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Verification of Job Mix Formula for Alaskan HMA

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Abstract

Some asphalt pavement does not last as long as it should. Every year, a significant amount of money is spent by the state on repairing and maintaining pavement, which raises the question: Are we getting the mix design we need? Since hot mix asphalt (HMA) is the main paving material in Alaska, it is critical to understand how the quality of this material is assured. Often, a properly lab-designed HMA is used in the field on a given project and performs in a substandard manner. Variability is inevitable during construction.

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EXECUTIVE SUMMARY

Some asphalt pavement does not last as long as it should. Every year, a significant amount of money is spent by the state on repairing and maintaining pavement, which raises the question: Are we getting the mix design we need? Since hot mix asphalt (HMA) is the main paving material in Alaska, it is critical to understand how the quality of this material is assured.

Often, a properly lab-designed HMA is used in the field on a given project and performs in a substandard manner. Variability is inevitable during construction. An ongoing National Cooperative Highway Research Program (NCHRP) study (Mohammad and Elseifi 2010) is investigating field-versus-laboratory volumetrics and mechanical properties in an effort to quantify variabilities and ensure sound quality assurance and pavement design approaches.

No research has been focused on the performance of HMA mixtures with respect to material types and climatic conditions typical of Alaska. Previous material quality assurance (QA) reviews of the Alaska Department of Transportation and Public Facilities (ADOT&PF), conducted by the Federal Highway Administration (FHWA), provided recommendations for improvement, such as transitioning to the Superpave mix design as standard practice, and moving away from the use of gradation as acceptance criteria, accepting asphalt mixes based on volumetric properties instead. To respond to the FHWA's comments and facilitate satisfactory construction of HMA pavements, a comprehensive study on field data collection, compilation, and analysis was conducted to investigate the variability of HMA performance due to production, and to verify the HMA job mix formula (JMF). The study is presented in this report.

Two asphalt paving projects—the Parks Highway Mile 287–305 rehabilitation and resurface project and the Anchorage International Airport (AIA) runway 7R/25L rehabilitation—were selected for fieldwork. Pertinent data from ADOT&PF and from contractors at lab/design and construction were obtained, including general information regarding the paving projects, details of the materials and JMF being used in the construction, quality control testing data from contractors, and acceptance testing results from the agency. To evaluate the variability of HMA involved in the construction process and the impact on its performance, specimens of four scenarios were prepared from these two paving projects: (1) specimens mixed and compacted in the laboratory using the same JMF (L&L), (2) loose mixtures collected from the windrow and compacted in the field (F&F), (3) loose mixtures collected from the windrow and compacted in the laboratory (F&L), and (4) cores retrieved from the field after paving. Three types of HMA properties were measured:

- Composition properties: gradation and binder content.
- Volumetric properties: voids in the total mix (VTM), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA).

- Mechanical properties: dynamic modulus (│E*│), creep stiffness, and indirect tensile strength (ITS).

Composition properties were measured on F&F and F&L scenarios. Because the L&L specimens were prepared on laboratory-blend mixtures according to the JMF, the gradation and binder content tests were not needed. Volumetric properties were evaluated on at least three replicates of specimens prepared from all four scenarios. Dynamic modulus and flow tests were only performed on L&L and F&L specimens due to the large sample size required for testing. Indirect tensile (IDT) creep tests were performed for all four scenarios at three testing temperatures: -10°C, -20°C, and -30°C. For L&L and F&L specimens, the ITS tests were performed at three temperatures as well: -10°C, -20°C, and -30°C. Due to the limited numbers of F&F specimens and field cores, the ITS tests were only performed at -20°C for field cores and at -10°C and -30°C for F&F specimens.

Among the three types of properties tested, mechanical properties had the greatest sublot-wise variance. Generally, the observed variances were close to those of previous studies and within the limits recommended by AASHTO R42. The variance of percentage passing of aggregate at different sieve size was less than 2.5%, though the extreme value reached 4.5%. The variance of binder contents was less than 0.25%. The variance of aggregate gradation was significantly affected by operator and sublot number. The statistical analysis indicates that the binder content was stable during the material production, but the data obtained using the ignition method varied among operators. The differences in volumetric properties between JMF and the specimens prepared from the four scenarios were observed. It was found that the differences are significantly affected by sublot and scenario. The variance of volumetric properties was only affected by testing scenario, that is, L&L, F&L, F&F, and field cores. The highest standard deviations (STDEVs) of VTM, VMA, and VFA were 1.4, 1.2, and 6.7, respectively.

The variations of composition properties, as measured by coefficient of variance (COV), were found to be approximately 5%. The COVs of volumetric properties ranged from 2% to 14%. The variations of mechanical properties were much higher than composition and volumetric properties. Among all mechanical properties investigated, ITS had the lowest COV (7%), and flow tests had the highest COV (up to 43%). The │E*│ of field-produced HMA was greatly affected by material production and testing conditions. The results of a multi-factor ANOVA analysis indicate that frequency, sublot, and temperature are significant factors. The variance of │E*│ was affected by sublot and temperature. Generally, creep stiffness obtained from three field scenarios—F&L, F&F, and field cores—differed from the value of L&L specimens. The percentage errors were significantly affected by scenario, sublot, temperature, and loading time. The variance of creep stiffness was not influenced by these factors. The results of ITS revealed a difference between field scenarios and the L&L scenario, which also changed during the production of HMA. The ITS testing results had the lowest variance among all mechanical properties.

The variances of mechanical properties were higher than those of both composition and volumetric properties. The reason for this could be that additional errors were introduced during specimen cutting, sensor installation, and loading, activities not required for composition and volumetric properties. Previous studies from others (Bonaquist 2008) confirmed this observation.

The correlations between composition and mechanical properties and between volumetric and mechanical properties were evaluated. Although volumetric properties provide a better correlation with mechanical properties than with composition properties, as indicated by higher R^2 values, the correlation was generally found to be weak.

The purpose of a QA program is to improve the quality of HMA mixtures and to make the best effort in ensuring that the performance of installed HMA mixtures reaches the levels specified in the design. Rather than measuring mechanical properties, which are considered directly related to pavement performance, composition and/or volumetric properties are measured in most QA programs. They are preferred because composition and volumetric properties can be measured easier and faster than mechanical properties, and fewer variations are introduced, as indicated by this study. However, the statistical analyses and results of this study were based on limited data collected from only two paving projects. More data from various paving projects are recommended to further confirm and validate the findings reported here.

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CHAPTER 1 INTRODUCTION

Since hot mix asphalt (HMA) is the main paving material used in Alaska, assurance of its quality is critical. It is important to assess elements related to HMA quality assurance (QA) specifications, to evaluate how well contractors meet the requirements of mix designs, and to revise current mix design protocols and contractor payment methods for asphalt paving in Alaska. This comprehensive study, an examination of field data collection, compilation, and analysis, was conducted to investigate the variability of HMA performance due to production and to verify the HMA job mix formula (JMF).

1.1 Problem Statement

Every year, a significant amount of state money is spent on repairing and maintaining pavement, partly because of asphalt pavement that fails prematurely. This recurring problem raises the question: Are we getting the mix design we need?

As HMA is the main paving material used in Alaska, it is critical that the quality of this material is assured. Some variability in quality is inevitable because tests are performed by different operators using different equipment and potentially different methods, and specimen sampling and compaction are not the same. These factors influence the chosen design property values. Often, a properly lab-designed HMA will be placed in the field for a given project and perform in a substandard manner. An ongoing National Cooperative Highway Research Program (NCHRP) study (Mohammad and Elseifi 2010) is investigating field-versus-laboratory volumetrics and mechanical properties to quantify the variabilities that arise in paving materials and to ensure sound quality assurance programs and pavement design approaches. Unfortunately, no research has been focused on the performance of HMA mixtures with respect to the material types and climatic conditions typical in Alaska.

