University of Nevada, Reno

P-401 MIXTURES: AGGREGATE GRADATION BANDS

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Abstract

The Federal Aviation Administrations (FAA) efficient specifications have delivered high quality airport pavement with good performance since those pavements will endure high load applications. Despite the efficiency of P-401 specifications, challenges arise for mix designers and contractors to meet the aggregate specification limits leading to adjustments that might compromise the volumetric properties of the mixtures and lead to more costs and delays. This research aims to replicate an airport paving project mix design that meets FAA aggregate and mix design specifications. A wide range of performance tests will then be conducted on two gradations, one inside and one outside of the aggregate gradation bands in the FAA specifications to propose more flexible gradation specification limits, focusing on critical sieve sizes and acceptable ranges.

In this report, gradations were developed using the Bailey Method and two performance tests have been covered: The IDEAL-CT and the TSR test. The data showed that deviating outside the gradation band specifications on specified sieves for this one mixture resulted in good resistance to moisture damage (without Freeze-Thaw cycling) but the cracking resistance for gradations inside of the gradation bands was better than outside of them. In this case the mixtures possessed very similar volumetric properties (e.g. effective asphalt content and voids in mineral aggregate).

The remaining tests (HWTT, Cantabro, I-FIT, DCT and Florida Permeability Test) will be conducted in the near future to recommend adjustments and analyze the influence of aggregate gradation change on performance.

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Chapter 1: Introduction

Airport pavements play a critical role in ensuring the safe and efficient operation of aircraft, particularly in the context of runways and taxiways constructed with asphalt surfaces. The performance of these surfaces is paramount, requiring resistance to deformation, weathering, and cracking while maintaining optimal frictional characteristics for aircraft maneuverability and safety. To meet such stringent performance demands, detailed mix design and construction requirements are established by the Federal Aviation Administration (FAA), notably through Item P-401 as outlined in Advisory Circular (AC) 150/5370-10H, "Standard Specifications for Construction of Airports" [1]. Dense-graded asphalt mixtures, primarily designed for civilian airport pavements, adhere closely to P-401 specifications, utilizing volumetric criteria and specialized compaction methods such as Marshall compaction [2] or Superpave gyratory compaction [3]. These mixtures are subjected to testing, including assessments for moisture susceptibility through the Tensile Strength Ratio Test (TSR) [4] and rutting resistance through methods like the Asphalt Pavement Analyzer (APA) [5] or Hamburg Wheel Tracking Test (HWTT) [6]. Moreover, the selection and blending of aggregate materials are important, with strict adherence to particle characteristics and cleanliness requirements. The asphalt mix design criteria in the P-401 specifications are shown in Table 1.

Table 1. Asphalt Design Criteria in P-401 Specifications

Test Property	Value	Test Method
Number of blows or gyrations	75	-
Air voids (%)	3.5	ASTM D3203 [7]
Percent voids in mineral aggregate (VMA), minimum	14 (NMAS*=3/4 inch) 15 (NMAS=1/2 inch) 16 (NMAS= 3/8 inch)	ASTM D6995 [8]
TSR	Not less than 80 at a saturation of 70-80%	ASTM D4867 [4]
HWTT**	Less than 10 mm @ 20000 passes	AASHTO T324 [6] at 50°C

*NMAS: Nominal Maximum Aggregate Size
**For rutting evaluation, APA [5] can be used also at 250 psi hose at 64°C where the required value shall be less than 0.4 inch at 4000 passes. APA at 100 psi hose pressure at 64°C test temperature may be used in the interim. If this method is used, the required value shall be less than 0.2 inch at 8000 passes.

Despite the efficacy of P-401 specifications in ensuring pavement durability and performance, challenges arise in reconciling these requirements with the availability of locally sourced aggregates. Gradation specifications pose significant difficulties for mix producers and designers, often necessitating adjustments that may compromise volumetric criteria or cause additional costs and delays in aggregate procurement. Such challenges result in critical questions regarding the necessity and flexibility of the existing P-401 gradation requirements, and their impact on mixture performance and construction feasibility.

This thesis delves into the complexities surrounding asphalt mix design for airport pavements, focusing on the challenges posed by current gradation requirements outlined in P-401 specifications as shown in Table 2. By examining the experiences and perspectives of industry stakeholders, including mix designers, contractors, and consultants, this study aims to better align with the realities of aggregate availability and pavement performance expectations. Through a comprehensive analysis of existing practices, potential adjustments, and advancements in mix design methodologies, this research endeavors to contribute valuable insights towards enhancing the effectiveness and feasibility of asphalt mix design for airport pavements, ultimately ensuring safer and more sustainable aviation infrastructure.

Table 2. P-401 Aggregate Gradation Requirements

Sieve Size	Percentage by Weight Passing Sieves		
	Gradation 1	Gradation 2	Gradation 3
1 inch	100	--	--
3/4 inch	90-100	100	--
1/2 inch	68-88	90-100	100
3/8 inch	60-82	72-88	90-100
No. 4	45-67	53-73	58-78
No. 8	32-54	38-60	40-60
No. 16	22-44	26-48	28-48
No. 30	15-35	18-38	18-38
No. 50	9-25	11-27	11-27
No. 100	6-18	6-18	6-18
No. 200	3-6	3-6	3-6

Chapter 2: Research Objective

This research aims to replicate an airport paving project mix design while still meeting FAA P-401 aggregate and mix design specifications, then conduct a range of performance tests covering aspects of asphalt mixture integrity and good functionality relative to airfields. Figure 1 illustrates the relative differences in performance demands of highway and airfield pavements. Then another aggregate gradation out of the FAA P-401 gradation specification limits will be developed using the Bailey Method [9] for gradation analysis to determine whether it is possible to adjust the gradation outside the standard specifications and still adhere to the volumetric mix design criteria in the P-401 specification, and then the same performance tests will be conducted. The aggregate gradation limits deviation will concentrate on increasing the upper gradation limits for all sieves except for the limits on No. 200 sieve, and on lowering the lower limits for the No. 16 sieve and those that are smaller. Importantly, these changes will not coarsen the gradation on the No. 8 sieve or any larger sizes, thereby preventing the asphalt mixture from becoming more permeable and safeguarding against the penetration of air and water that can lead to durability concerns. The overall aim is to compare the results of performance tests for both gradations and if applicable allow more flexible gradation specification limits criteria, specifying on critical sieve sizes and acceptable ranges, with the goal of maintaining mixture performance while reducing restrictions that will allow mixture producers to more successfully make good performing P-401 mixtures using a broader range of aggregates.

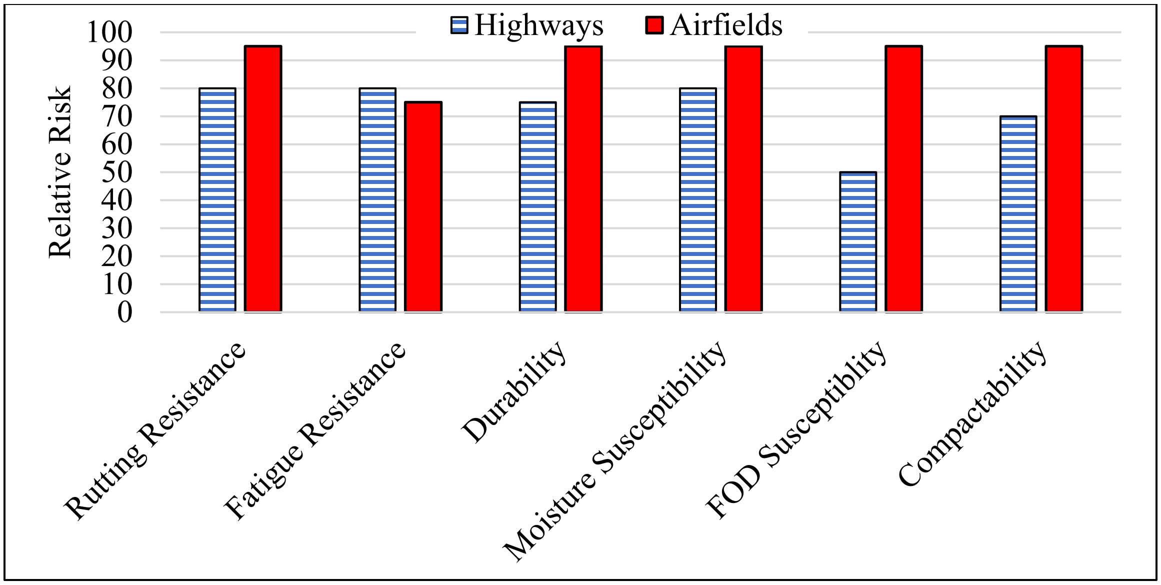


Figure 1. Relative Comparison of Highway and Airfield Mixture Performance Demands

Chapter 3: Literature Review

Aggregate gradation plays a vital role in determining the overall quality and performance of an asphalt mixture. According to Huber et al., the relationship between gradation and mixture performance was recognized early in the development of mix design methods [10]. Almost all essential properties of Hot Mix Asphalt (HMA), including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and moisture damage resistance, are affected by the gradation of aggregates. Furthermore, the volumetric properties of the mix, such as the asphalt content, VMA and Void Filled with Asphalt (VFA) are crucial for ensuring durability and optimal performance. Among these, VMA is considered the most critical parameter and is emphasized in P-401 mix-design specifications to prevent the use of poor mixture durability.

3.1 Influence of Aggregate Source

Advanced testing and evaluation were performed on laboratory prepared Marshall specimens from eight asphalt concrete mixes [11]. Five of these mixes contained steel slag aggregates and the others contained different proportions of coarse and fine natural aggregates. The mixes that contained slag aggregates were characterized and results were compared to the remaining three conventional asphalt concrete mixes commonly used in the province of Nova Scotia, Canada. Mix performance testing included indirect tensile strength, resilient modulus, creep and permanent deformation, moisture damage, and fatigue. Laboratory results showed that asphalt mixtures containing steel slag aggregates exhibited superior characteristics than those of conventional mixes. Pavement performance of three idealized pavement cross-sections were modelled using VESYS software and with measured material properties. Mixes which contained 100% steel slag aggregate had shown better resistance to rutting and to cold temperature cracking. To conclude, the aggregate type and properties have a direct influence on the performance of asphalt mixes.

3.2 Impact of Aggregate Gradation

The gradation of aggregates in asphalt concrete mixtures is a critical determinant that substantially influences the pavement's resistance to various distresses, such as rutting, moisture damage, low-temperature cracking, and fatigue. Over the past 10 to 15 years, Interstate pavements in northern Florida have experienced performance issues, primarily due to rutting. It was believed that the present fine-graded, 50-blow Marshall-designed mixes were inadequate to withstand current loading conditions [12]. Several states recommend the use of coarse graded mix for high traffic volume pavement due to its perceived better rutting performance attributed to a more robust structure [13]. However, the implementation of coarse graded mixes has faced significant challenges in many states [14]. One major issue is achieving target density on the roadway, which has proven to be consistently problematic for coarse graded mixes due to the higher level of compaction energy required. Additionally, excessive breakdown of aggregate occurs due to the high number of passes needed to reach the desired density, resulting in a significant loss of pavement life. Consequently, many states prefer the use of fine graded mixes because they are easier to construct, produce, and manage from a quality control perspective. Several studies have also indicated that fine graded mixes perform at least as well as coarse graded mixes in terms of rutting [15]. However, these mixes also pose considerable challenges. For instance, reaching the target density on the road has been consistently difficult with coarse graded mixes, as they demand more compaction energy. The increased number of compactor passes required not only raises the risk of aggregate breakdown, but also could shorten the lifespan of the pavement. In the Westrack study, Figure 2 shows the gradation of the HMA mixtures used [16] (Replacement = Coarse graded mixture, Fine = Fine graded mixture, and Fine+ = Fine graded mixture with baghouse fine added).

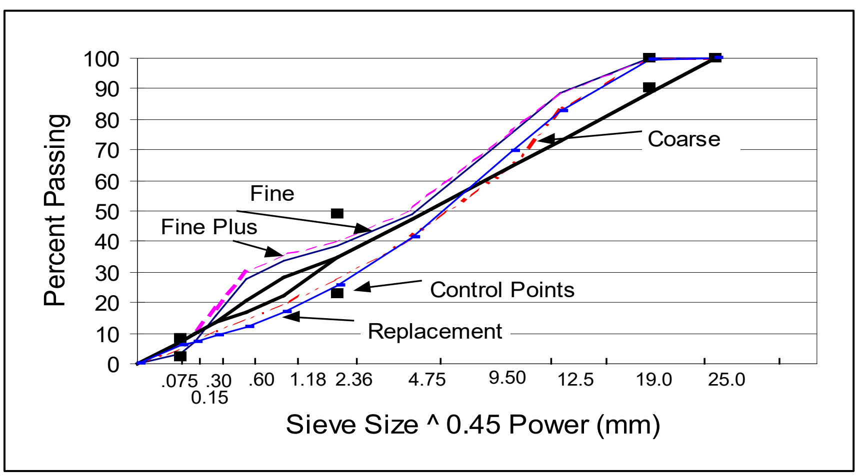


Figure 2. Westrack HMA Aggregate Gradation

The rutting performance of both coarse and fine-graded mixtures was found to be responsive to asphalt content. Coarse graded mixtures were highly sensitive to decreases in asphalt content, while both types of mixtures showed sensitivity to increases in asphalt content. Figures 3 and 4 highlight the fatigue and rutting results for each type of gradation in the Westrack study and showed that the coarse graded mixtures were more sensitive to variability in asphalt content and gradation what could lead to more performance problems with coarse graded mixtures as compared to fine-graded mixtures.

