Thickness, mm	62.38	62.43	62.50
Dry mass in air, g	1172.1	1174.3	1173.9
SSD mass, g	1173.9	1175.8	1175.0
Mass in water, g	679.4	679.0	678.0
Bulk specific gravity	2.370	2.364	2.362
Maximum specific gravity	2.460	2.460	2.460
AV, %	3.6	3.9	4.0
Stability, lbf	6462	6199	5599
Corrected Stability, lbf	6656	6385	5767
Stability COV, % (≤6)	6%		
Stability Acceptable Range, % (≤16)	14%		
Average Corrected Stability, lbf	6269		
Flow, inch	0.13	0.13	0.13
Average Flow, inch	0.13		
Flow COV, % (≤9)	0%		
Flow Acceptable Range, % (≤26)	0%		

Table 51: Mix S2 Stability Samples

Mix ID	Sample 1	Sample 2	Sample 3
Diameter, in	4.00	4.00	4.00
Thickness, mm	62.90	62.83	62.33
Dry mass in air, g	1198.5	1197.8	1197.3
SSD mass, g	1202.2	1200.8	1199
Mass in water, g	707.9	709	709
Bulk specific gravity	2.425	2.436	2.443
Maximum specific gravity	2.519	2.519	2.519
AV, %	3.7	3.3	3.0
Stability, lbf	5316	4932	5120
Corrected Stability, lbf	5396	5018	5274
Stability COV, % (≤6)	3%		
Stability Acceptable Range, % (≤16)	7%		
Average Corrected Stability, lbf	5229		
Flow, inch	N/A	N/A	N/A

Table 52: Mix S2-X Stability Samples

Mix ID	Sample 1	Sample 2	Sample 3
Diameter, in	4.00	4.00	4.00
Thickness, mm	63.53	63.07	63.40
Dry mass in air, g	1199.0	1197.4	1198.0
SSD mass, g	1202.6	1199.5	1201.0
Mass in water, g	705.4	708.7	709.0
Bulk specific gravity	2.412	2.440	2.435
Maximum specific gravity	2.524	2.524	2.524
AV, %	4.5	3.3	3.5
Stability, lbf	4330	4833	4593
Corrected Stability, lbf	4330	4881	4604
Stability COV, % (≤6)	5%		
Stability Acceptable Range, % (≤16)	12%		
Average Corrected Stability, lbf	4605		
Flow, inch	0.18	0.17	0.17
Average Flow, inch	0.17		
Flow COV, % (≤9)	3%		
Flow Acceptable Range, % (≤26)	6%		