In previous material QA reviews of the Alaska Department of Transportation and Public Facilities (ADOT&PF), the Federal Highway Administration (FHWA) made recommendations for improvement such as using Superpave mix design as a standard practice and moving toward asphalt acceptance criteria based on volumetric properties instead of gradation. The current study is an effort to respond properly to FHWA's comments and facilitate satisfactory construction of HMA pavements.

1.2 Objectives

The purpose of this research was to investigate how the properties of HMA mixtures vary due to mixture production, and how production factors affect current mix design and QA specifications. The following objectives were addressed:

- Comparison of volumetric properties of as-built and JMF properties of HMA for asphalt paving projects.

- Evaluation of the variability involved in construction processes and the impact of construction processes on HMA performance.
- Investigation of essential causes or significant influencing factors related to variabilities in HMA performance.
- Recommendations regarding current HMA design and QA specifications.

1.3 Research Methodology

The following major tasks were accomplished to achieve the objectives of this study:

- Task 1: Literature Review
- Task 2: Development of Field Work Plan and Experimental Design
- Task 3: Field Data Collection, Specimen Fabrication, and Testing
- Task 4: Data Processing and Analyses
- Task 5: Project Summary and Conclusions

Task 1: Literature Review

A comprehensive literature review of previous studies and current research efforts and progress in the area of quality control (QC) and quality assurance was conducted. The purpose of the review was to gather information on key subjects pertaining to this study such as the current status of national QA programs, types of material quality characteristics, variance of quality characteristics associated with construction and testing processes, and influencing factors. Chapter 2 presents the summary of this task.

Task 2: Development of Field Work Plan and Experimental Design

The fieldwork plan and experimental design were developed based on information collected from the literature review and on discussions among members of the research team and ADOT&PF personnel. Two asphalt paving projects—the Parks Highway Mile 287–305 rehabilitation and resurfacing project and the Anchorage International Airport (AIA) runway 7R/25L rehabilitation—were selected for study. To evaluate the variability of HMA used in the construction process and the impacts on performance of HMA, specimens for use in four scenarios were prepared from these two paving projects: (1) specimens mixed and compacted in the laboratory using the same JMF (L&L), (2) loose mixtures collected from the windrow and compacted in the field (F&F), (3) loose mixtures collected from the windrow and compacted in the laboratory (F&L), and (4) cores retrieved from the field after paving. Three types of HMA properties were measured as follows:

- Composition properties: gradation and binder content.
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- Mechanical properties: dynamic modulus (|E*|), creep stiffness and indirect tensile strength (ITS).

The details of this task are included in Chapter 3.

Task 3: Field Data Collection, Specimens Fabrication, and Testing

During the process of each paving project, pertinent data from ADOT&PF and the contractors at lab/design, production, and newly constructed phases were obtained. This included general information regarding the paving projects, details of the materials and JMF used in the construction, quality-control testing data from contractors, and acceptance testing results from the agency. The F&F specimens were prepared in the field, and tested for composition and volumetric properties. In addition, materials were collected and shipped to the University of Alaska Fairbanks (UAF) laboratories for preparation of L&L and F&L specimens. Volumetric and mechanical properties were investigated using specimens from these two scenarios. Cores retrieved from the field were used to verify volumetric properties of field mixtures and to conduct indirect tensile (IDT) tests in the laboratory for low-temperature performance evaluation. The details of laboratory and fieldwork are described in Chapter 3, and testing results are presented in Chapter 4.

Task 4: Data Processing and Analyses

Compilation and analyses of laboratory and field data were performed under this task. Variance and error analyses were conducted to measure sources of variation found in material properties data. The significance of potential influencing factors, such as operator, sublot, and scenario, was examined. Relationships among composition properties, volumetric properties, and mechanical properties were established and compared. This task is presented in Chapter 4.

Task 5: Project Summary and Conclusions

Research results and findings were summarized in this task, as provided in Chapter 5.

CHAPTER 2 LITERATURE REVIEW

Quality assurance programs have been developed to ensure that HMA placed in the field performs in the manner expected from the designed JMF. Currently, quality (process) control (QC)/quality acceptance (QA) is the most-used quality assurance specification, a combination of end-result specification and materials and methods specification. The definition of types of quality assurance specification and related concepts may vary among different publications. The definitions used in this report follow those in *The Glossary of Highway Quality Assurance Terms*, published by the Transportation Research Board (TRB) Committee on Management of Quality Assurance (Transportation Research Board, 2002).

2.1 Types of Quality Assurance Specification

Before the 1990s, method-based specification was widely used by state highway agencies. This specification requires a contractor to use specified materials, proportions, equipment, and methods to place material, and each step is directed by a representative of the state highway agency (Transportation Research Board, 2002). Under this type of specification, highway agencies must field a large labor force to oversee both the design and construction phases of a project, and the contractor's flexibility in exercising invoice techniques is limited (Transportation Research Board, 2009).

The end results specification gives contractors the flexibility to use new materials, techniques, and procedures to improve the quality and/or economy of a product. This specification requires the contractor to take full responsibility for supplying a product or an item of construction. The highway agency's responsibility is to accept or reject the final product or to apply a price adjustment commensurate with the degree of compliance with the specification (Transportation Research Board, 2002). However, no definitive criteria have been found that can guarantee identification of full service-life performance based on material measurement and/or pavement characteristics during construction. This limitation hampers quantification of substantial compliance or determination of price adjustment factors related to reduced or enhanced quality (Smith, 1998).

During the last two decades, state highway agencies have been working with contractors to implement QC/QA specification, moving away from traditional method-based specification (Dobrowolski and Bressette, 1998; Willoughby and Mahoney, 2007). The QC/QA specification, which has improved paving quality and reduced construction variance, allows innovations during construction that reduce an agency's labor costs (Patel et al., 1997; Douglas et al., 1999; Hand et al., 2001). Patel et al. (1997) reported that the QC/QA specification resulted in more-uniform asphalt concrete mixtures and potentially led to a 15% increase in fatigue life. Douglas et al. (1999) showed that a review of QC data revealed lower standard deviations of quality characteristics than national averages.

The QC/QA specification has three integral components: quality or process control (QC), acceptance, and independence assurance (IA) (Hughes, 2005). Generally, a contractor is responsible for QC, while the highway agency is responsible for acceptance of product. The IA is performed by an independent third party to provide an objective assessment of the testing process, the product, and/or reliability of test results (Hughes, 2005). Most states require contractors to adhere to mix designs and provide QC plans (Schmitt et al., 1998). A typical QC plan contains types and frequencies of tests and inspections, methods for material storage and handling, identification of personnel responsible for various QC functions, and methods to ensure that testing equipment is in adequate operating condition.

Nearly all state highway agencies have acceptance tests (Schmitt et al., 1998; Butts and Ksailbati, 2003), but the ratio of QA to QC varies significantly among state highway agencies. According to the survey conducted by Butts and Ksailbati (2003), the ratio was in the range of 1:1 to 1:10 (QA: QC). Based on acceptance results, pay adjustment is applied congruent with the degree of compliance with specifications, as represented by percent within limit (PWL). According to Schmitt et al. (1998),

> In theory, pay adjustments are the difference between planned life-cycle costs from design and expected life-cycle costs from as-built construction quality. It is assumed that the pay adjustment quantifies the difference in reduced service life and an increase in the life-cycle costs.

Generally, the pay adjustment is implemented through pay factors, which are calculated based on PWL. The survey (Schmitt et al., 1998) indicated that the final calculated pay factor could range from 0.5 to 1.1 among state highway agencies.