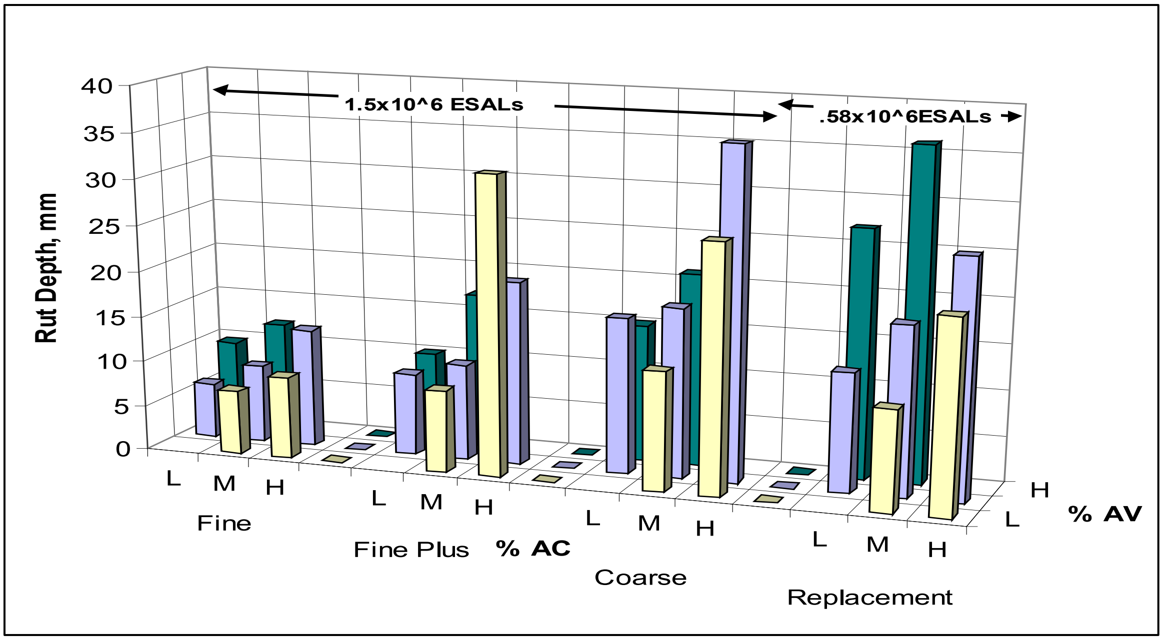


Figure 3. Westrack Rutting Performance

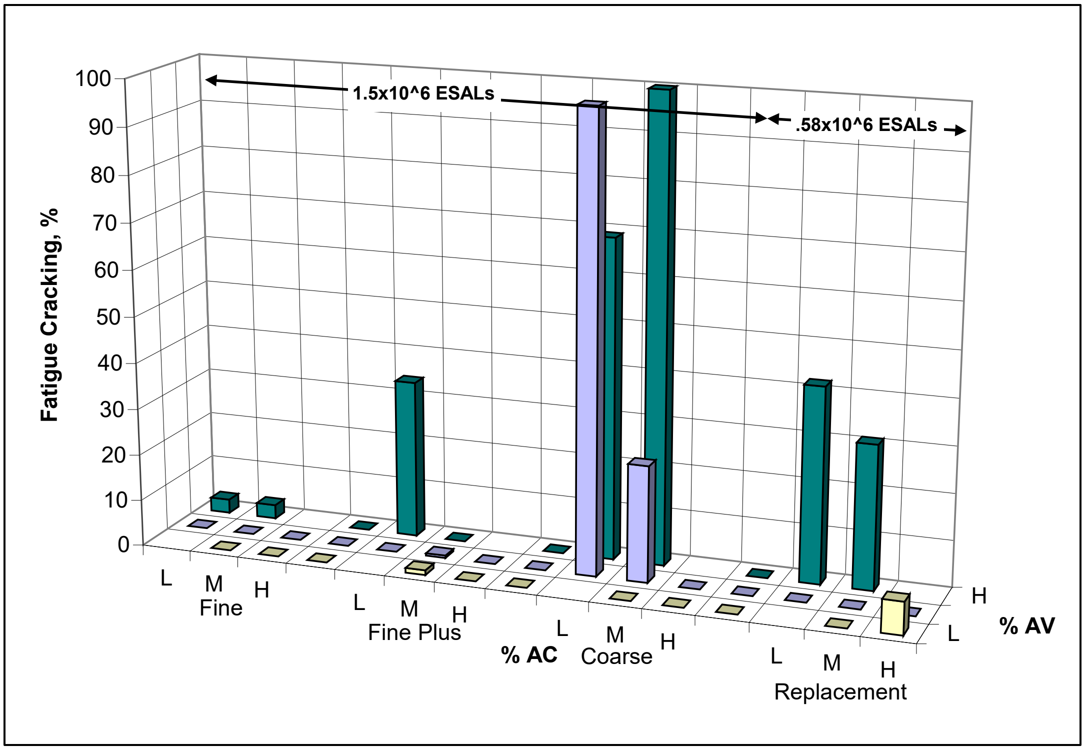


Figure 4. Westrack Fatigue Performance

In addition, a study has shown that medium graded mixtures demonstrated significantly better performance in rutting compared to coarse graded mixtures [17]. Consequently, several states have shown a preference for fine-graded mixes, which are simpler to construct, produce, and control quality-wise. Additionally, researchers have indicated that fine-graded mixes can match or even surpass the rutting performance of coarse graded mixes [18, 19]. Transverse and longitudinal shoving of asphalt paving mixtures primarily occurs due to the inadequacy of current test methods in identifying the properties of mixtures at various levels of traffic densification and understanding the influence of aggregate properties on the mixtures resistance to plastic deformation (shoving). Additional research was conducted [20] to explore the use of the air roller-equipped Gyratory Testing Machine (GTM) for evaluating asphalt mixtures containing aggregates from the same sources with different amounts of crushed and natural sand aggregates (varying blend proportions) to produce both identical and different gradations. Analyses performed on the test results indicated an overall positive correlation between Gyratory shear (Gs) after 200 revolutions of densification and asphalt content, VMA, and air void content (AV) at as-compacted densities. Similarly, statistical regression analyses indicated that asphalt, mineral filler, fine aggregate, and coarse aggregate contents have a significant effect on the Gs value for different mixtures. As a result, it was concluded that VMA and AV contents are not essential for mixture design or mixture evaluation. It was suggested that the GTM air roller procedure for testing asphalt mixtures is likely all that is needed for evaluating a mixture's resistance to plastic deformation. In the National Cooperative Highway Research Program (NCHRP) 09-64 project [21], the influence of gradation on interlayer shear strength (ISS) in AC mixtures was investigated. The study compared two gradations, fine and coarse, both using the same PG 64-22 binder and targeting a 7% AV level. Despite similar volumetric characteristics, including VMA, the finer graded mixture demonstrated higher ISS than the coarser graded mixture. This finding highlights the critical role of gradation in enhancing ISS and mitigating shoving and slippage failures in AC pavements.

3.3 Effect of Aggregate Gradation on Mix Performance

Both laboratory and prototype scale performance tests showed that adequate rutting performance can be obtained with gradations plotting above restricted zone (ARZ), through restricted zone (TRZ), and below restricted zone (BRZ) of the Superpave specifications. Laboratory tests suggested that above and through the restricted zone gradations might provide slightly better permanent deformation resistance than below the restricted zone gradations. This leads to the recommendations that the restricted zone be excluded from the Superpave mix design procedure and that a performance test be used to optimize mixture characteristics such as aggregate gradation, aggregate type and asphalt content for rutting performance [19].

In addition, a study on dense graded mixes where the APA was used showed that the rut depth data obtained on all mixes indicate a significant difference between rut depths of mixes with gradations passing above, through, and below the Superpave restricted zone. For granite and limestone BRZ showed the highest amount of rutting, TRZ showed the lowest amount of rutting and ARZ showed an intermediate amount of rutting. For gravel mixes, BRZ generally showed the lowest amount of rutting, ARZ generally showed the highest amount of rutting, and TRZ generally showed an intermediate amount of rutting. The effect of VMA on rutting appears to be associated with the effect of binder film thickness. An increase in VMA and film thickness causes an increase in rutting for granite and limestone mixes, whereas it causes a decrease in rutting for gravel mixes. Currently, the effect of VMA on rutting is not clearly understood, and further study is required to understand fully the effect of VMA on rutting. The Shear Strain Test (SST) test data in terms of peak shear strain indicates no significant difference between ARZ, TRZ, and BRZ gradations of granite wearing and binder mixes. In the case of limestone wearing and binder mixes, BRZ had the highest peak shear strain (potential of rutting) like APA rut depth test data. In the case of gravel wearing and binder course mixes, TRZ showed the lowest peak shear strain and ARZ showed the highest peak shear strain [18].

Nukunya et al., emphasized that aggregate gradation plays a pivotal role in the rutting resistance of asphalt mixtures since aggregates primarily bear the loads [22]. Aggregates are fundamental construction materials widely used in the building industry, comprising the majority of asphalt pavements. As such, the properties of aggregates significantly influence the performance of these pavements. Among these properties, gradation plays a crucial role in determining the permanent deformation behavior of hot mix asphalt [23]. In their research, Lv et al., assessed the rutting resistance of 26 different asphalt mixtures through the Hamburg Wheel Tracking Test (HWTT) [24]. A crucial threshold was identified where a passing ratio of 4.75 mm around 41% significantly affects the structural integrity of the coarse aggregate skeleton, thereby weakening the mixture's resistance to rutting and moisture damage.

Samples of pavements from 14 states across the United States were collected to assess the aggregate properties influencing rutting [25]. Figure 5 shows the participating states. Among these, twelve pavements had provided excellent service for five or more years, while 30 pavements had experienced premature rutting in less than five years of service. The aggregates from cores obtained at 1-foot intervals transversely across each pavement were subjected to tests for gradation and maximum aggregate size, fractured face count, and the National Aggregate Association Flow Test. Additionally, the cores were tested for in-place air void content and asphalt cement content. The remaining cores were reheated and recompacted using the Gyratory Testing Machine (GTM).

The data indicated that aggregate properties have little effect on rutting when the voids are low. However, when the voids exceed 2.5%, mixes with higher fractured face counts and more angular fine aggregate demonstrate increased resistance to premature rutting.

Figure 5. States Participating in the Rutting Study

Another study involved the analysis of rutting data obtained from the Alabama Highway Department's pavement condition database [26]. Field sites were evaluated, sampled, and subjected to laboratory tests on aggregate from the field samples.

Analyses of the Department's pavement condition database suggest that rutting in Alabama was on the rise, and this increase was attributed to either increased loading intensity or increased asphalt concrete rutting susceptibility. The analyses also indicated that rutting varied geographically and can be explained by the quality of locally available aggregate. Regions with crushed stone and angular natural sands are less susceptible to rutting and that rutting is generally confined to the top 2.5 to 4 inches. Poor correlations between aggregate properties were observed and suggested that rutting is a very complicated process affected by multiple factors, emphasizing the importance of both aggregate properties and asphalt content during material selection and mix design.

A comparative study of Coarse, Fine, and Fine+ mixtures specifically designed for intersection use revealed that fine mixes could perform comparably in terms of cracking and rutting resistance when the particle size is less than 0.2 inch. The study also recommended maintaining a No. 200 sieve range between 3% and 8%, which helps in preserving the durability of the mix without compromising the VMA of the asphalt mixtures [27].

Additionally, in an Airfield Asphalt Pavement Technology Program (AAPTP) project [28], the gradation specifications for airport asphalt surfaces were studied with an emphasis on how gradation influences asphalt permeability. Permeability is a crucial property of asphalt mixtures because it determines how air and water penetrate the pavement structure. Air penetration allows oxygen to react with the asphalt binder, leading to accelerated aging and increasing the likelihood of cracking and raveling. Water penetration, on the other hand, can cause moisture damage, compromising the integrity of the mixture and contributing to raveling, which poses significant Foreign Object Debris (FOD) hazards to aircraft safety. Consequently, non-permeable, fine-graded asphalt mixtures are essential for airport pavements. In this study, the permeability was assessed by modifying the gradations of five fine-graded airport asphalt mixtures consisting of one 3/8 inch, three 1/2 inch, and one ¾ inch NMAS mixtures. The mixtures were prepared and compacted at various target air voids to replicate different in-situ densities. The findings indicated that coarser gradations resulted in increased permeability leading to potential permeability issues on-site. Consequently, the study advised against altering the lower gradation limits specified in the P-401 standards. Also, an empirical model to estimate HMA permeability with the use of common compositional factors has been developed [29]. The model is an improvement of one originally developed as part of NCHRP Projects 9-25 and 9-31 but uses an expanded data set to provide a better model. The elimination of unrealistic mixture compositions from the data set and the consideration of additional potential predictors have resulted in a model with significantly improved accuracy and usefulness. The model predicts that permeability increases primarily with increases in air voids. However, aggregate properties also affect permeability: An increase in nominal maximum aggregate size and a decrease in mean aggregate particle size (D50) tend to decrease HMA permeability. The model suggests that, when durability is an important concern, fine aggregate gradations should be used for HMA mix designs.

In addition, diametral fatigue tests and uniaxial incremental static creep tests were conducted in a study under varying temperatures and mixture variables, including aggregate type and gradation [30]. The effects of aggregate type and gradation on permanent deformation were evaluated under test combinations with changing asphalt type, asphalt content, air voids content, temperature, and applied stress level. For the fatigue study, the effect of aggregate type was assessed by altering asphalt content, air voids content, and temperature. The test results were analyzed using statistical analysis and graphical comparison of data. Analysis of variance (ANOVA) tests were conducted to investigate the main effects and interactions of the test variables with the aggregate type or gradation. The analysis revealed that, within the scope of experimentation used in this study, aggregate type had significant effects on fatigue resistance and permanent deformation of asphalt concrete, indicating better performance from mixtures comprised of aggregates with rough surface texture and angular shape. Coarse gradation, meaning a larger proportion of coarse aggregates with the same NMAS compared to medium gradation, did not exhibit significant effects on permanent deformation. Interactions of aggregate type with gradation, asphalt type, air voids, and temperature were found to be significant for the permanent deformation of asphalt concrete, whereas no interaction appeared to be significant for fatigue with the given scope of experimentation.

3.4 Influence of Baghouse Fines on HMA performance

Baghouse fines can influence the performance of HMA mixtures. Depending on the particle size, fines can act as a filler or an extender of asphalt binder [31]. An HMA mix over-rich in fines can lead to flushing and/or rutting. In many cases, the amount of asphalt cement used must be reduced to prevent a loss of stability or pavement bleeding. Some fines have a considerable effect on the asphalt cement making it act as a much stiffer grade of asphalt cement compared to the neat asphalt cement grade and, thereby, affecting the HMA pavement performance including its fracture behavior. Rheological responses of asphalt fine aggregate matrix (FAM) were studied using the dynamic shear rheometer (DSR) [32]. Results showed that rheological performances of FAM are significantly affected by asphalt content, gradations and air void content.

Some fines make HMA mixtures susceptible to moisture-induced damage [31]. The presence of harmful clays in fine aggregate of fine baghouse fines has the potential of inducing stripping in HMA mixes. International reported issues were mentioned as follow: Water-sensitivity of one source of slag baghouse fines has been reported in the United States, water-sensitivity of other stone dusts has been reported in Germany and stripping of HMA mixtures as related to the properties of filler/asphalt combinations has also been reported in Japan.

3.5 Effect of Passing No. 200 Material

Excessive amounts of passing No. 200 material in asphalt mixtures can negatively impact their performance. High levels of passing No. 200 material can lead to increased mixture stiffness, cause the asphalt binder film thickness to be reduced, heighten moisture susceptibility, accelerate mixture aging, and diminish both workability and compaction qualities. Additionally, an increase in passing No. 200 material typically results in reduced VMA and thinner asphalt films [33]. While there are cases where excessive passing of No. 200 material can serve as an extender and augment the binder volume within the mix, this benefit is only apparent when the size of the passing No. 200 material is smaller than the thickness of the asphalt film.