From the perspective of engineering management, responsibilities during production processes differ in method specification, QC/QA specification, and end results specification. Improved management and efficient cooperation between contractors and state agencies have advanced paving quality. While the techniques used in quality quantifying tests might be the same among all three specifications, the quality specifications themselves may be classified according to the types of quality characteristics used in the specification: performance specification, performance-based specification, and performance-related specification.

Performance specification describes how the finished product should perform over time; for HMA, such factors as rutting, fatigue cracking, etc., would be specified. Performance specification has not been used for HMA because of the lack of appropriate nondestructive tests to measure long-term performance right after construction, except for warranty specifications.

Several state highway agencies and research institutes are trying to improve current standards by implementing *performance-based specification*, which describes the desired levels of fundamental engineering properties (e.g., modulus, strength, fatigue properties) that are predictors of performance and that appear in primary prediction relationships, including rutting, fatigue and low-temperature cracking. Mechanical properties that could be used as quality characteristics include flow number (Dongre et al., 2009) and dynamic modulus (Katicha et al., 2010). In both studies, the proposed alternative testing methods greatly reduce testing time with acceptable accuracy.

Performance-related specification describes the desired levels of the key materials characteristic, such as air voids and binder content of HMA, and construction quality characteristics, which have been found to correlate with fundamental engineering properties. The currently used QC/QA specifications could be considered a performance-related specification, since the measurements and parameters used during QC and QA tests are assumed to correlate with fundamental engineering properties and pavement performance. As mentioned by Buttlar and Harrell (1998), the development of links between key material characteristics, engineering properties, and performance was very difficult; the link between material characteristics and engineering properties was particularly challenging to establish. The correlation between these two links depends on the type of material, and complicated interactions exist. In addition, the variances caused by production, construction, sampling, equipment, and operator need to be considered.

2.2 Key Material Characteristics and Influencing Factors of HMA

The current QC/QA specification was considered a performance-related specification. Thus, it relies on measured key material characteristics to quantify the compliance of construction to the required performance. Choosing appropriate material characteristics for use in QC/QA tests and for studying variance associated with these characteristics is of great importance therefore. The mechanical properties of HMA used in performance-based specification and associated study reviews are presented in the next section.

2.2.1 Key Material Characteristics

The material characteristics of HMA used for quality assurance programs vary among states. A survey conducted by Butts and Ksailbati (2003) investigated the quality characteristics used during QA procedures in 39 states (Figure 2.1). At that time, 13 candidate characteristics could be used for QC, QA, or both. According to this survey, 36 of 39 states were using mat density as a control parameter; other most frequently used characteristics included aggregate gradation, asphalt content, and air voids. Clay content was the least-used material characteristic. Tensile strength ratio (TSR) was the only mechanical characteristic used by state agencies, and it was the least-used quality characteristic.

Figure 2.2 shows the number of characteristics used by each state highway agency. ADOT&PF was among the 4 agencies using 4 characteristics; 10 of 39 states were using 7 characteristics for the QC/QA program; and only 2 agencies were using 12 characteristics. The key material characteristics of HMA could be grouped into two categories: composition properties (i.e., binder content and aggregate gradation) and volumetric properties, such as voids of total mix (VTM), voids of mineral aggregate (VMA), and voids filled with asphalt (VFA).

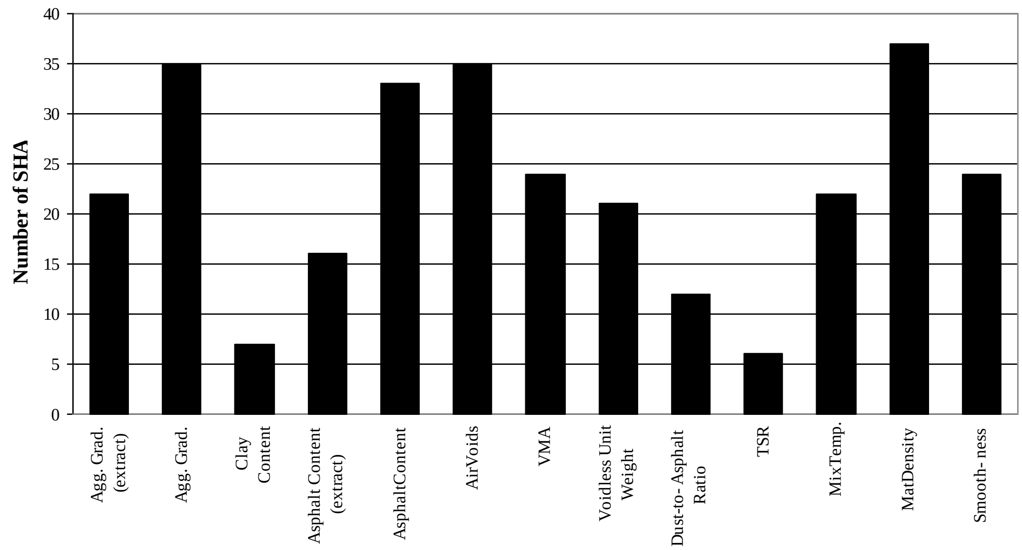


Figure 2.1 Quality characteristics used by state highway agency (SHA)

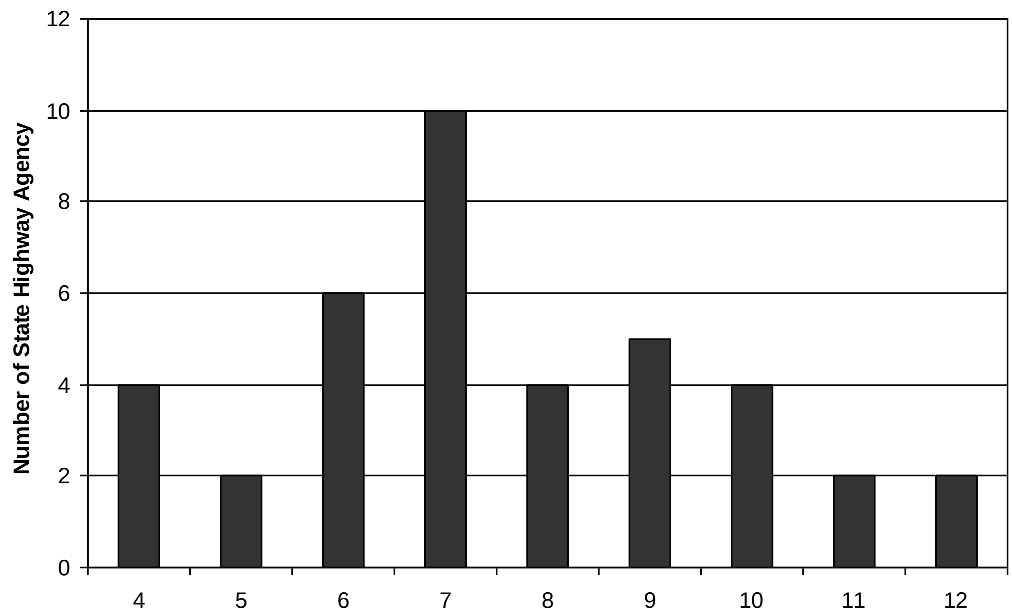


Figure 2.2 Summary of number of quality characteristics used by SHA for QC/QA

2.2.1.1 Composition Properties

Composition properties of HMA are the most widely used material characteristics in QC and QA testing; they are the "must have" properties for QC tests, since they indicate quality compliance and provide guideline information on how to adjust production in the event of noncompliance. Adjustments of volumetric properties also reply on information provided by composition properties, and will eventually be implemented through the adjustments of composition properties and/or construction process (Cominsky et al., 1998).

Measurement of binder content can be obtained by three different methods: extraction (AASHTO T164), nuclear gage (AASHTO T187), and ignition furnace (AASHTO T308). The aggregate obtained after extraction or ignition can be used to determine gradation according to AASHTO T30. Some variance in binder content is inevitable during construction. The latest survey conducted by (Mohammad and Elseifi, 2010) shows the variance of binder content and aggregate gradation measured by the contractor, state highway agency, and third party. Table 2.1 lists the variance of binder content based on responses from 30 states, and generally, the variance obtained from the three operators is similar. For reference, the table also includes the typical industry standard deviation and the recommended limits listed in AASHTO R42. As indicated by AASHTO R42, among the three testing methods, extraction has the highest variance, and ignition method has the lowest variance.

Table 2.1 Summary of standard deviation for binder content of plant mix lab measured sample (data of contractor, SHA, and third party were obtained from Mohammad and Elseifi, 2010)

	Contractor	SHA	Third Party	Typical Industry STDEV (AASHTO R42)			Recommended Specification Limits (AASHTO R42)		
				Extraction	Nuclear Gage	Ignition	Extraction	Nuclear Gage	Ignition
Min	0.17	0.17	0.18	n/a	n/a	n/a	n/a	n/a	n/a
Max	0.22	0.24	0.21	n/a	n/a	n/a	n/a	n/a	n/a
Average	0.19	0.20	0.20	0.25	0.18	0.13	0.41	0.30	0.21

Aggregate gradation is represented by the percentage of aggregate passing through a series of specified sieve sizes. Measured gradation during QC does not necessarily include all sieve sizes specified in the JMF. Hughes et al. (2007) reported that the percentage passing through 3/8 in., No. 4, No. 8, and No. 200 sieves was used most among contractors in Virginia. The percentage passing through No. 4 and No. 200 sieves was used in the acceptance test to calculate the pay factor. The testing frequency of aggregate gradation was determined according to the frequencies of QC and QA tests.

According to Burati et al. (2003), for QC purposes, historical data were used to set control limits, and data collected must be in the same manner and under the same general conditions of use. The historical data on aggregate gradation from one quarry may not be appropriate for use in establishing control limits for aggregate from a different quarry. Or, historical data for dry aggregate gradations would not be appropriate if the new QC plan called for a washed gradation analysis. Table 2.2 summarizes the results of a recent national survey conducted by Mohammad and Elseifi (2010) on variances of aggregate gradation at each sieve size. Generally, larger sieve sizes are associated with greater variance. Data obtained from the third party have the lowest variance, followed by the SHA. The average variance found among all three operators is below the typical industry standard deviation according to AASHTO R42.

Table 2.2 Summary of standard deviation for aggregate gradation (Mohammad and Elseifi, 2010)

Sieve Size	Contractor			SHA			Third Party			Typical Industry STDEV (AASHTO R42)
	Range		Avg.	Range		Avg.	Range		Avg.	
	Min	Max		Min	Max		Min	Max		
1"	1.70	2.66	2.12	1.74	1.79	1.77	0.68	0.68	0.68	3
3/4"	0.82	2.59	1.93	0.91	2.26	1.64	1.28	1.28	1.28	3
1/2"	0.91	3.54	2.14	1.08	2.54	1.79	0.89	2.15	1.52	3
3/8"	1.61	3.75	2.60	1.82	2.54	2.25	1.65	2.29	1.97	3
#4	1.87	3.48	2.71	2.19	3.08	2.66	2.37	2.56	2.47	3
#8	1.75	2.05	2.13	2.12	2.73	2.30	1.76	2.07	1.92	2
#16	1.56	2.38	1.81	1.70	1.76	1.73	n/a	n/a	n/a	2
#30	1.37	1.73	1.54	1.43	1.89	1.62	n/a	n/a	n/a	2
#50	1.12	1.28	1.18	10.7	1.27	1.17	n/a	n/a	n/a	2
#100	0.64	0.99	0.78	0.76	0.83	0.80	n/a	n/a	n/a	2
#200	0.34	0.84	0.60	0.39	0.66	0.52	0.40	0.40	0.40	0.7

2.2.1.2 Volumetric Properties

As shown in Figure 2.1, volumetric properties also are widely used for QC/QA programs, especially for air void content. The use of volumetric properties is to confirm that the properties of plant-mixed material are within established tolerances of the volumetric mix design. Volumetric properties provide a better correlation with pavement performance than composition properties (Von Quintus and Killingsworth, 1998; Hughes et al., 2007).

However, volumetric properties offer less control during QC. Volumetric properties may fail to detect changes in gradation or asphalt content and indicate that the process is in control when it is not. This situation is most commonly seen when the asphalt content and gradation vary simultaneously (Von Quintus and Killingsworth, 1998). When the plant product is found to be out of limit as indicated by volumetric properties, appropriate process adjustment requires measurement of composition properties. Volumetric properties are included in QC/QA programs in many states, but not all of the states apply a pay adjustment factor to them. The Virginia DOT measures volumetric properties, but only uses them as “shutdown” devices (Hughes et al., 2007).

Willoughby and Mahoney (2007) compared the mix performance of 32 Superpave non-volumetric pay factor projects and 43 volumetric pay factor projects in Washington State, concluding that there is no significant difference between them. They also mentioned that volumetric field testing is more complicated and expensive, and has greater operator error than field testing of composition properties. Additionally, it was found that volumetric properties are affected by binder content and gradation (Von Quintus and Killingsworth, 1998; Hughes, 2005). Pay factor should not be based on multiple items that are correlated.

The attempt to predict change in volumetric properties of HMA by using aggregate degradation was not successful. Generally, however, a 0.71% decrease in air voids was observed for every 1.0% increase in material finer than the 0.075 mm sieve, and VMA exhibited an average 0.63% change for every 1.0% increase in dust. The author recommended that minimum VMA values for Superpave mix design be increased by 1% for all dense-graded mixes to compensate for the amount of aggregate degradation and loss of VMA during HMA production and construction (Todd et al., 2007).

The variance of volumetric properties from a recent survey is listed in Table 2.3. The data indicate that variance obtained from the contractor, SHA, and third party is below the typical industry standard deviation listed in AASHTO R42. In addition, Gedafa et al. (2011) found that the significant differences of volumetric properties were observed at lot-wise comparison, but at sublot-wise comparison, there was not a significant difference.

Table 2.3 Summary of standard deviation for volumetric properties (Mohammad and Elseifi, 2010)

Sieve Size	Contractor			SHA			Third Party			Typical Industry STDEV (AASHTO R42)	Recommended Specification Limits (AASHTO R42)
	Range		Avg.	Range		Avg.	Range		Avg.		
	Min	Max		Min	Max		Min	Max			
VTM	0.40	0.84	0.60	0.36	0.99	0.61	0.68	0.91	0.81	1	1.6
VMA	0.37	0.58	0.49	0.38	0.65	0.53	0.51	0.64	0.58	1	1.6
VFA	3.40	4.08	3.73	4.01	4.93	4.34	4.20	5.16	4.68	5	8
G_{mb}	0.013	0.017	0.015	0.008	0.018	0.014	0.016	0.016	0.016	0.022	n/a
G_{mm}	0.012	0.012	0.012	0.008	0.012	0.009	0.011	0.011	0.011	n/a	n/a
Field Density	0.74	1.44	1.13	0.79	1.49	1.23	0.9	0.9	0.9	1.4	2.3

2.2.1.3 Mechanical Properties

Recent studies (Dongre et al., 2009; Katicha et al., 2010) showed the possibility of moving the quality assurance program toward performance-based specification, where the mechanical properties of HMA are measured beside traditional composition properties and volumetric properties. It is believed that pavement performance can be predicted based on measured mechanical properties under a mechanistic-empirical pavement design guide (MEPDG) framework, which would allow the development of pay factors based on the predicted loss/gain of pavement life through the use of life-cycle cost analysis (Katicha et al., 2010). A similar study performed by El-Basyouny and Jeong (2010) integrated MEPDG with the asphalt mixture performance test to develop a probabilistic quality specification for quality assurance of HMA construction. The difference between the as-built and the as-design distress provided the predicted difference in quality of construction from the mix design. This difference was used to calculate the pay factor for distress; additionally, the initial, international roughness index (representing the ride-quality pay factor) was considered.