While a higher binder volume can lower the demand for asphalt binder, it may also speed up the oxidation of the mixture, resulting in decreased durability. Research has shown that excessive passing No. 200 material can notably impact the mixture's resistance to fatigue and its thermal cracking temperature [34], though it appears to have minimal or no effect on rutting. The reviewed literature indicates that the impact of passing No. 200 materials on mixture performance varies considerably. The influence of No. 200 is substantial in altering the properties of mixtures and affects performance tests such as the Hamburg Wheel Tracking Test (HWTT), Tensile Strength Ratio (TSR), Ideal Cracking Test (IDEAL-CT) [35]. In addition, a study on the influence of minus No. 200 aggregates on the fracture behavior of HMA [36] concluded that the use of mineral fillers increases the fracture toughness of the HMA.

3.6 Analyzing Aggregate Gradations

The packing characteristics of coated aggregate particles in an asphalt mixture are influenced by the particle shape, surface properties and gradation of the aggregate [37]. Particle angularity and surface texture are key surface properties of aggregates. While selecting aggregates for a project, specific surface characteristics are often not selected with the intent to achieve a particular VMA; rather, VMA is typically a byproduct of the mixture's composition. If there is a need for additional VMA, adjustments must be made to the gradation.

In recent years, the Bailey Method has gained prominence as an effective tool for choosing aggregate gradations in HMA mixture design, thereby minimizing experimental trials. Originally developed by the Illinois Department of Transportation, this method has advanced into a structured technique for aggregate blending, cost savings, that is suitable for all types of dense-graded asphalt mixtures, regardless of the maximum aggregate size [38, 39]. The Bailey Method relies on two core principles: the packing of aggregates and the classification of aggregates into coarse and fine categories, which fundamentally influences the relationship between aggregate gradation and mixture volumetrics.

3.7 Influence of Dust Proportion (DP)

The performance of asphalt concrete (AC) mixtures can be influenced by their DP, which is determined by the effective binder content and the amount of material passing the No. 200 sieve. Alterations in these components can significantly affect the mixture's DP. A deficiency in fines within the mix can make the asphalt susceptible to rutting. To counteract this, one strategy is to enhance the voids in mineral aggregate (VMA) and DP by increasing the effective binder content and incorporating more material that passes through the No. 200 sieve [40]. Additionally, adding more passing No. 200 materials to the mixture can enhance rutting resistance by increasing the stiffness of the mixture [33]. A study on percent fracture of gravels in Indiana [41] validated that DP should be between 0.6 to 1.2 because without enough "dust" in the mixture for proper initial asphalt stiffening and dispersion, many pavements of an early age are at risk. In addition, proper levels of minus No. 200 and No. 100 are also needed for gravels because of their rugosity.

3.8 Influence of Portland Cement

The integrity of HMA is greatly influenced by the quality of aggregates used. Many nations, including the United States of America, face challenges due to the scarcity of high-quality aggregates. A potential remedy to this issue is the enhancement and amelioration of the widely available but substandard aggregates. Cement coating technique aims to refine the surface texture of aggregate particles, thereby strengthening their bond with the asphalt binder. This technique entails encasing the aggregates with a layer of hydrated Portland cement, thus creating a protective film over the particles. Aggregates treated using this method can then be incorporated into asphalt mixtures using standard mixing procedures. Mixtures prepared with such treated aggregates are called "CEMPHALT". Key factors influencing the efficacy of this coating method include the amount of cement, the ratio of water to cement, and the duration of hydration, for which optimal levels have been identified. Comparative assessments of CEMPHALT mixtures reveal notable enhancements in resistance to rutting, fatigue, and moisture damage [42].

Additionally, some newly constructed highway pavements in the Kingdom of Saudi Arabia have experienced premature failures, resulting in adverse impacts on both roadway safety and the economy [43]. One of the primary types of these failures is permanent deformation (rutting). Fillers were suspected to be significant contributors to rutting susceptibility. The results of this study indicate that the partial replacement of limestone dust by hydrated lime or Portland cement aggravates the resistance of the mixes to rutting.

3.9 Influence of Crush Percentage Particles and Aggregate Absorption on HMA

In recent times, there has been a push to enhance asphalt concrete mixtures, resulting in higher fractions of crushed aggregate [44]. With gravel sources depleting, the extraction of coarse aggregate has become more challenging, consequently driving up the cost of supplying crushed aggregate. However, adding excessive crushed aggregate can lead to two problematic scenarios. The first issue comes from the crushing and washing of the manufactured fines portion of the aggregate. Hammermill, impact, or cone crushers tend to produce gradations for fine aggregates below the maximum density line when washed. This process can reduce the voids in mineral aggregate, which is crucial for resisting rutting. A theory has been proposed suggesting that aggregate water absorption can predict the bonding surface volume, which can improve the results of heavy traffic mixes. Let the bonding surface volume be defined as the volume around each particle opened by pores. The second issue can be described as the propensity for shearing of mastic to aggregate bonds over time when aggregates with low water absorption values are used. Marshall stability tests for a mix using aggregates with generally high values of water absorption were compared to tests for a mix using aggregates with low values of water absorption.

The conclusion supported the premise that shearing under load increases as average water absorption values decrease.

3.10 Investigations

The 1948 investigation of the design and control of asphalt paving mixtures [45] highlighted many discoveries connected to aggregate gradations from testing using the Hubbard-Field method and the Marshall method in addition to test strips. Key finds follow:

1) Six gradations of one type of sand and nine gradations with one type of coarse aggregate were studied. For sand asphalt mixtures (mixtures made from fine aggregates, filler and asphalt binder) with 10 to 20 percent filler, it was shown that the addition of coarse sand (No.10 to No.40) up to a maximum of 50 percent improved the test properties of the mixture.
2) Adding coarse aggregates to an asphalt mixture reaching a maximum of 60 per cent lead to an improvement in the test properties of the mixture.
3) It has been shown that stability and unit weight of mixture increased when the amount of aggregates coarser than No. 40 increased.
4) Gradation limits are controlled as part of specifications which have proven to be satisfactory over a long period of time.
5) During World War II, airports where designed, constructed and supervised by men not familiar with the locally available aggregates. There was a need to find a better way to control the construction of pavements with confidence. This is why an investigation had to take place.

6) It has been shown that the most important factor in a paving mixture is the quantity of asphalt binder. From a durability standpoint, it is desirable to include as much asphalt as possible. It is good to mention that too much asphalt will result in bleeding in the asphalt mixture leading to rutting and shoving under traffic. While adding too little asphalt will result in cracking and raveling.
7) In order to compare factors related to aggregate gradations, this comparison should be made using the same amount of asphalt binder.

Chapter 4: Design Approach and Performance Tests

4.1 Design Approach

A ¾” NMAS mix design from an airport in Arizona that presented joint compaction challenges, and where prime coat was applied to prevent the mix from moving to achieve mat compaction was used in this research. Aggregates, cement and a PG76-22 PM binder used in the mix design were sampled and shipped to the University of Nevada, Reno for further use in this study. Aggregates consisted of 5 stockpiles as follow: 3/4”, 3/8”, Washed Crusher Dust (WCD), Crusher Dust (CD) and Washed Asphalt Sand (WAS).

4.1.1 Accurate Aggregate Batching

A unique technique was used to batch aggregates since the project was looking for small variations in the P-401 aggregate bands. The methodology recognizes that when dry-sieved, fine materials passing through the No. 200 sieve are prone to adhering to larger aggregate particles. This adhesion leads to a higher-than-anticipated amount of fine materials in the mix when samples are created from these dry-sieved fractions. To prevent an excess of No. 200 material in the final mix, it's crucial to correct the aggregate batching process to address this.

A pragmatic approach would be to aim for a gradation that is cleaner than the target since fines tend to bond with larger particles, resulting in a finer gradation than originally anticipated. While targeting a gradation that precisely matches the desired level, it is important to understand that this will likely require multiple adjustments to find the precise blend for batching. This careful process, however, is key in preventing an overabundance of Passing No. 200 material, thus aiding in the creation of a cleaner and more robust mix.

The batching goal was to the following differential thresholds, as outlined:

- A variance of 0.5% or less for the coarsest sieve
- A variance of 0.1% or less for the No. 200 sieve
- For sieve sizes in between the largest and the smallest, the variance should be between 0.5% and 0.1%, depending on the specific sieve size.

In this process, each stockpile was sieved individually using a fully automatic sieve shaker into all sieves ranging from ¾" to Pan sieves and placed individually in buckets. This was done intentionally to have the ability to make changes to individual stockpile bin percentages after estimating the outcome of the mix using the Bailey Method without compromising the material sieved previously and to be the most accurate regarding aggregate sampling.

The different steps to accurately batch a sample that reflects accurately the gradation in the Job Mix Formula (JMF) with tables highlighting the process for each step:

1. Assume a gradation that will reflect the JMF blend gradation (Table 3).

Table 3. Step 1 in the Adjustment Process

Sieve Size	Cement Gradation	Combined Blend Gradation JMF with Cement	**Combined Blend Gradation JMF without Cement**	**Assumed Blend Gradation w/o Cement**
1"	100.0	100.0	**100.0**	**100.0**
3/4"	100.0	97.1	**97**	**97.0**
1/2"	100.0	84.5	**84.4**	**84.0**
3/8"	100.0	77.6	**77.3**	**76.9**
#4	100.0	58.7	**58.3**	**57.9**
#8	100.0	38.9	**38.3**	**37.5**
#10	100.0	34.6	**33.9**	**33.0**
#16	100.0	24.7	**23.9**	**23.0**
#30	100.0	16.4	**15.6**	**14.8**
#40	100.0	12.8	**11.9**	**11.0**
#50	100.0	10.4	**9.5**	**8.7**
#100	100.0	7.5	**6.6**	**4.9**
#200	100.0	5.8	**4.9**	**2.7**
Pan	0.0	0.0	**0.0**	**0.0**

2. Batch a 4.4 lbfsample while normalizing to know the exact amount of aggregates to be added from every stockpile on every sieve. Figure 8 highlights an example for one stockpile out of 5 stockpiles (Table 4). The Equations used throughout this process on sieve "X" are:

$$\text{Difference} = \text{Batch Weight required from sieve “X”} - \sum_{k=1}^{n=5} (\text{Sample size} \times \text{\% retained on sieve "X" from stockpile "k"} \times \text{stockpile "k" bin \%}) \qquad \textbf{Eq. 1}$$

$$Normalization = \sum_{k=1}^{n=5} \%\, retained\ on\ sieve\ "X"\ from\ stockpile\ "k" \qquad \textbf{Eq. 2}$$

$$Final\ weight\ needed\ from\ stockpile\ \text{"k" on sieve "X"} =$$

$$= (Sample\ size \times \%\, retained\ on\ sieve\ "X"\ from\ stockpile\ "k"$$

$$\times\ stockpile\ "k"\ bin\ \%) \qquad \textbf{Eq. 3}$$

$$+ \frac{Difference\ on\ Sieve\ "X" \times \%\, retained\ on\ sieve\ "X"\ from\ stockpile\ "k"}{Normalization\ on\ sieve\ "X"}$$

Table 4. Steps 2 for the 3/4" Stockpile in the Adjustment Process

Sieve Size	A	B	**C**	**D**	E	F	G	H	I
1"	100.0	0.0	**100.0**	**0.0**	0.0	0.0	0.0	0.0	0.0
3/4"	86.7	13.3	**97.0**	**3.0**	59.1	0.0	13.3	59.1	59.1
1/2"	29.6	57.1	**84.0**	**13.0**	260.9	7.1	57.1	253.8	260.9
3/8"	10.4	19.2	**76.9**	**7.1**	142.0	1.7	36.2	85.3	86.2
#4	4.8	5.6	**57.9**	**19.0**	380.0	-1.6	101.0	24.9	24.8
#8	4.1	0.7	**37.5**	**20.4**	408.0	8.9	82.2	3.1	3.2
#10	4.1	0.0	**33.0**	**4.5**	90.0	2.6	20.8	0.0	0.0
#16	4.1	0.0	**23.0**	**10.0**	200.0	0.0	50.4	0.0	0.0
#30	3.7	0.4	**14.8**	**8.2**	164.0	-3.4	48.9	1.8	1.7
#40	3.7	0.0	**11.0**	**3.8**	76.0	3.2	20.2	0.0	0.0
#50	3.7	0.0	**8.7**	**2.3**	46.0	-1.9	15.6	0.0	0.0
#100	3.7	0.0	**4.9**	**3.8**	76.0	17.1	18.9	0.0	0.0
#200	3.3	0.4	**2.7**	**2.2**	44.0	9.7	9.7	1.8	2.2
Pan	0.0	3.3	**0.0**	**2.7**	54.0	-43.5	25.7	14.7	9.1

A: ¾” Stockpile gradation
B: ¾” Stockpile retained percentage
C: Assumed blend gradation without cement
D: Assumed blend retained percentage
E: Batch weight required
F: Difference
G: Normalization
H: ¾” weight required 22%
I: Final ¾”

<u>Numerical example:</u>

Note: On the 1/2” sieve all the aggregates are coming from the ¾” stockpile.

Calculated numbers may defer by decimals due to rounding the numbers down to one decimal.

- Difference on 1/2” sieve= 260.9- (2000*0.571*0.222) = 7.1
- Normalization on ¾” sieve= 57.1% (since all 1/2” sieve aggregates are coming for ¾” stockpile.
- Final weight needed from 1/2” sieve from ¾” stockpile= (2000*0.571*0.222) + [7.1*57.1/57.1] = 260.9.

3. Determine the actual gradation of the batched sample by performing a washed sieve analysis (AASHTO T11 [46] and AASHTO T27 [47])
4. Based on actual gradation determined by the sieve analysis, batch another sample adjusting for deviations from targets.

Table 5. Step 4 in the Adjustment Process

Sieve Size	Combined Blend Gradation w/o Cement	Actual Batching Percent	Measured Gradation washed sieve analysis	Difference In Combined Blend w/o Cement & Measured	New Batch Percent (For Wash 2)
1"	100.0	100.0	100.0	0.0	100.0
3/4"	97.0	97.0	97.1	0.0	97.0
1/2"	84.4	84.0	84.3	0.0	84.0
3/8"	77.3	76.9	77.7	-0.3	76.6
#4	58.3	57.9	59.9	-1.7	56.2
#8	38.3	37.5	39.0	-0.7	36.8
#10	33.9	33.0	34.6	-0.7	32.3
#16	23.9	23.0	24.4	-0.4	22.6
#30	15.6	14.8	15.8	-0.2	14.6
#40	11.9	11.0	12.3	-0.4	10.6
#50	9.5	8.7	9.7	-0.2	8.5
#100	6.6	4.9	7.1	-0.5	4.4
#200	4.9	2.7	5.4	-0.6	2.1
Pan	0.0	0.0	0.0	0.0	0.0

5. Repeat step 3.
6. Repeat step 4 until actual gradation and target gradation are within the above-described tolerance range (difference between combined blend without cement and measured gradation from washed sieve analysis).
7. Batch all necessary test specimens using the adjusted batching gradation to account for adhesion.

4.1.2 Aggregate Testing

To be able to use the Bailey Method throughout the project, aggregate unit weights had to be measured [48]. For the coarse stockpiles (3/4" and 3/8") a 1/2 ft^3 metal bucket as shown in Figure 6 was used to determine the loose and rodded unit weight. For the fine stockpiles (CD, WCD and WAS) a 1/30 ft^3 Proctor mold was used.

Figure 6. 1/2 ft^3 Metal bucket

In addition, coarse and fine aggregate specific gravities were measured for each individual stockpile [49, 50]. Figure 7 shows an important step while performing the fine specific gravity test on a fine stockpile.

Figure 7. Checking for SSD Condition in the Fine Specific Gravity Test

Table 6 summarizes the following aggregate properties: stockpiles JMF (Mixture ID 3082) Gradation, Loose Unit Weight, Rodded Unit Weight, Coarse Specific Gravities, and Fine Specific Gravities.

Table 6. Summary of Stockpile Gradations, Unit Weights and Specific Gravities

Stockpile ID	3/4"	3/8"	Crusher Dust	Washed Crusher Dust	Washed Asphalt Sand
Sieve Size	(%) Passing	(%) Passin g	(%) Passing	(%) Passing	(%) Passing
1"	100	100	100	100	100
3/4"	86.7	100	100	100	100
1/2"	29.6	100	100	100	100
3/8"	10.4	83.0	100	100	100
#4	4.8	10.0	91.5	87.1	99
#8	4.1	4.0	65.0	49.1	88
#10	4.1	3.6	58.8	41.7	81.2
#16	4.1	3.0	45.5	25.6	60.8
#30	3.7	2.5	33.5	15.2	35.2
#40	3.7	2.4	29.7	9.8	24.3
#50	3.7	2.2	26.4	7.4	14.6
#100	3.7	2.0	21.6	4.5	3.6
#200	3.3	1.80	17.10	2.90	0.60
Average Loose Unit weights (kg/m3)	1456.0	1498.9	1774.0	1685.9	1632.9
Average Rodded Unit Weights (kg/m3)	1548.8	1561.1	1979.0	1777.5	1661.9
Average Coarse Gsb	2.666	2.666			
Average Coarse Gsa	2.716	2.734			
Average Coarse %Absorption	0.689	0.930			
Average Fine Gsb			2.453	2.601	2.570
Average Fine Gsa			2.707	2.711	2.656
Average Fine %Absorption			3.827	1.563	1.254

After performing the aggregate bulk specific gravity (Gsb) tests, a difference compared to the specific gravities from the mix design was observed. This difference could have been due to a change in the sampling timing from the Quarry between the airport project and the laboratory testing at UNR and variability associated with the test method. There were also differences in the individual stockpile gradations when sieve analyses were conducted on each individual stockpile which is anticipated. Table 7 shows the difference between the specific gravity results from UNR testing and the results from the Original JMF. Equation 4 is used to calculate the Specific Gravity of the blend:

$$G_{sb} = \frac{\sum Bin\ Percentages}{\sum \frac{Stockpile\ bin\ percentage}{Gsb\ of\ individual\ Stockpile}} \quad \textbf{Eq. 4}$$

Table 7. Specific Gravities Difference between UNR Testing and Original JMF

Source	UNR Testing					Original JMF				
Stockpile	3/4"	3/8"	CD	WCD	WAS	3/4"	3/8"	CD	WCD	WAS
Gsb	2.666	2.666	2.543	2.601	2.570	2.684	2.672	2.679	2.641	2.581
Bin (%)	22.2	16.2	16.2	35.4	10.1	22.2	16.2	16.2	35.4	10.1
Gsb Coarse	2.666					2.679				
Gsb Fine	2.580					2.641				
Gsb Blend without cement	2.613					2.656				
Gsb Blend with cement	2.617					2.661				

4.1.3 Portland Cement

Type II Portland cement was used in the mix design as a mineral filler. Each sample was mixed with 1% cement and 3% water by dry weight of aggregates. Mixing was done using automatic mixers, where every sample was mixed until all aggregates were coated with cement as shown in Figure 8. There was no specific timing for marination, so samples were then placed in the oven at mixing temperature along with the asphalt binder for 2 hours before going through the mixing process.

Figure 8. Fully Coated Aggregates with Cement

4.1.4 Mix Design

The Superpave mix design method was conducted using the Superpave Gyratory compactor (SGC) at 75 Gyrations for this project [51]. The goal was to replicate the mix design job mix formula (JMF) from a Tucson Arizona P-401 mixture and try to meet FAA volumetric requirements highlighted in Table 1. The optimum binder content was selected at 3.5% air voids. The mixing temperature used was 345°F and the compaction temperature was 295°F. All asphalt mixes were short-term aged at compaction temperature since the binder used was polymer-modified [52].

4.1.4.1 Gradation Inside the FAA Specifications

Initially the bin percentages used in the "Original JMF" were adopted. As outlined before, the difference between the target gradation and the gradation used should conform to a set of limits. In fact, variations will always show up and the goal is to always be as close as possible to the target gradation. Table 8 shows a comparison between the "Original JMF" and the "Actual JMF" gradation after going through the adjustment process.

Table 8. Comparison between the "Original JMF" Gradation and the "Actual JMF" Gradations

Sieves	"Original JMF" Gradation with cement	"Actual JMF" Gradation without cement After Washed Sieve Analysis	"Actual JMF" Gradation with cement	Difference between "Actual JMF" Gradation and "Original JMF" Gradation
1"	100.0	100.0	100.0	0.0
3/4"	97.1	96.6	96.7	-0.4
1/2"	84.5	83.8	83.9	-0.6
3/8"	77.6	77.1	77.3	-0.3
#4	58.7	58.3	58.7	0.0
#8	38.9	37.9	38.5	-0.4
#10	34.6	34.0	34.6	0.0
#16	24.7	23.9	24.6	-0.1
#30	16.4	15.6	16.4	0.0
#40	12.8	12.6	13.5	0.7
#50	10.4	9.2	10.1	-0.3
#100	7.5	6.9	7.8	0.3
#200	5.8	5.2	6.2	0.4

Two theoretical maximum specific gravity (Gmm) [53] samples were prepared and tested at the original JMF optimum binder content (5.26% AC) as shown in Table 9. In addition, two other Gmm samples were also prepared at 5% AC content for better verification as outlined in Table 10.

Table 9. Theoretical Maximum Specific Gravity (Gmm) for "Actual JMF" at 5.26% AC

G_{mm} at 5.26% AC		
Sample ID	Sample 1	Sample 2
Mass Oven Dry (A) (g)	2681.6	2681.8
Mass of the Sample in Water+Basket (g)	3044.2	3043.4
Mass of the Basket in Water (g)	1441.4	1441.4
Mass Sample in Water (C) (g)	1602.8	1602
G_{mm}	2.486	2.484
G_{mm} Standard Deviation < 0.0051	0.0015	YES
Average G_{mm}	2.485	

Table 10. Theoretical Maximum Specific Gravity (Gmm) for "Actual JMF" at 5% AC

G_{mm} at 5% AC		
Sample ID	Sample 1	Sample 2
Mass Oven Dry (A) (g)	2677.9	2697.4
Mass of the Sample in Water+Basket (g)	3044.4	3055.1
Mass of the Basket in Water (g)	1441.1	1441.1
Mass Sample in Water (C) (g)	1603.3	1614
G_{mm}	2.492	2.490
G_{mm} Standard Deviation < 0.0051	0.0016	
Average G_{mm}	2.491	

Two bulk specific gravity samples were compacted at 5% AC and at 5.5% AC [54]. With every set of Gmb samples, an extra sample was also batched ready to go through a washed sieve analysis to investigate if results were deviating. The Gsb used in the "Original JMF" was adopted to evaluate the volumetric properties [55] of the "Actual JMF" mix design (Gsb= 2.661) for the purposes of comparing gradations. The Superpave volumetric results are shown in Table 11.

Table 11. Superpave Volumetric Results of the "Actual JMF" mix design

Actual JMF					Original JMF
Binder Content Used (%)	5.0	5.0	5.5	5.5	5.26
Sample ID	4	2	1	2	3082
Number of Gyrations	75	75	75	75	75
Air Mass (g)	4770	4693.5	4696.3	4692.4	
Underwater Mass (g)	2810.1	2767.4	2765.5	2773.9	
SSD Mass (g)	4774.2	4698.1	4699	4696	
G_{mb}	2.429	2.431	2.429	2.441	2.402
Average Gmb	2.430		2.435		
Standard Deviation (d1s)	0.0017		0.00875		
Gmm	2.491		2.472		2.488
Height of specimen	113.9	112.5	110.8	111.7	
Difference (d2s)	0.002		0.0124		
d1s < 0.013 and d2s < 0.037 [56]	YES		YES		
Air Voids (%)	2.5	2.4	1.7	1.2	3.5
Average Air voids (%)	2.5		1.5		
VMA (%)	13.3	13.2	13.8	13.3	14.5
Average VMA(%)	13.3		13.5		
VFA	81%	82%	87%	91%	76%
Average VFA	82%		89%		
Gse (using Gmm at 5%)	2.690				2.699
Pba	0.4				
Pbe	4.595	4.595	5.132	5.132	4.740
DP	1.2	1.2	1.0	1.0	1.2

Comparing the "Actual JMF" with the "Original JMF" that needs to be replicated, and conducting additional Gmb specimens at 4.5% AC, the results showed that an optimum binder content of 4.7% AC should be used to have 3.5% air void content as shown in Figure 12. Unfortunately, the "Actual JMF" was not adopted because VMA was at 13.7 compared to the "Original JMF" VMA of 14.5.

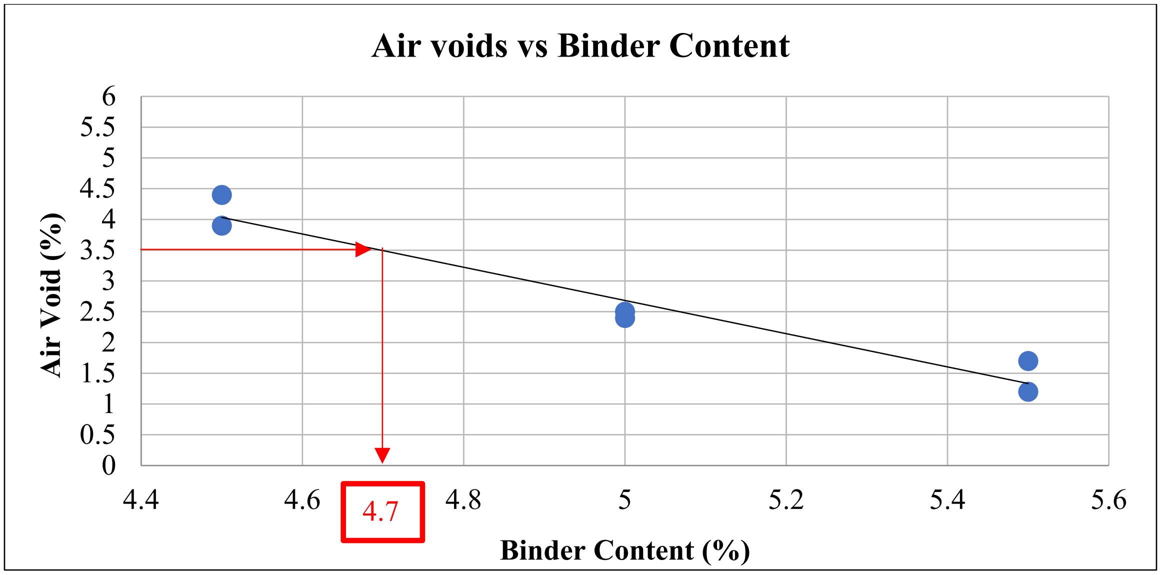


Figure 8. Relationship between Air Void and AC Content for "Actual JMF" Gradation

Using the Bailey Method, a new set of stockpiles bin percentages were analyzed to estimate a VMA and percent effective binder (Pbe) close enough from the JMF (±0.2%). The new developed blend meeting Gradation 1 in the P401 aggregate gradation requirements in Table 2 will be referenced as "New Control Blend". The blend Gsb is outlined in Table 12 using the individual stockpiles Gsb values from the "Original JMF" and a Gsb of 2.659 wase used as an average value between the calculated Gsb and the Gsb from the Original JMF.

Table 12. Calculated Gsb of the New Control Blend Gradation

New Control Blend					
Stockpile	3/4"	3/8"	CD	WCD	WAS
Gsb	2.684	2.672	2.679	2.641	2.581
Bin Percentage	17.2%	20.2%	12.1%	40.4%	10.1%
Gsb Coarse	2.678				
Gsb Fine	2.638				
Gsb Blend without cement	2.653				
Gsb Blend with cement	2.657				

Table 13 shows a comparison between the "New control Blend" and the "Actual New Control Blend" gradations after going through the adjustment process.

Table 13. Comparison between the "New Control Blend" Gradation and the "Actual New Control Blend" Gradation

Sieves	"New Control Blend" Gradation with Cement	"Actual New Control Blend" Gradation without Cement After Washed Sieve Analysis	"Actual New Control Blend" Gradation with Cement	Difference between "New Control Blend" Gradation and "Actual New Control Blend" Gradation
1"	100.0	100.0	100.0	0.0
3/4"	97.7	98.3	98.3	0.6
1/2"	88.0	87.6	87.7	0.3
3/8"	81.4	80.7	80.9	0.4
#4	59.5	58.9	59.4	0.2
#8	38.7	38.5	39.1	0.3
#10	34.3	33.8	34.5	0.2
#16	24.1	23.1	23.9	0.2
#30	15.7	15.0	15.9	0.1
#40	12.0	11.4	12.3	0.3
#50	9.7	8.5	9.5	0.2
#100	6.8	6.0	6.9	0.2
#200	5.2	4.4	5.4	0.2

Two Theoretical maximum specific gravity (Gmm) samples were prepared and tested at 5.2% AC as shown in Table 14. An Additional Gmm sample was also prepared and tested at 5.45% AC for more verification as outlined in Table 15.