The dynamic modulus was considered a quality measurement for QC/QA specification, as it is also an essential material input for flexible pavement design in MEPDG (Katicha et al., 2010). The specimens were made of field-collected loose mixture that was compacted in the laboratory. Alternative testing procedures used the effective reduced frequency, which allows characterizing the mix dynamic modulus using a single test at room temperature (21.1°C) and greatly reduces the testing time and cost. The dynamic modulus measured at 1 Hz was used to predict the rutting resistance of HMA based on a power function. Predicted rutting was compared with MEPDG calculated rutting; the average deviation between these two was 6.8%.

Mohammad et al. (2004) found good correlation between the complex shear moduli of Superpave gyratory compactor (SGC) samples and field cores. In general, SGC samples possessed about 50% higher complex shear moduli than field cores. The ITS of SGC samples was higher than that of field cores, and the ITS of field cores showed better correlations to the air voids than ITS of SGC samples. The deformation modulus from light falling weight deflectometer (LFWD) tests, which are easier to perform in the field, had a linear relationship with deflections of the falling weight deflectometer (FWD) tests. Thus, the LFWD test may be used as an alternative to the FWD test in pavement structure evaluation.

Dongre et al. (2009) evaluated the potential of using flow number (F_N) as a quality characteristic. The study further validated the Francken model (Biligiri et al., 2007) for calculating F_N by using field data. A strong correlation was found between additional parameters, such as steady-state slope (SSS) and slope at permanent strain values, with F_N values calculated by means of the Francken model. This finding indicates that the F_N test time may be greatly reduced by recording the number of cycles at which the specimen reaches steady state or 2%

strain. With this improved protocol, most F_N tests can be completed in 15 minutes or less, with a maximum test time of 1 hour (3600 cycles).

However, the variance found in mechanical properties was much higher than the variance found in key material characteristics. Table 2.4 listed the coefficient of variation of mechanical properties obtained from the survey conducted by Mohammad and Elseifi (2010). Compared with key material characteristics, more variation sources were introduced, including complicated specimen-fabrication processes and testing methods, and this was considered the reason for the higher variance observed from mechanical properties.

Table 2.4 Summary of coefficient of variation for mechanical properties (Mohammad and Elseifi, 2010)

Mechanical property	COV Range		Avg. COV
	Min	Max	
Dynamic Modulus	10.0	23.8	13.9
Phase Angle	3.9	15.4	7.1
Flow Number	37.3	52.1	45.2
ITS	11.9	15.4	13.7

2.2.2 Influencing Factors

The factors that influence material characteristics in the QC/QA tests include mix design method, material sampling, laboratory compaction, and testing.

2.2.2.1 Design Method

Design method was considered an influencing factor for material characteristics. Currently, most states use either the Superpave mix design method or Marshall mix design method. Parker and Hossain (2002) found that asphalt contents of Superpave mixes were consistently close to the target values, and accuracy and variability were comparable to those of Marshall mixes. The VTM and mat density measurements were consistently lower (0.4% and 0.8%, respectively) than the target values and were not comparable to those of Marshall mixes. The variability of mat density measurements (1.1%) for Superpave mixes was comparable to that of Marshall mixes. The variability of air void content measurements (0.9%) for Superpave mixes was higher than that for Marshall mixes (0.6%).

2.2.2.2 Sampling

The quality of a HMA sample can significantly affect QC/QA testing results. A sample should be representative of the HMA mixture that will be placed on the roadway. A theoretical study conducted by Tsai and Monismith (2009) presented a sampling scheme during the QC/QA process by using a statistical simulation combined with a field case study. The results indicated that the best sampling strategy is either to take two QC samples and one QA sample from behind the paver at randomly selected locations about every 30 feet or randomly to take two QC samples and one QA sample from each 20-ton truck.

Tuner and West (2006) investigated the effects of sample location on HMA properties. Four sample locations were considered: sampling by regular shovel on trucks, sampling by a specially designed device on trucks, sampling behind the spreader, and field cores. The authors found that there was little statistical difference in the laboratory properties caused by sampling location, but finer gradation, higher asphalt content, and lower percent air voids were observed in samples taken from the truck using a shovel, which may be due to segregation occurring during the sampling process.

The effect of material segregation on flexible pavement performance was evaluated by Stroup-Gardiner (2000). In this study, the changes in gradation, binder content, and air voids were measured on field cores, and laboratory-simulated segregated samples were manufactured for further performance tests. The testing results indicated that the primary causes of performance deterioration due to segregation were the loss of mixture stiffness, the loss of tensile strength, and the increase in moisture susceptibility. These findings were confirmed by field survey. The study also indicated that rutting was caused by temperature segregation and poor compaction rather than by gradation separation. The segregation-related loss of pavement life could be 2 to 7 years of an anticipated 15-year service life, the cost of which takes up to 50% of present worth of HMA.

Lynn et al. (2007) evaluated aggregate gradation changes by comparing four sampling points: cold feed material, post-production material sampled at the hot-mix plant (truck), post-placement material sample from behind the paver, and post-compaction material sampled after final rolling but before the mat completely cooled. It was concluded that aggregate degradation did result from plant mixing and field compaction activities, and generally the degradation happened during production rather than during post-production processes. Nominal maximum aggregate size (NMAS) did not affect aggregate degradation significantly. Aggregate degradation was a function of aggregate source, but it cannot be predicted by L.A. abrasion or micro-deval test results.

In addition, Kandhal and Cooley (2003) mentioned that during the assurance application, a plant mix sample for rutting test is commonly cooled down, taken to a central laboratory, reheated, and then compacted for testing. Reheating may apply additional aging to HMA, leading to a stiffer mix. However, the effect of reheating was not investigated in this study.

2.2.2.3 Laboratory Compaction

One important aspect of laboratory compaction is the simulation of ultimate compaction achieved in field construction. An early study by Von Quintus et al. (1991) indicated that by comparing the diametric resilient modulus, the Texas gyratory compactor best simulated the results of roadway cores among five compaction methods, including the Marshall hammer, the California kneading compactor, the Texas gyratory shear compactor, the Arizona vibratory/kneading compactor, and the Mobil steel wheel simulator. The Marshall hammer showed the least correlation with field cores.

Both the single-operator and multi-laboratory precisions of the SGC were found to be superior to past data obtained with the Marshall hammer (Benson, 1999). Similar results were found by Douglas et al. (1999), indicating that the precision of the SGC is better than that of the Marshall hammer. The precision values calculated for the three gyratory compactors evaluated and the three testing programs were determined to be 0.0094 (standard deviation of G_{mb}) and 0.0132, respectively, for single-operator and multi-laboratory precision. These values are lower than the corresponding value obtained using a Marshall hammer: 0.012 for single-operator precision and 0.022 for multi-laboratory precision (Brown and Adettiwar, 1991).

After the gyratory compactor was adopted for Superpave mix design compaction, Peterson et al. (2003) compared field compaction and Superpave gyratory compaction using a Superpave shear tester. Field compaction was conducted with three compaction patterns. Laboratory compaction was performed using a Superpave gyratory compactor that monitored several parameters, including gyratory angle, compress pressure, specimen height, and model temperature. It was found that field cores and laboratory-compacted specimens performed differently. Field compaction patterns do not affect the mechanical properties of field cores; however, the adjustment parameters of SGC significantly affect the mechanical properties of compacted specimens. Gyratory angle has the most important effect, and mold temperature has the least. The author recommended a 1.5° compaction angle with a specimen height of 50 or 75 mm for laboratory compaction to most closely emulate the mechanical properties of field cores.