Table 14. Gmm for the "Actual New Control Blend" at 5.2% AC

G_{mm} at 5.2% AC		
Sample ID	Sample 1	Sample 2
Mass Oven Dry (A) (g)	2656.5	2656.5
Mass of the Sample in Water+Basket (g)	3030.8	3029.2
Mass of the Basket in Water (g)	1441.2	1441.2
Mass Sample in Water (C) (g)	1589.6	1588
G_{mm}	2.490	2.486
G_{mm} Standard Deviation < 0.0051	0.0026	
Average G_{mm}	2.488	

Table 15. Gmm for the "Actual New Control Blend" at 5.45% AC

G_{mm} at 5.45% AC		
Sample ID	Sample 1	Calculation based on Gmm at 5.2%AC
Mass Oven Dry (A) (g)	2655	
Mass of the Sample in Water+Basket (g)	3027.5	
Mass of the Basket in Water (g)	1440.8	
Mass Sample in Water (C) (g)	1586.7	
G_{mm}	2.485	2.479
G_{mm} Standard Deviation < 0.0051	0.0045	
Average G_{mm}	2.482	

Two Gmb specimens were compacted at 5.2% AC and 5.45% AC. An interpolation was performed at 5.32% AC (optimum binder content) and results showed in Table 16 that the "Actual New Control Blend" is a good candidate for this study being very close to the "Original JMF." Figure 13 to Figure15 highlight the different volumetric properties of the "Actual New Control Blend." Table 17 shows the different developed gradations inside of the P-401 gradation specifications.

Table 16. Superpave Volumetric Results of the "Actual New Control Blend" Mix Design

Actual New Control Blend						Original JMF
Binder Content Used (%)	5.2	5.2	5.45	5.45	5.32	5.26
Sample ID	1	2	1	2	Interpolation	3082
Number of Gyrations	75	75	75	75		75
Air Mass (g)	4784.7	4782.4	4781.5	4787.7		
Underwater Mass (g)	2783.1	2785	2799.3	2808.6		
SSD Mass (g)	4789.5	4787.6	4785.2	4791.4		
G_{mb}	2.385	2.388	2.408	2.415		
Average Gmb	2.386		2.411			2.402
Standard Deviation (d1s)	0.0024		0.0049			
Gmm	2.488		2.482			
Height of specimen	116.3	115.7	115.0	114.8		
Difference (d2s)	0.003		0.007			
d1s < 0.013 and d2s < 0.037	YES		YES			
Air Voids (%)	4.2	4.0	3.0	2.7		
Average Air voids (%)	4.1		2.9		3.5	3.5
VMA (%)	15.0	14.9	14.4	14.1		
Average VMA(%)	14.9		14.3		14.6	14.5
VFA	72%	73%	79%	81%		
Average VFA	73%		80%		76%	76%
Gse	2.696		2.689		2.689	
Pba	0.5		0.4		0.4	
Pbe	4.692	4.692	5.044	5.044	4.860	4.740
DP	1.1	1.1	1.1	1.1	1.1	1.2

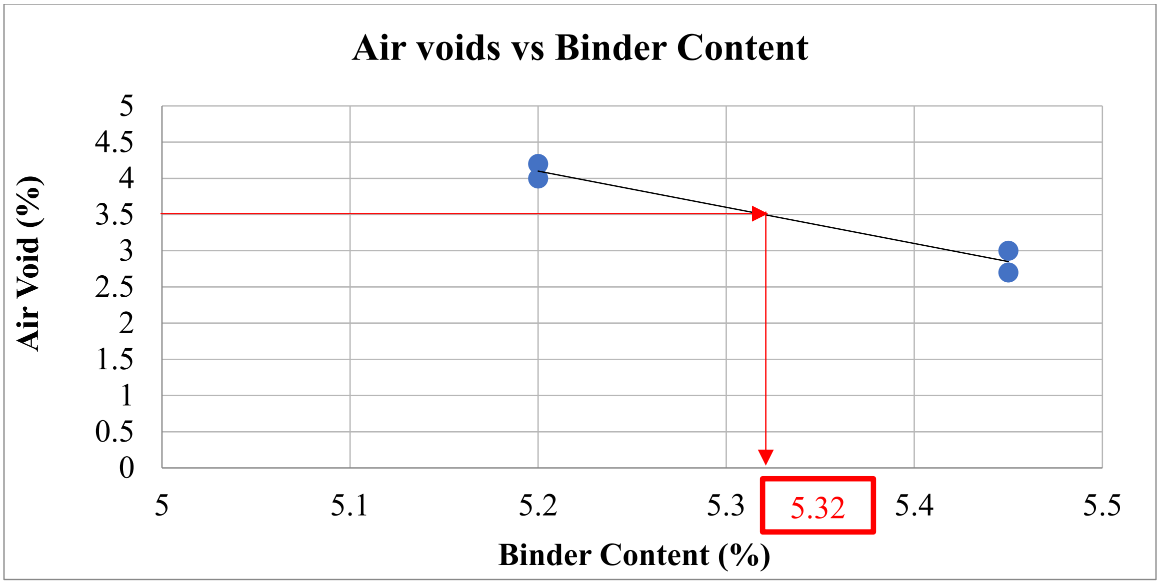


Figure 9. Relationship between Air Void and AC Content for "Actual New Control Blend"

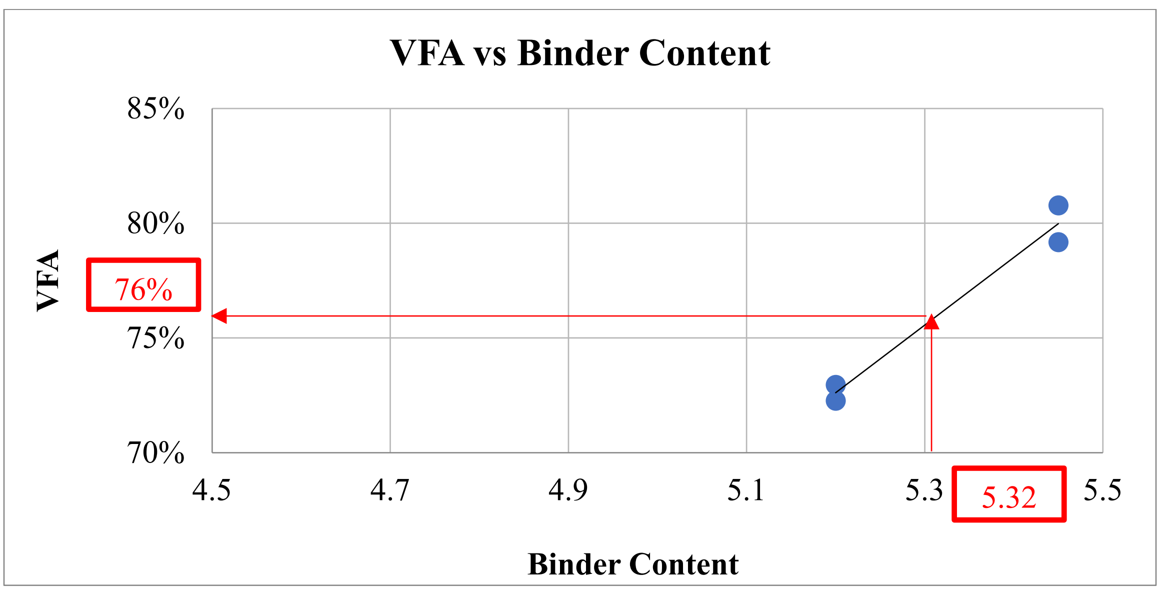


Figure 10. Relationship between VFA and AC Content for the "Actual New Control Blend"

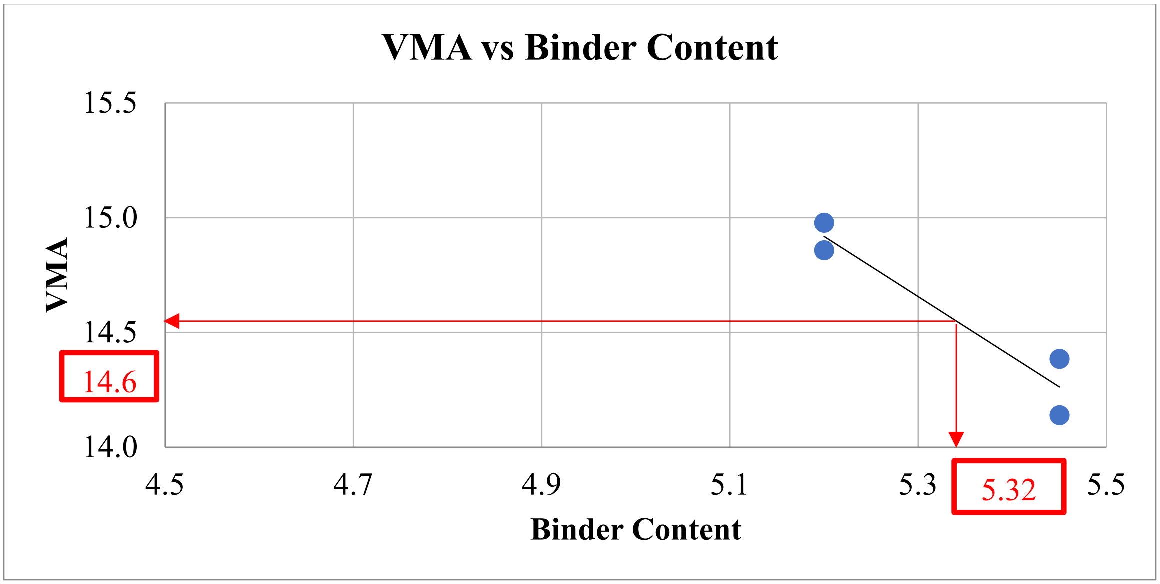


Figure 11. Relationship between VMA and AC Content for the "Actual New Control Blend"

Table 17. In Spec Developed Gradations

Sieves	"Actual JMF" Gradation with Cement	"Actual New Control Blend" Gradation with Cement
1"	100.0	100.0
3/4"	96.7	98.3
1/2"	83.9	87.7
3/8"	77.3	80.9
#4	58.7	59.4
#8	38.5	39.1
#10	34.6	34.5
#16	24.6	23.9
#30	16.4	15.9
#40	13.5	12.3
#50	10.1	9.5
#100	7.8	6.9
#200	6.2	5.4

4.1.4.2 Gradation Outside the FAA Specifications

Using the Bailey Method, a new gradation outside of the P-401 gradation band specifications was developed by changing the bin percentages and estimating VMA. In this process an important condition was that both mix designs inside and outside of the specification should have similar VMA and percent effective binder (Pbe) (±0.2) to compare them using the performance tests. The developed gradation is referenced as "Out of Spec 1." Table 18 shows a comparison between the "Out of Spec 1" and the "Actual Out of Spec 1" gradation after going through the adjustment process. Gsb was also calculated as shown Table 19 and a value of 2.659 was adopted.

Table 18. Comparison between the "Out of Spec 1" Gradation and the "Actual Out of Spec 1" Gradation

Sieves	"Out of Spec 1" Gradation with Cement	"Actual Out of Spec 1" Gradation without Cement After Washed Sieve Analysis	"Actual Out of Spec 1" Gradation with Cement	Difference between "Out of Spec 1" Gradation and "Actual Out of Spec 1" Gradation
1"	100.0	100.0	100.0	0.0
3/4"	96.4	95.9	95.9	0.5
1/2"	81	81.0	81.2	0.2
3/8"	72.7	72.5	72.8	0.0
#4	52.4	51.9	52.4	0.1
#8	33.8	32.7	33.4	0.4
#10	29.8	29.2	29.9	0.0
#16	20.9	20.3	21.1	0.2
#30	13.6	12.9	13.8	0.2
#40	10.3	9.5	10.4	0.1
#50	8.3	7.2	8.1	0.2
#100	5.9	4.9	5.9	0.0
#200	4.6	3.7	4.7	0.1

Table 19. Calculated Gsb of the Out of Spec 1 Gradation

Out of Spec 1					
Stockpile	3/4"	3/8"	CD	WCD	WAS
Gsb	2.684	2.672	2.679	2.641	2.581
Bin Percentage	27.3%	18.2%	7.1%	38.9%	8.6%
Gsb Coarse	2.679				
Gsb Fine	2.636				
Gsb Blend without cement	2.656				
Gsb Blend with cement	2.660				

Two Theoretical maximum specific gravity (Gmm) samples were prepared and tested at 5.4% AC as shown in Table 20. Two bulk specific gravity (Gmb) samples were compacted also at 5.4% AC and Superpave volumetrics were calculated as outlined in Table 21.

Table 20. Gmm for the "Actual Out of Spec 1" at 5.4% AC

G_{mm} at 5.4% AC		
Sample ID	Sample 1	Sample 1
Mass Oven Dry (A) (g)	2622.4	2603
Mass of the Sample in Water+Basket (g)	3004.6	2996
Mass of the Basket in Water (g)	1440.9	1440.9
Mass Sample in Water (C) (g)	1563.7	1555.1
G_{mm}	2.477	2.484
G_{mm} Standard Deviation < 0.0051	0.005	
Average G_{mm}	2.481	

Table 21. Superpave Volumetric Results of the "Actual Out of Spec 1" Mix Design

Adjusted Out of Spec 1		
Binder Content Used (%)	5.4	5.4
Sample ID	1	2
Number of Gyrations	75	75
Air Mass (g)	4773.3	4774.4
Underwater Mass (g)	2814.1	2810.1
SSD Mass (g)	4776.5	4778.7
G_{mb}	2.432	2.425
Average Gmb	2.429	
Standard Deviation (d1s)	0.0050	
Gmm	2.481	
Height of specimen	114.2	114.4
Difference (d2s)	0.007	
d1s < 0.013 and d2s < 0.037	YES	
Air Voids (%)	1.9	2.2
Average Air voids (%)	2.1	
VMA (%)	13.5	13.7
Average VMA(%)	13.6	
VFA	86%	84%
Average VFA	85%	
Gse	2.687	
Pba	0.4	
Pbe	5.02	5.02
DP	0.9	0.9

Analyzing the results, it was concluded that there was too much binder in the mix leading to lower than expected air void (%). In addition, the target VMA of 14.5 wasn`t met knowing that if the binder content were reduced to reach 3.5% air voids, VMA would be reduced too. It was concluded that this gradation was not suitable for further analysis and another gradation had to be developed.

Changing the bin percentages with an estimated VMA of 14.9 (±0.3) at 3.5 air void level using the Bailey Method and taking into account what led to a lower VMA previously in the "Actual Out of Spec 1", a new "Out of Spec 2" gradation was developed as shown in

Table 22. Gsb was calculated also using the new bin percentages as shown in Table 23 and a value of 2.659 was adopted.

Table 22. Comparison between the "Out of Spec 2" Gradation and the "Actual Out of Spec 2" Gradation

Sieves	"Out of Spec 2" Gradation with Cement	"Actual Out of Spec 2" Gradation without Cement After Washed Sieve Analysis	"Actual Out of Spec 2" Gradation with Cement	Difference between "Out of Spec 2" Gradation and "Actual Out of Spec 2" Gradation
1"	100.0	100.0	100.0	0.0
3/4"	97.7	97.5	97.5	0.2
1/2"	87.7	88.5	88.6	0.9
3/8"	79.6	79.4	79.7	0.1
#4	52.9	52.8	53.3	0.4
#8	33.8	32.8	33.5	0.3
#10	29.8	29.3	30.0	0.2
#16	20.8	20.2	21.0	0.2
#30	13.5	13.0	13.9	0.4
#40	10.2	9.7	10.6	0.4
#50	8.2	7.5	8.4	0.2
#100	5.7	5.0	5.9	0.3
#200	4.4	3.7	4.7	0.3

Table 23. Calculated Gsb of the Out of Spec 2 Gradation

Out of Spec 2					
Stockpile	3/4"	3/8"	CD	WCD	WAS
Gsb	2.684	2.672	2.679	2.641	2.581
Bin Percentage	17.7%	27.8%	7.1%	38.9%	8.6%
Gsb Coarse	2.677				
Gsb Fine	2.636				
Gsb Blend without cement	2.654				
Gsb Blend with cement	2.659				

The same process was followed as two Gmm samples were prepared at 5.3% AC as shown in Table 24 and two Gmb specimens were compacted at 5.3% and volumetric properties were calculated as depicted in Table 25.

Table 24. Gmm for the "Actual Out of Spec 2" at 5.3% AC

G_{mm} at 5.3% AC		
Sample ID	Sample 1	Sample 2
Mass Oven Dry (A) (g)	2615.1	2626.1
Mass of the Sample in Water+Basket (g)	3006.2	3009.9
Mass of the Basket in Water (g)	1440.7	1440.7
Mass Sample in Water (C) (g)	1565.5	1569.2
G_{mm}	2.492	2.485
G_{mm} Standard Deviation < 0.0051	0.0048	
Average G_{mm}	2.488	

Table 25. Superpave Volumetric Results of the "Actual Out of Spec 2" Mix Design

Actual Out of Spec 2		
Binder Content Used [%]	5.3	5.3
Sample ID	3	4
Number of Gyrations	75	75
Air Mass [g]	4767.5	4769.1
Underwater Mass [g]	2784.6	2786.5
SSD Mass [g]	4773.8	4775.1
G_{mb}	2.397	2.398
Average Gmb	2.397	
Standard Deviation (d1s)	0.0011	
Gmm	2.488	
Height of specimen	115.9	115.8
Difference (d2s)	0.002	
d1s < 0.013 and d2s < 0.037	YES	
Air Voids [%]	3.7	3.6
Average Air voids [%]	3.6	
VMA (%)	14.6	14.6
Average VMA[%]	14.6	
VFA	75%	75%
Average VFA	75%	
Gse	2.696	
Pba	0.5	
Pbe	4.792	4.792
DP	1	1

Analyzing the results, this gradation showed better results and could be adopted for further analysis in this study. Table 26 shows the different bin percentages used with the developed gradations outside of the specification limits when compared with the P-401 gradation bands limits.

Table 26. Out of Spec Developed Gradations

Sieves	"Actual Out of Spec 1" Gradation with Cement	"Actual Out of Spec 2" Gradation with Cement
1"	100.0	100.0
3/4"	95.9	97.5
1/2"	81.2	88.6
3/8"	72.8	79.7
#4	52.4	53.3
#8	33.4	33.5
#10	29.9	30.0
#16	21.1	21.0
#30	13.8	13.9
#40	10.4	10.6
#50	8.1	8.4
#100	5.9	5.9
#200	4.7	4.7

Table 27 summarizes the contractor JMF gradation, the Inside of Specification and Outside of Specification Gradations and their volumetric properties in comparison with the P-401 gradation band and volumetric specifications. Figure 16 shows the different gradations plotted on the maximum density line graph with the respective P-401 gradation bands limits.

Table 27. Summary of Final Adopted Gradations with their Corresponding Superpave Volumetric Properties

Sieves	JMF from Contractor	Gradation In Spec	Gradation Out of Spec	P-401 Gradation Bands
1”	100	100.0	100.0	100
3/4"	97.1	98.3	97.5	90-100
1/2"	84.5	87.7	88.6	68-88
3/8"	77.6	80.9	79.7	60-82
#4	58.7	59.4	53.3	45-67
#8	38.9	39.1	33.5	32-54
#10	34.6	34.5	30.0	
#16	24.7	23.9	21.0	22-44
#30	16.4	15.9	13.9	15-35
#40	12.8	12.3	10.6	
#50	10.4	9.5	8.4	9-25
#100	7.5	6.9	5.9	6-18
#200	5.8	5.4	4.7	3-6
Superpave Volumetric Properties				P-401 Requirements
Ndesign	75 Gyrations	75 Gyrations	75 Gyrations	75 Gyrations
OBC (%)	5.26	5.32	5.3	4.5-7
Va (%)	3.5	3.5	3.5	3.5
VMA (%)	14.5	14.6	14.6	≥14
Pbe (%)	4.74	4.86	4.79	

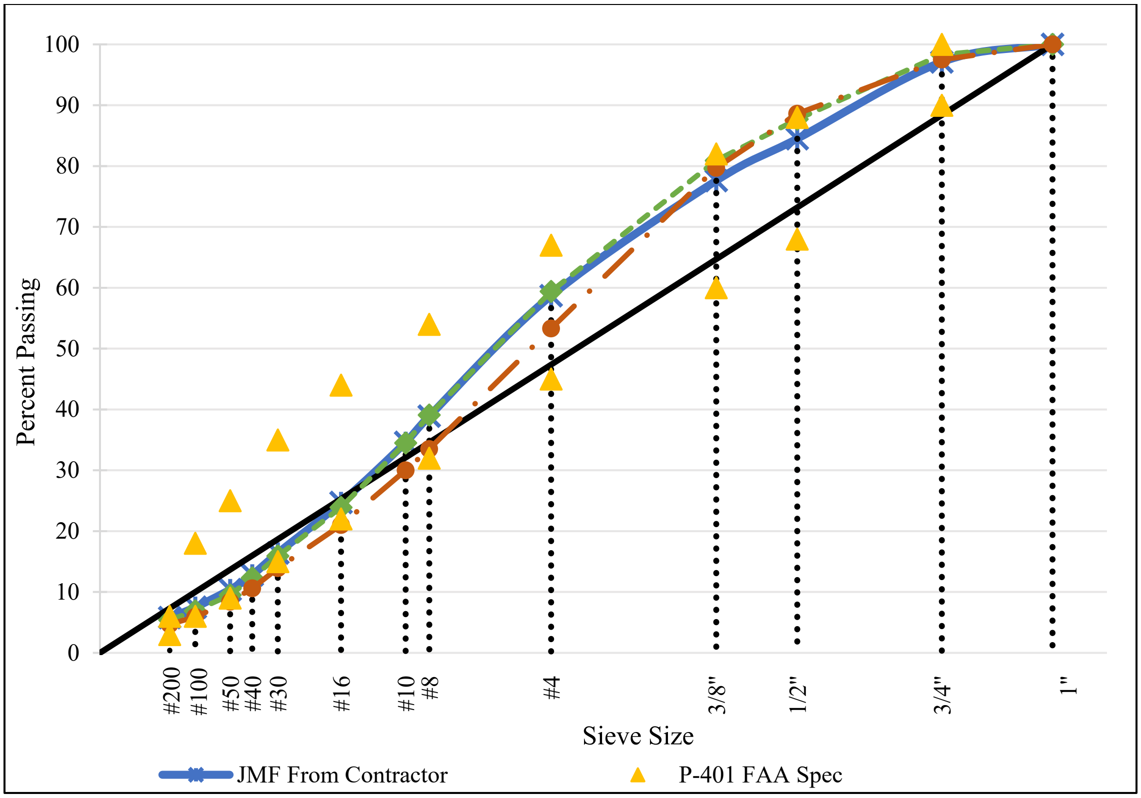


Figure 12. Aggregate Gradations and Limit Specifications used in the Research.

4.2 Performance Tests

Performance test specimens were prepared using a Superpave gyratory compactor. These specimens were tested to assess the impact of gradation changes on mixture resistance to rutting, top-down cracking, low-temperature cracking, moisture damage, raveling and permeability. Permeability affects air and water infiltration, which can lead to durability issues. Raveling is a common form of distress for airport asphalt pavements. The Florida Permeability Test [57] will be conducted to assess the permeability of P-401 asphalt mixtures. The Cantabro test [58] was conducted to assess the overall durability of P-401 asphalt mixtures. While traditionally used for evaluating the raveling resistance of open-graded friction courses, recent studies have shown that it can also discriminate dense-graded asphalt mixtures with different durability ranges. Rutting evaluation will be conducted using the APA [5] or HWTT [6]. Test specimens will be conditioned as required in the P-401 specifications. TSR [4] will be conducted following P-401 specification requirements for moisture susceptibility evaluation. Mixture cracking tests will include Illinois Flexibility Index Test (I-FIT) [59] and the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) [60] for evaluating cracking and the disc-shaped compact tension (DCT) [61] for evaluating low-temperature cracking. These tests were recommended because they are among the most popular cracking tests considered for Balanced Mix Design (BMD) [62] implementation by state highway agencies and efforts to develop correlations with cracking data from highway asphalt pavements have been undertaken. These performance properties will be evaluated using test methods summarized in Table 28.

Table 28. Performance Tests Used in this Study.

Performance	Test	Aging	Air Void (%)	Minimum Replicates	Specimen Thickness (inch)
Rutting	HWTT	2 hours at compaction temperature	7±0.5	2 sets	2.5±0.1
Moisture	TSR	2 hours at compaction temperature	7±0.5	2 sets of 3 replicates	3.7±0.2
Top-Down Cracking	I-FIT	2 hours at compaction temperature	7±0.5	4 reps	2±0.04
Top-Down Cracking	IDEAL-CT	2 hours at compaction temperature	5±0.5	4 reps	2.5±0.1
Low-Temperature Cracking	DCT	2 hours at compaction temperature	5±0.5	4 reps	2±0.04
Durability	Cantabro	2 hours at compaction temperature	7±0.5	3 reps	4.5±0.2
Permeability	Florida Permeability Test	2 hours at compaction temperature	7±0.5	3 reps	2.5±0.1

4.2.1 Rutting Performance Evaluation

4.2.1.1 Hamburg Wheel Track Test (HWTT)

The HWTT is described in and performed following AASHTO T324-23 Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures [6]. To evaluate both moisture susceptibility and rutting of the mixture, the Hamburg Wheel Track Test (HWTT) was used. This test is commonly employed across many states for rutting evaluation purposes. The HWTT apparatus is comprised of a conditioning water bath and a weighted steel wheel. The test starts with the water temperature set to 50°C and a conditioning phase for 45 minutes. Rut depth is recorded at 11 located on the sample during the testing. While the required number of passes varies depending on the PG grade, the FAA recommends in their P-401 specifications a rut depth less than 0.4 inch at a maximum of 20000 passes (Average of point 4 to point 8). The HWTT specimens from each gradation in this study were initially subjected to a short-term oven aging (STOA) process at 295°F for a duration of 2 hours, and then compacted to a height of 2.5±0.1 inch, with the targeted air voids being 7±0.5%. Following this, a small segment was trimmed from each specimen to ensure proper fitting within the mold of the HWTT apparatus. For accurate results, 4 cylindrical compacted specimens (2 specimens on each side of the HWTT device) are needed and then averaged in terms of results obtained. Figure 13 highlights the HWTT test Machine set up.

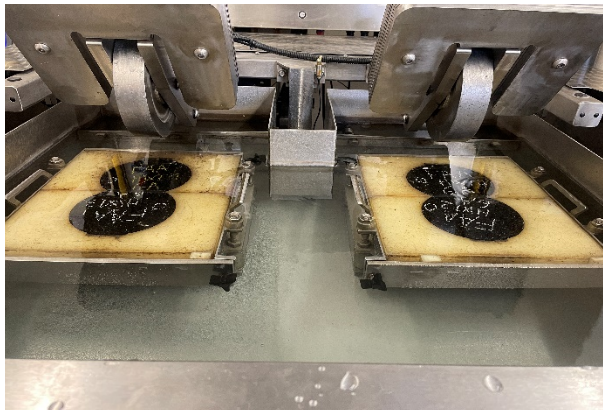


Figure 13. HWTT Conditioning Phase

Figure 14 shows the HWTT result for the In Spec gradation, where a maximum rut depth of 0.22 inch was observed after 20000 passes. This mixture meets the criteria set by the FAA specification of 0.4 inch (10 mm) max rut depth at 20000 passes.

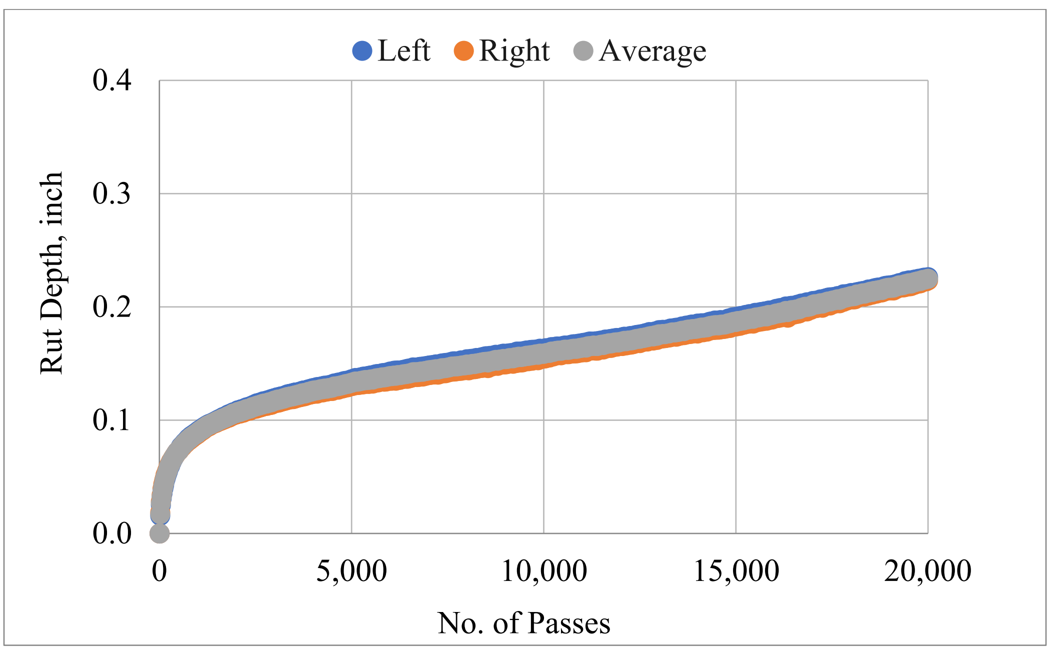


Figure 14. HWTT Results for In Spec Gradation

Testing for the Out of Spec Gradation is in progress.