Considerable disparity exists between properly calibrated SGCs. Benson (1999) reported that for the same mixture, significant differences of calculated air voids were observed on specimens compacted by different, properly calibrated SGCs. The maximum difference was almost 2%. Optimum asphalt content variation can occur between designed mixes and verified mixes when using two different compactors. An optimum asphalt content difference of 1.3% was reported in one case, which corresponded to a 2.5% change in the VMA. Significant differences between QC and QA air void results can occur even though properly calibrated gyratory compactors have been used.

2.2.2.4 Testing

Measurements performed by different operators may not be consistent with each other. Based on Georgia DOT (GDOT) QA data for eight sieves and asphalt content, Turochy et al. (2006) found a significant difference between GDOT and contractors' results. In general, the differences in variance tend to be more common and more likely significant than differences in means. A comparison of contractor and GDOT QC test results revealed higher variances in GDOT data in every property with a significant variance.

Schmitt et al. (2001) conducted a similar study on field split-sample HMA testing based on measurements from the agency, the contractor, and a third party. Split samples control variables except those related to the testing itself. Split sample testing between contractor and the agency was conducted in ten projects, and three-way split sample testing between the agency, contractor, and the Asphalt Institute was conducted in six projects. The measurements included aggregate gradation, asphalt content, G_{mm}, G_{mb}, VTM, VMA, and VFA. The authors found that mean bias was mostly within allowable differences, as described in state specifications. However, the biases were not consistent when comparing the results from three labs. In addition, although the mean bias was under tolerance limits, the difference between individual split-sample test results often exceeded the allowable variability.

Surface Dry (AASHTO T-166) and CoreLok (ASTM D6752-02) are the two most frequently used laboratory testing methods for measuring the specific gravity of HMA specimens, a metric used to calculate air voids content within the total mix. A study conducted by Mohammad et al. (2004) found a strong correlation between air voids, calculated by using the specific gravity obtained from two methods. In general, CoreLok measured air voids about 0.5% higher than the air voids determined from the Surface Dry method.

Al-Qadi et al. (2003) reported the potential of using ground-penetrating radar (GPR) to measure the thickness of newly constructed HMA pavement for QA/QC purposes. An average error of 2.9% was reported based on the comparison of GPR results to thicknesses directly measured from field cores. The authors pointed out that an erroneous thickness would be obtain for aged pavement by using GPR due to error of the dielectric constant.

CHAPTER 3 FIELD AND LABORATORY TESTS

Chapter 3 describes this study's fieldwork plan and experimental design, including the details of sample collection, specimen fabrication, and laboratory tests. The information collected from contractor and agency is presented, including general information on paving projects, details of the materials, and the JMF, as well as quality control and acceptance testing results.

3.1 Fieldwork Plan

Based on information collected from the literature review and discussions between the research team and ADOT&PF personnel, two asphalt paving projects—the Parks Highway Mile 287–305 rehabilitation and resurface project and the Anchorage International Airport (AIA) runway 7R/25L rehabilitation—were selected for fieldwork.

The Parks Highway Mile 287–305 rehabilitation and resurface project, located near Nenana, is referred to in the report as the Nenana paving project. The project involved pulverizing existing asphalt materials, repaving, upgrading guardrail end terminals, and associated tasks. Asphalt binder PG 58-34 and the Marshal mix design method (50 blows) were used for the HMA. Detailed JMF information is listed in Table 3.1. During construction, HMA was divided into lots of 5000 tons of HMA. Each lot was further divided into 10 sublots of 500 tons of HMA each. The QA program followed QC/QA specification. The contractor performed QC tests measuring asphalt content and aggregate gradation by the ignition method. ADOT&PF performed acceptance tests measuring binder content and aggregate gradation by the ignition method and density of field cores. Except gradation tests during the QC process, the QC and QA tests were performed at the sublot level. Loose mixtures from the windrow of nine sublots (HMA63-HMA67 and HMA69-72 by ADOT&PF Sample Number) were collected during two days of construction, following a random sampling strategy.

The other project selected was the Anchorage International Airport Runway 7R/25L rehabilitation (the AIA paving project), where PG 64-34 binder was used, and the Superpave mix design method (75 gyrations) was used. The details of the JMF are summarized in Table 3.1. The size of a lot and a sublot equaled 5000 tons and 500 tons, respectively. The QA program used was the same as for the Nenana paving project. Hot mix asphalt samples were collected from four sublots during one day of construction (HMAV118-HMAV121 by ADOT&PF sample number).

Table 3.1 Job mix formula of AIA and Nenana paving projects

Projects		% Passing 3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200	Binder Content (%)	VTM (%)	G_{mm} (g/cm^3)	VMA (%)	VFA (%)
AIA	Design	100.0	87.0	76.0	52.0	36.0	26.0	19.0	12.0	9.0	6.0	5.2	3.6	2.540	14.6	76.0
	Upper	100.0	93.0	82.0	58.0	42.0	31.0	23.0	16.0	12.0	8.0	5.6				
	Lower	100.0	81.0	70.0	46.0	30.0	21.0	15.0	8.0	6.0	4.0	4.8				
Nenana	Design	100.0	86.0	73.0	52.0	37.0	27.0	20.0	13.0	9.0	5.8	5.0	3.5	2.549	14.4	75.0
	Upper	100.0	92.0	79.0	56.0	43.0	32.0	24.0	17.0	12.0	7.8	5.4				
	Lower	100.0	80.0	67.0	46.0	31.0	22.0	16.0	9.0	6.0	3.8	4.6				

3.2 Experimental Design

To evaluate the variability of HMA involved in the construction processes and the impact of this variability on pavement performance, specimens of four scenarios were prepared or collected from these two paving projects:

- L&L specimens mixed and compacted in the laboratory using the same JMF for each paving project.
- F&F specimens compacted in the field using loose mixtures collected from the windrow.
- F&L specimens compacted in the laboratory using loose mixtures collected from the windrow.
- Field cores retrieved from the field after paving when pavement had cooled down.

Three types of HMA properties were measured as follows:

- Composition properties (i.e., gradation and binder content).
- Volumetric properties (i.e., VTM, VMA, and VFA).
- Mechanical properties (i.e., │E*│, creep stiffness, and ITS).

Details of the experimental design are summarized in Table 3.2. The composition properties were measured from the loose mixture. Because the L&L specimens were prepared on a laboratory blend mixture according to the JMF, the gradation and binder content tests were not needed. Volumetric properties were evaluated on at least three replicates of specimens prepared for all four scenarios. Dynamic modulus (│E*│) and flow tests were only performed on L&L and F&L specimens due to the large sample size required for testing. Indirect tensile (IDT) creep tests were performed for all four scenarios at three testing temperatures: -10°C, -20°C, and -30°C. For L&L and F&L specimens, the ITS tests were performed at three temperatures as well: -10°C, -20°C, and -30°C. Due to a limited numbers of F&F specimens and field cores, the ITS tests were only performed at -20°C for field cores and at -10°C and -30°C for F&F specimens.

Table 3.2 Experimental design

Scenario	Composition Properties		Volumetric Properties			Mechanical Properties			
	Gradation	Binder Content	VTM	VMA	VFA	│E*│	Flow Test	Creep Stiffness	ITS
L&L			√	√	√	√	√	√	√
F&L	Performed on Loose Mixture	Performed on Loose Mixture	√	√	√	√	√	√	√
F&F			√	√	√			√	√
Field Cores			√	√	√			√	√

3.3 Specimen Fabrication

The L&L specimens were made of laboratory-mix HMA, and specimens for F&L and F&F scenarios were made of loose mixtures collected from the field. Cores were retrieved from compacted pavement.

The field sampling procedure used to collect loose mixtures for F&L and F&F specimens was the same as the procedure used by ADOT&PF and contractors. The sampling locations were the same as those used by ADOT&PF, following a random strategy, and the loose HMA mixtures were taken from the windrow. As shown in Figure 3.1, the sampling procedure included six steps: (a) warm up the shovel in the windrow, (b) clean the shovel, (c) shovel off the top of the windrow, (d) use the shovel vertically to shovel off the front corner of the windrow to make a square corner of HMA mixture, (e) take a sample and transfer it into a sampling container making sure the surface of the shovel is parallel to that of the fresh HMA mixture, and (f) scrape the mixture from the shovel into the sampling container.

Two types of field samples were collected: (1) two buckets of samples immediately delivered to the mobile field lab (Figure 3.2) for compaction to make F&F specimens and (2) another 250 lb of samples collected for each sublot and stored in paper boxes for UAF laboratory testing purposes. The mobile testing lab was set on a pickup truck and consisted of a Superpave gyratory compactor (SGC), an oven, a scale, a generator, and other testing accessories (Figure 3.2). The oven was used to heat the compaction molds only. For each sublot, three specimens (150 mm in diameter and 115 mm in height) were compacted using the SGC. The same number of gyrations used on the JMF (75 gyrations) was used to compact specimens for samples from the AIA project. Because the Marshall mix design method was used in the Nenana paving project, an equivalent number of gyrations was predetermined to reproduce specimens compacted by means of the Marshall hammer. The equivalency of compaction was based on the assumption that the same compaction effort would lead to the same air voids. The relation between the number of gyrations and air void content was obtained through trial compactions in the laboratory prior to the fieldwork. The equivalent number of gyrations was determined to be 20 to achieve 3.5% of design air void content for the Nenana HMA mixture.

Specimens with different sizes were prepared in the laboratory compaction for L&L and F&L scenarios. Specimens of 150 mm diameter and 115 mm height were used for volumetric property measurements. After volumetric property measurement, these specimens were cut for IDT tests, with a target height between 38 and 50 mm. Field-cored samples were also cut to the required heights for IDT tests. Specimens of 150 mm diameter and 180 mm height were prepared and then cored and cut to the final size (100 mm diameter and 150 mm height) for dynamic modulus and flow tests.

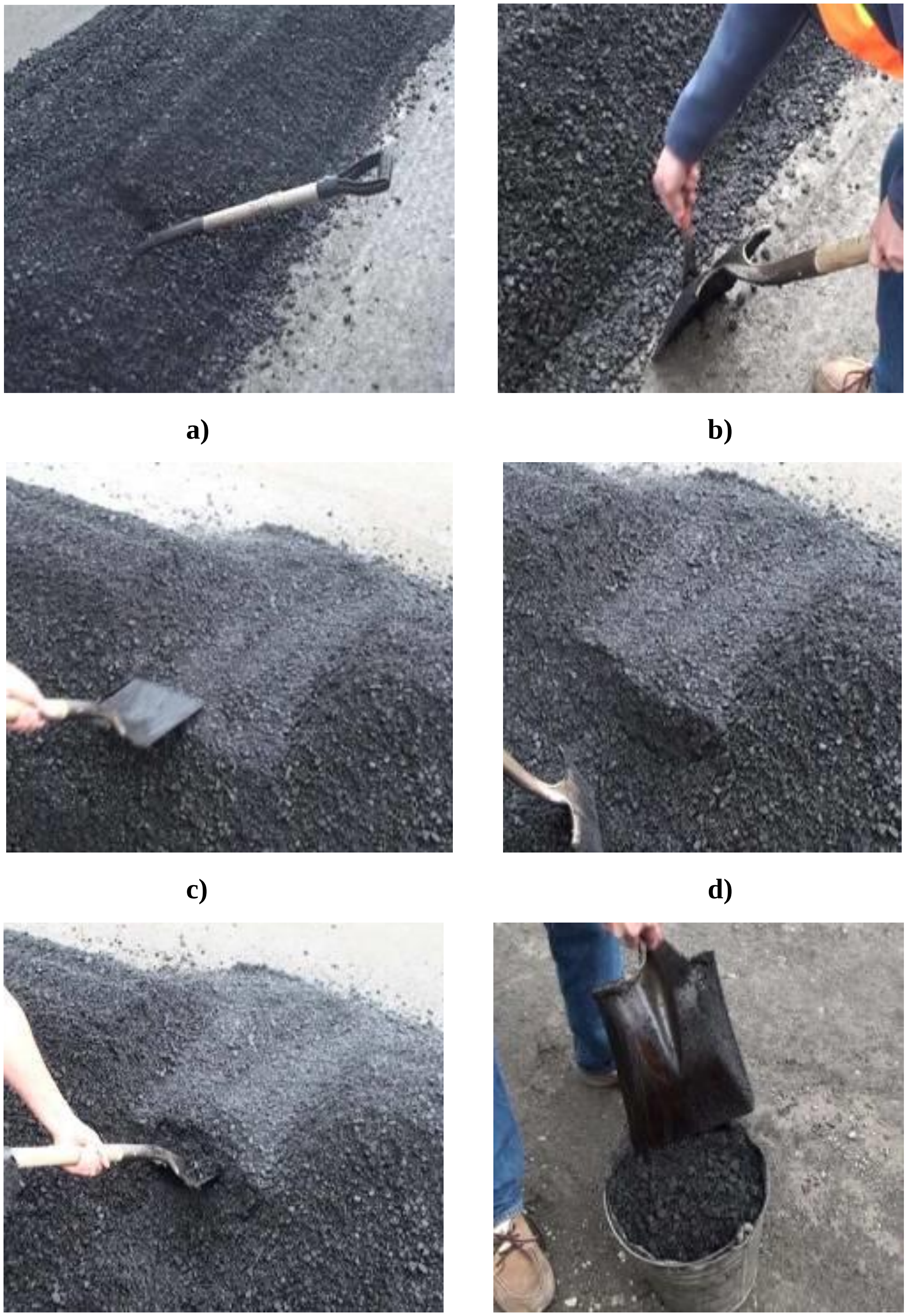


Figure 3.1 Field sampling procedures

Figure 3.2 Field lab for AIA paving project

3.4 Laboratory Testing

3.4.1 Composition Properties

The binder content of HMA samples collected from the field was measured using the ignition method (AASHTO T308-08). The sample was subjected to an elevated temperature of 538°C in the NCAT burning oven, and the asphalt was ignited and burned from the mixture. The oven is capable of weighing the sample during the burning process. When the sample reached a constant weight, the burning process was considered complete. The percentage of loss due to burning was then calculated as the binder content of the loose mixture sample.

A part of aggregate particles would be burned during the ignition process, leading to a higher weight lost than the weight of asphalt itself. The correction factor procedure was performed for each paving project. A mix with known asphalt binder content and gradation according to the JMF was prepared in the laboratory and placed in the burning oven for the ignition process. The difference between the actual and measured asphalt binder contents was calculated, and the correction factor was the average of results of two replicates.

The aggregate gradation was measured on the extracted sample from the ignition test following AASHTO T30-08 (2008). After the sample cooled to room temperature, it was placed on a #200 sieve and washed. The sample was then dried in the oven at 105°C. The difference in dry weight before and after washing was measured and recorded. Sieving analyses were performed to measure the percentage that passed at each sieve size. The weight lost during the washing process was added to the percentage that passed the #200 sieve.

3.4.2 Volumetric Properties

Volumetric properties were calculated for specimens of all four scenarios based on the measurements of bulk specific gravity and theoretical maximum specific gravity according to AASHTO T166 and AASHTO T209. The bulk specific gravity of aggregate was based on the information provided in the JMF.