4.2.2 Cracking Evaluation

4.2.2.1 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The IDEAL-CT test is performed in accordance with ASTM D8225-19: Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature [60]. The test procedure considers both crack initiation and propagation in asphalt mixtures and is developed based on fracture mechanics. The equipment used in this test consists of an indirect tensile cracking test apparatus with a load cell and loading strips to impart indirect tension at a rate of 2 inches per minute. This test is becoming very popular because the equipment is simple and inexpensive, the sample fabrication does not require any cutting or trimming or attachment of targets, it is run at room temperature and can be conducted rapidly.

The IDEAL-CT test is being widely used in the asphalt industry to evaluate the effectiveness of different asphalt mix designs and additives in preventing cracking. It is a quick test that provides valuable information on the crack resistance of asphalt mixtures and measures the top-down cracking within the pavement allowing for more effective pavement design and maintenance. The IDEAL-CT test is designed to evaluate how well asphalt mixtures resist cracking at intermediate temperatures, typically ranging from 41 to 95°F (5 to 35°C). This test produces a cracking tolerance value known as the CT-Index, which indicates the mixture's ability to resist cracking. A higher CT-Index value suggests better resistance to cracking, which translates to fewer cracks in real-world conditions. Therefore, 4 specimens for each gradation were short-term oven aged (STOA) for 2 hours at 295°F, and then compacted in the Superpave Gyratory Compactor at a height of 2.5

inches (N_{mas} = ¾ inch) and a diameter of 6 inches [51]. The targeted air void was 5±0.5% for all samples, which ensures consistency in the test results. The samples were conditioned for 2 hours before testing at 25°C. Figure 15 is a picture of the equipment used for the CT Index test.

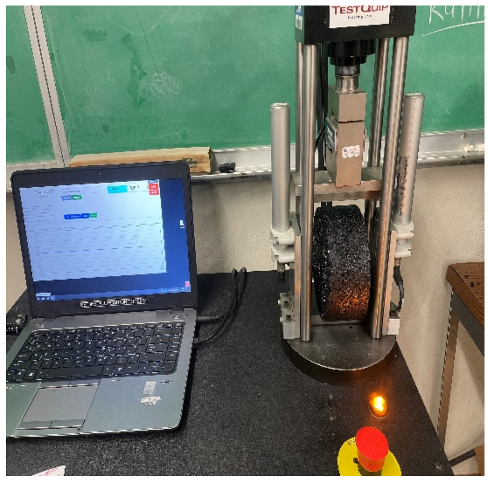


Figure 15. CT index Test Machine Set up

The test equipment calculates the work of failure (Wf) by finding the area under the load-displacement curve. This value is then used to determine the failure energy (Gf), which is calculated by dividing the work of failure by the specimen's cross-sectional area. The CT-Index is then determined using Equation 5 and Figure 16 highlights the different components of the CT-Index.

$$CT_{index} = \frac{t}{62} \ x \ \frac{l_{75}}{D} \ x \ \frac{G_f}{|m_{75}|} \ x \ 10^6 \qquad \textbf{Eq. 5}$$

Where:

l_{75}: displacement at 75% of the peak load after the peak (mm)

t: specimen thickness (mm)

$|m_{75}|$: the absolute value of the post-peak slope m_{75} (N/m)

D: specimen diameter (mm)

G_f: failure energy (joules/m^2)

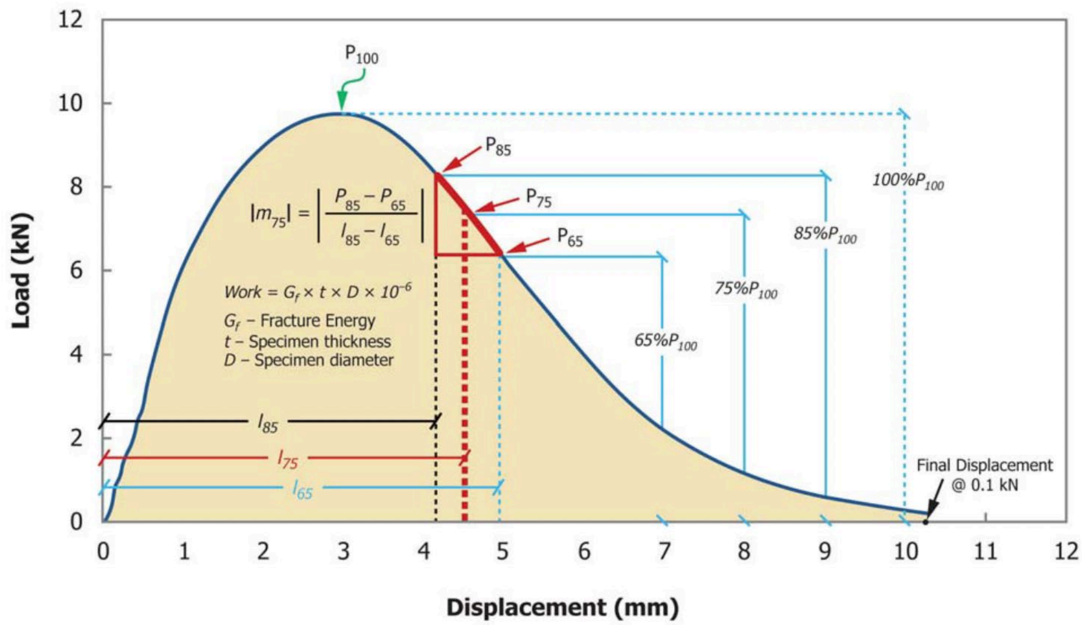


Figure 16. CT-Index Graphic Representation

Table 29 shows the results of the IDEAL-CT test for both In Spec and Out of Spec gradations. Three specimens for each gradation were tested and their results were reported. In Figure 17, the values in grey in Table 29 were used to access the cracking tolerance index since some IDEAL-CT results were outliers. Comparing the average CT-Index results, it was shown that the cracking tolerance of the In Spec gradation was higher than the Out of Spec gradation indicating a higher cracking resistance for the In Spec gradation.

Table 29. IDEAL-CT Test Results

	In spec			Out of Spec		
Sample Identification	CT1	CT2	CT3	CT1	CT2	CT3
Diameter (mm)	150	150	150	150	150	150
Thickness (mm)	62	62	62	62	62	62
% Air Voids	4.8	4.9	4.9	5.0	5.5	4.8
CT-Index	194.2	163	218.1	60.7	127.2	102.7
Average CT- Index	206.15			114.95		
SD	11.95			12.25		
CV (%)	13.5			13.8		

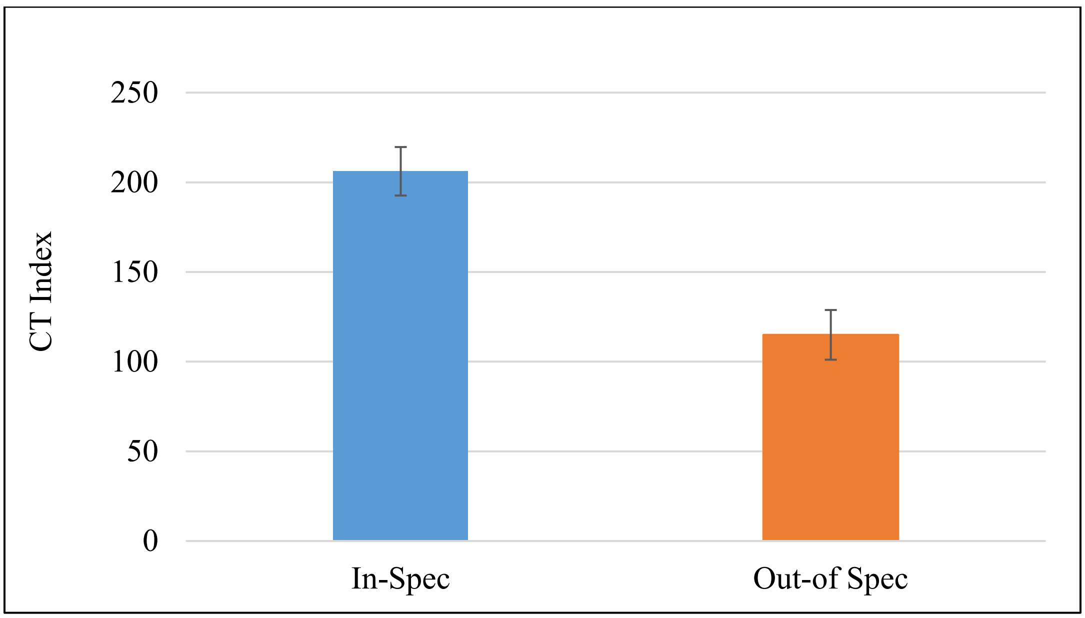


Figure 17. IDEAL-CT Test Results

4.2.2.2 Illinois Flexibility Index Test (I-FIT)

Cracking performance was also assessed using the Illinois Flexibility Index Test (I-FIT) following the procedure outlined in AASHTO T 393 Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index

Test (I-FIT) [59]. The I-FIT test, which is based on the Semi-Circular Bend (SCB) test, includes similar sample preparations as SCB samples with a notch across the center of the flat width as shown in Figure 18.

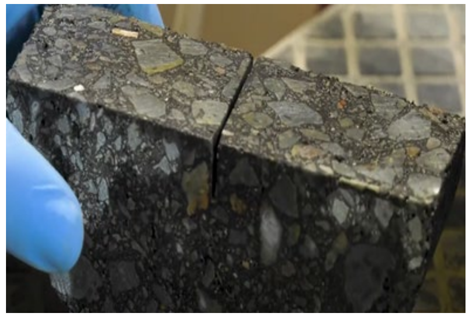


Figure 18. I-Fit Specimen

Loose asphalt mixtures were compacted using a Superpave gyratory compactor to achieve an air void range of 5 ± 0.5%. at 6 inches in diameter and height. From each sample, two 2 ± 0.05 inches thick discs were sawed from the middle and split into two halves, resulting in four identical semicircular replicates. After that, a tile saw was used to cut a notch, 0.6 ± 0.05 inches in height and 0.1 inch in width, in the center of the flat side of each semicircular sample. This notch was created only to determine the location where the crack would initiate during testing. The I-FIT test was conducted at an intermediate temperature of 25°C. Hence, the test samples were conditioned at this temperature for 2 hours in an environmental chamber. During the test, a load of 0.1 ± 0.01 kN was applied to the semi-circular samples using loading piston in stroke control mode. The loading piston had a loading rate of 0.05 kN/s. Once the applied load reached 0.1 kN, the loading piston switched to load line displacement control, applying a load at a rate of 50 mm/min. This displacement caused a crack to form at the notch and propagate through the sample. As a result, the applied load started to decrease, and the test automatically stopped when load values fell below 0.1 kN. Figure 19 shows the load displacement curve used to calculate the Illinois Flexibility Index.

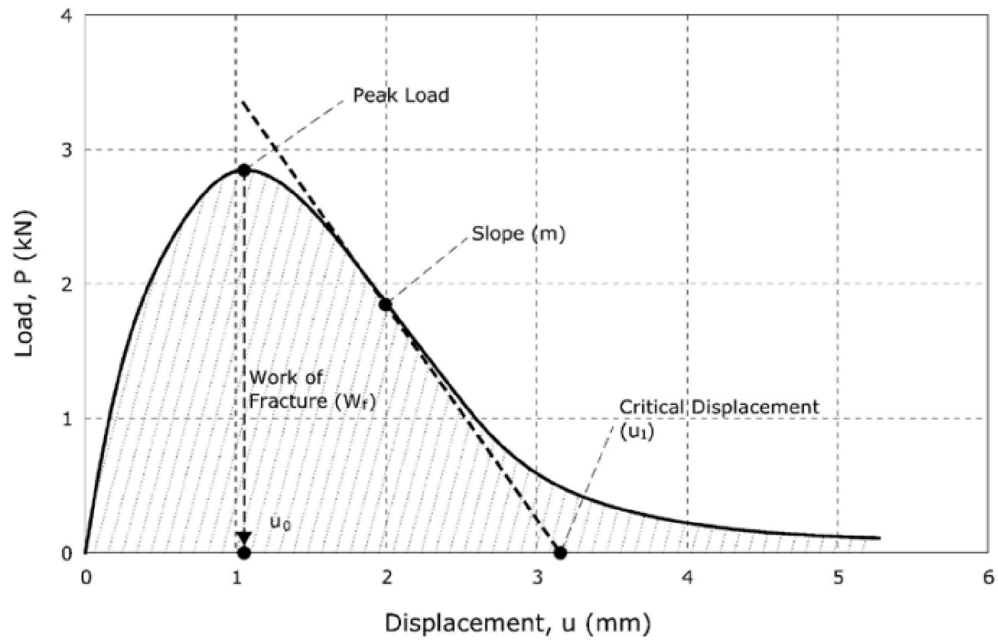


Figure 19. Recovered Load (P) versus Load Line Displacement (u) Curve

The post-peak slope in the load-displacement curve represents the rate at which energy is dissipated by a material and serves as a key indicator of its ductility. A steeper post-peak slope indicates a more brittle material. The point where the post-peak slope intersects the displacement axis is called the critical displacement. A higher post-peak slope corresponds to a lower critical displacement value, and vice versa. Both the peak load and post-peak slope affect the fracture energy, which is the total energy required to completely fracture an I-FIT sample. The flexibility index of an I-FIT specimen is determined by dividing the fracture energy by the post-peak slope. A lower flexibility index indicates a higher potential for fatigue cracking. The Illinois Department of Transportation has set a minimum flexibility index of 8 to assess the cracking performance of asphalt mixtures. There was not a specific criteria selected to evaluate the I-FIT test results, as the comparison is whether or not the Out of Spec gradation mixture provided equal or better performance than the In Spec gradation mixture. Specimens are ready and testing is in progress.

4.2.3 Moisture Resistance Evaluation

4.2.3.1 Tensile Strength Ratio Test (TSR)

The moisture resistance of the mixtures was evaluated in accordance with AASHTO T283 Indirect tensile strength (ITS) before and after exposure to moisture, as well as their indirect tensile strength ratio (TSR) [4], with an air void of 7 ± 0.5% were used to quantify resistance of the mixtures to moisture damage. This process assesses the impact of water infiltration through saturation. The mixture was from Tucson Arizona and the mixture place did not include freeze-thaw (F-T) cycling step wasn`t required since Arizona is in dry no freeze climate zone. To prepare the samples for TSR testing, the following steps were taken:

- Compact a total of 6 cylindrical specimens with a diameter of 6 inches and a height of 3.7±0.2 inch using the Superpave Gyratory Compactor (SGC).
- Measure the ITS for the unconditioned subset (3 compacted specimens) at a temperature of 77°F (25°C). To acclimate the unconditioned subsets, wrap the samples in leak-proof plastic bags and submerge them in a water bath set to the required temperature, keeping them in the water bath for 2 ± 0.5 hours.
- Apply 75 ± 5% vacuum saturation to the three samples in the moisture-conditioned subsets.

- Moisture condition the partially saturated specimens by soaking in distilled water at 60±1°C for 24 hours.
- The temperature of the subset is then adjusted for 1 hour at 25±1°C.
- The specimen is placed in the loading apparatus and a diametral load at 50 mm/min is applied until maximum load is reached.

Figure 20 is a picture of the TSR test equipment.

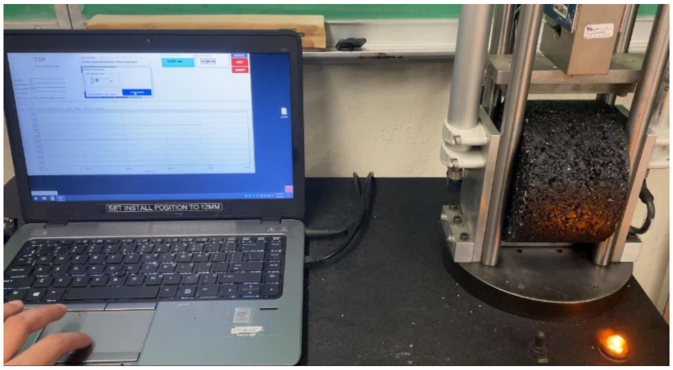


Figure 20. TSR Test Machine Set up.

The tensile strength is determined by dividing the peak load by the cross-sectional area, as demonstrated in Equation 6.

$$Tensile\ STrength\ (kPa) = \frac{P}{2\pi t} \quad \textbf{Eq. 6}$$

Where:

P: Maximum load (kN)

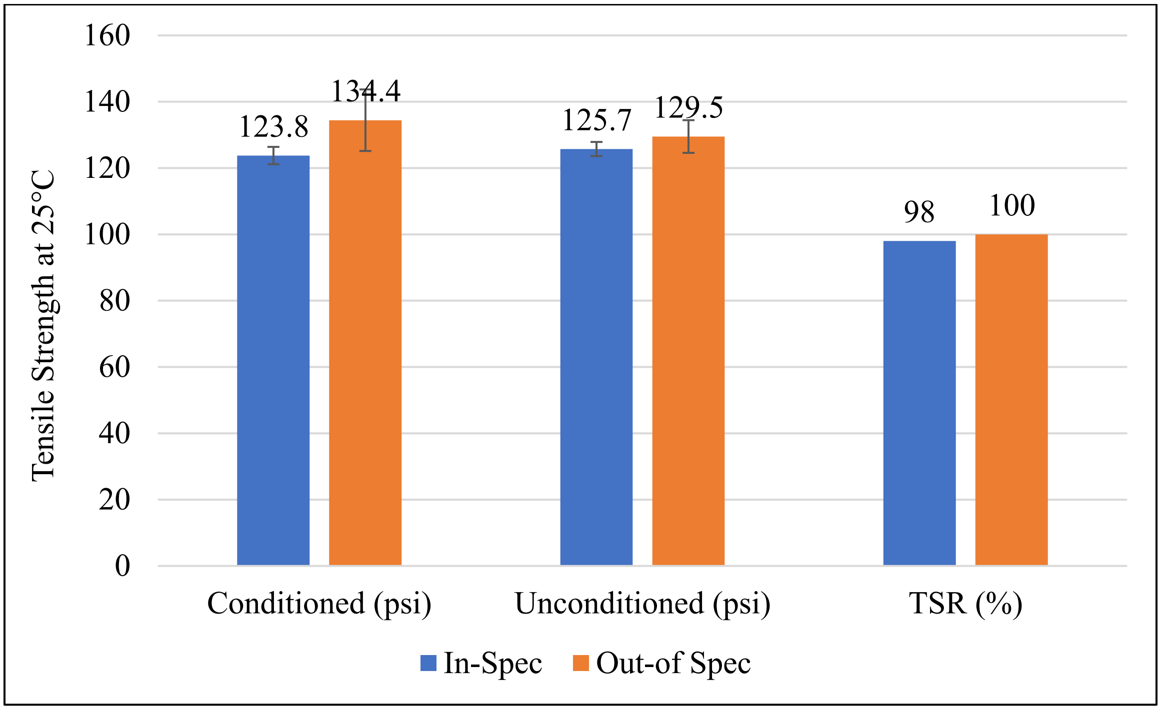
r: Radius of the sample (mm)

t: Thickness of the sample (mm).

Table 20 and Figure 21 highlight the results of the TSR test for both In Spec and Out of Spec gradations. To calculate the TSR, the average of the dry subset ITS is divided by the average of the conditioned subset ITS. The results showed that both In Spec and Out of Spec gradations are resistant to moisture damage with higher results for the Out of Spec gradations making both gradations very comparable in terms of moisture resistance.

Table 30. TSR Test Tensile Strength Results

	Conditioned			Unconditioned		
ITS In spec (psi)	124.4	120.7	126.2	127.9	123.3	126.1
ITS Out of spec (psi)	145.3	125.5	132.5	135.0	129.2	124.3



4.2.4 Durability Performance Evaluation

4.2.4.1 Cantabro Test

The Cantabro Abrasion Test was conducted following AASHTO T401-22 Standard Method of Test for Cantabro Abrasion Loss of Asphalt Mixture Specimens [58]. It is a common method used to evaluate the durability of asphalt mixtures. This test simulates the abrasion that asphalt pavements experience due to traffic and environmental factors. During the test, a compacted specimen of asphalt mixture is placed in a rotating steel drum (LA abrasion machine) along with steel spheres. The drum is rotated for a specified number of revolutions (300 revolutions), causing the steel spheres to repeatedly impact and abrade the specimen.

The Cantabro test helps assess the resistance of asphalt mixtures to abrasion and the ability of the mixtures to maintain its integrity and functionality under traffic loads. The test results can provide valuable insights into the performance and durability of asphalt mixtures, helping engineers and researchers optimize mixture designs for longer lasting and more resilient pavements. In this test, three 6 inches diameter specimens are compacted at 4.5±0.2 inch thickness using the SGC. The target air void for this test is 7±0.5%. Figure 21 shows a specimen before and after the Cantabro Abrasion Test and Table 31 highlights the results of the Cantabro test for both gradations In spec and Out of Spec.

Figure 21. Cantabro Specimens Before and After Testing

Table 31. Cantabro Abrasion Test Results for In Spec and Out of Spec Gradations

	In Spec Gradation			Out of Spec Gradation		
Sample Identification	Canta 1	Canta 2	Canta 3	Canta 1	Canta 2	Canta 3
Diameter, mm	150	150	150	150	150	150
Thickness, mm	115	115	115	115	115	115
% air voids	6.8	7	6.5	7.5	7.2	7.1
Mass Before (g)	4568.1	4567.3	4603.7	4555.4	4555.3	4554.6
Mass After (g)	4465.1	4417.5	4535.6	In Progress		
Mass Loss (%)	2.26	3.28	1.48			
Average Mass Loss (%)	2.34					

4.2.5 Lower Temperature Cracking

4.2.5.1 *Disc Shaped Compact Tension Test (DCT)*

The DCT test was performed following ASTM D7313-20 Standard Test Method for Determining Fracture Energy of Asphalt Mixtures Using the Disk-Shaped Compact Tension Geometry [61]. It is a common test method used to evaluate the cracking resistance of asphalt mixtures and is particularly useful for assessing low-temperature cracking potential. The fracture energy parameter is particularly useful in the evaluation of asphalt mixtures with ductile asphalt binders, such as polymer-modified asphalt mixture. The test specimen is typically a disk-shaped sample, hence the name "Disk-shaped Compact

Tension." The specimen is prepared by compacting an asphalt mixture into a circular mold to achieve a specified density and air void content. In our study, a 150 mm diameter SGC compacted specimen with 6.3 inches thickness is needed. This specimen is cut from both sides and then in half to obtain two 2±0.04 inches specimens with a target air void of 5±0.5%. The specimen is then cut on the side to create a flat surface for the clip gage. A notch is then cut into the center of the specimen. This notch serves as the initiation point for cracking during the test. In addition, 2 drills are fabricated at 1 inch diameter to create 2 loading holes. The specimen is placed in a temperature-controlled chamber, which can be cooled to the desired testing temperature. The DCT test is often conducted at temperatures ranging from -10°C to -30°C, as low-temperature cracking is a common concern for asphalt pavements. Figure 22 shows the measurements used for the DCT sample preparation.

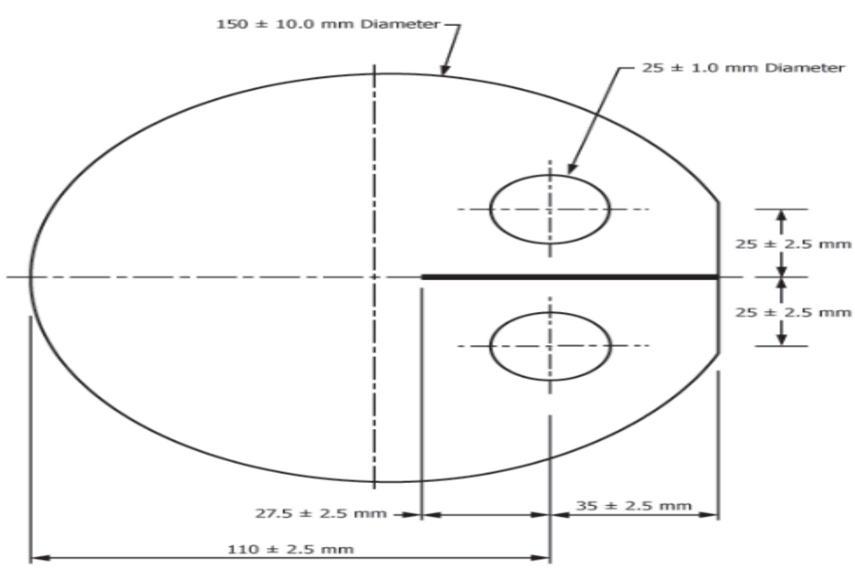


Figure 22. DCT Specimen Dimensions

A small seating load between 0.045 lbf and 2248 lbf is applied prior to starting the test. A constant crack mouth opening displacement rate of 0.0007 inch/s until the specimen cracks. The test is complete when the post-peak load level has reduced to 22.5 lbf.

During the test, data such as the applied load and displacement are recorded. These data are used to calculate parameters such as the fracture energy, which is a measure of the energy required to propagate a crack through the specimen. The data collected during the test are analyzed to evaluate the cracking resistance of the asphalt mixture. Parameters such as the fracture energy and critical crack tip opening displacement (CTOD) are often used to assess the performance of the mixture.

DCT specimens were prepared and shipped to another facility for testing and the result of the testing is not included in this report.

4.2.5.2 Florida Permeability Test

The Florida Permeability test was performed following FM 5-565 Florida Method of Test for Measurement of Water Permeability of Compacted Asphalt Paving Mixtures [57]. It`s a laboratory method used to determine the water conductivity of a compacted asphalt paving mixture sample. Specimens used in this test are 6 inches diameter compacted at 4.5 inches using the SGC. Those specimens are then cut from both sides and the cuts are at least the NMAS of the mixture.

In this test, a falling head permeability test apparatus as shown in Figure 23 is employed to measure the rate of water flow through the specimen. The test involves allowing water from a graduated cylinder to flow through a saturated asphalt sample and recording the time interval required to reach a known change in head. The coefficient of permeability of the asphalt sample is then calculated using Darcy's law.

The coefficient of permeability, k, is determined using the following equation:

$$k = \frac{aL}{At}\ln\left(\frac{h1}{h2}\right) * tc \qquad \textbf{Eq. 7}$$

Where:

k = coefficient of permeability (inch/s)

a = inside cross-sectional area of the buret ($inch^2$)

L = average thickness of the test specimen (inch)

A = average cross-sectional area of the test specimen ($inch^2$)

t = elapsed time between h1 and h2 (s)

h1 = initial head across the test specimen (inch)

h2 = final head across the test specimen (inch)

tc = temperature correction for viscosity of water

Florida Permeability Test specimens were prepared and shipped to another facility for testing and the results of the testing is not included in this report.

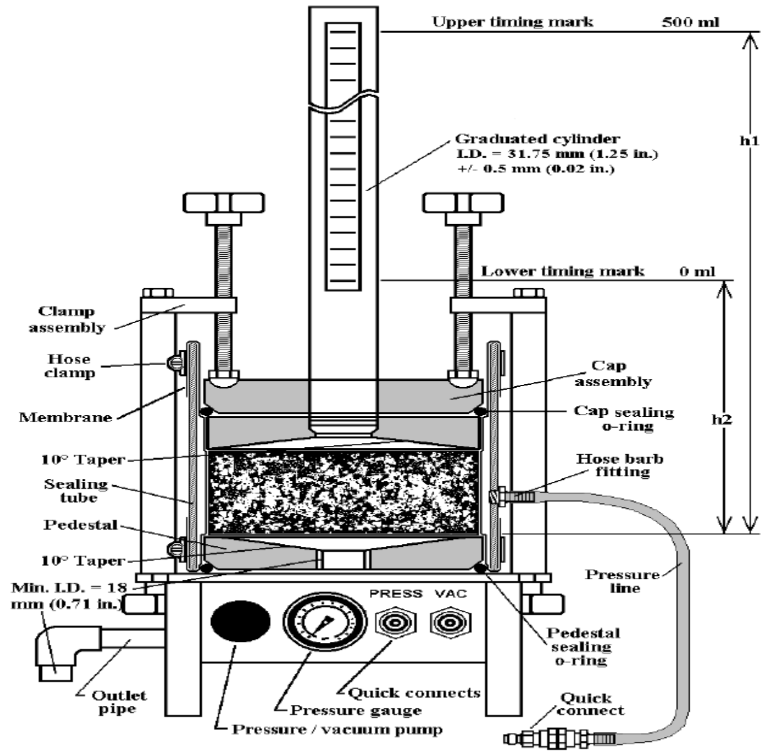


Figure 23. Florida Permeability Test Apparatus

Chapter 5: Findings and Recommendations

5.1 Findings

This effort illustrated that very small changes in gradation can result in significant differences in volumetric properties for the same aggregate and asphalt binder source. The limited mixtures compared in this study had very similar volumetric properties (essentially identical effective asphalt content and VMA). However, the performance test results ranged from similar to quite different although the volumetrics were very similar. The resistance of the mixtures to moisture sensitivity, as measured by TSR were similar and both mixtures met the P-401 requirements. In terms of cracking resistance, the In Spec gradation presented better cracking resistance than the Out of Spec gradation with the CT Index test. However, both mixtures exhibited CT Index test results significantly greater than the minimum of 70 criteria being used by some State DOTs.

5.2 Recommendations

The methodology and tests methods used for this effort should be applied to multiple FAA P-401 mixtures with gradations in specification and out of specification while maintaining very similar volumetric requirements. This data would provide a basis for determination of rational revisions to FAA P-401 gradation specification if similar performance were observed for in and out of specification mixtures.

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