3.4.3 Mechanical Properties

3.4.3.1 Dynamic Modulus ($|E^*|$)

The $|E^*|$ tests were performed on L&L and F&L specimens using the asphalt mixture performance tester (AMPT) according to AASHTO T342-11 (2011). The $|E^*|$ test is a strain controlled test, as a 100 mm (4 in.) diameter, 150 mm (6 in.) tall cored cylindrical specimen is subjected to a continuous haversine axial compressive load. The test is performed over a range of loading frequencies (25, 20, 10, 5, 2, 1, 0.5, and 0.1 Hz) and at four temperatures (4.4°C, 21.1°C, 37.8°C, and 54°C). The AMPT used to perform the test is a digital servohydraulic control testing machine equipped with a continuous electronic control and data acquisition system (CDAS). The cored cylindrical samples are placed within the machine and affixed with three radially mounted linear variable displacement transducers (LVDTs). Each LVDT measures displacement between two mounting points where LVDT is glued. The distance between two mounting points equals 70 mm. Figure 3.3 shows the setup of the AMPT.

Figure 3.3 Setup of the asphalt mixture performance tester (AMPT)

3.4.3.2 Flow Number and Flow Time

Flow number (F_N) and flow time (F_T) tests were performed on L&L and F&L specimens. The F_N test is a repeated-load permanent deformation test used to evaluate the creep characteristics of HMA as related to permanent deformation. A repeated uniaxial compressive load is applied in haversine form with a loading time of 0.1 seconds and a rest duration of 0.9 seconds for a maximum of 10,000 cycles or until a deformation of 50,000 microstrain is reached. Specimens are tested at a temperature of 54°C. The same AMPT used for the $|E^*|$ testing is used for F_N testing with exclusion of the previously mentioned LVDTs. Permanent deformations are measured internally by the displacement of the load frame.

Permanent strains of samples used in F_N evaluation demonstrate themselves in three distinct stages: primary zone, secondary zone, and tertiary zone. The primary zone is a period of rapid strain accumulation at the beginning of the test, followed by the secondary zone, which is identifiable by a constant accumulated strain rate. As the secondary zone continues and the pavement structure breaks down, a jump to the tertiary zone eventually occurs, marked by an increase in strain rate. The point at which the permanent strain rate is at its minimum and tertiary flow begins is noted as the F_N of the mixture.

Flow tests were performed under confined conditions due to the concern that without confinement, an HMA designed for low-volume traffic would demonstrate extremely low F_N and F_T values. The statistical analysis would be hard to perform on such low F_N and F_T values. In addition, previous study indicated that confined flow tests more closely match field conditions (Roberts et al., 1996). According to Roberts et al. (1996) and Bonaquist (2008), the confining pressure of 137 KPa was selected.

The F_T test is similar to the F_N test, but uses a static compressive load instead of a repeated compressive load. The F_T is defined as the postulated time when shear deformation starts under constant volume. The applied stress and the resulting permanent and/or axial strain response of the specimen is measured and used to calculate the flow time.

3.4.4 Indirect Tensile (IDT) Tests

The properties measured by IDT tests included IDT creep and strength. Indirect tensile tests were conducted on specimens of all four scenarios. The IDT device (Figure 3.4) was coupled with an environmental chamber and a programmed data acquisition system to determine the tensile creep stiffness $S(t)$ and tensile strength S_t under low temperatures according to AASHTO T322-07.

The IDT test is performed by loading a cylindrical specimen under a uniform compressive load, developing a relatively uniform tensile stress that ultimately causes the specimen to fail by splitting along the vertical diameters. The tensile creep compliance $D(t)$ of each mixture was monitored at three different temperatures: -20°C, -10°C, and 0°C. At each temperature, normalized horizontal and vertical deformations from six specimen faces (three specimens, two faces per specimen) were measured with LVDTs, shown in Figure 3.4.

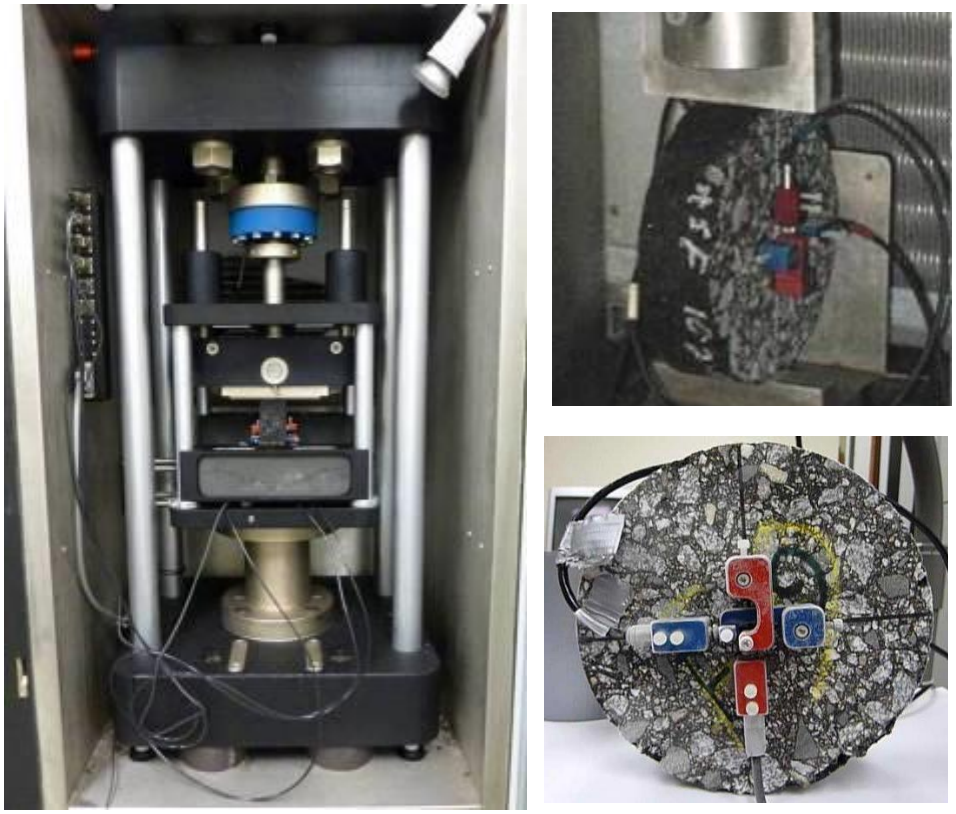


Figure 3.4 Setup for indirect tensile (IDT) test

CHAPTER 4 TESTING RESULTS AND DATA ANALYSIS

Chapter 4 presents the testing results of HMA properties and data analysis. The chapter is organized according to the material property categories: composition properties, volumetric properties, and performance properties. For each property type, testing results are summarized in figures and tables, followed by an analysis of variance and error. The variance was measured by standard deviation (STDEV) or coefficient of variance (COV). The error was calculated as the absolute value of the difference between design values and measured values. For mechanical properties, the results from L&L scenarios were considered the design values. The significance of potential influencing factors, such as sublot, operator, and testing scenario, have been analyzed for both variation and error, and the correlations among these three categories of material properties have been analyzed and compared.

4.1 Composition Properties

Composition properties describe the basic components of HMA including the percentage of aggregate passing at designated sieve sizes and the binder content. These properties and parameters are directly used during the production of HMA. Composition properties are adopted in nearly all the QC/QA procedures. Using these properties in QC/QA procedures not only indicates the degree of compliance with requirements, but also provides information on how to adjust the manufacturing process for unqualified products and how to improve the quality of current products. Such information cannot be directly obtained from either volumetric properties or mechanical properties.

4.1.1 Testing Results

The composition properties were obtained from contractors' quality control testing results, the state agency's acceptance testing results, and third party tests conducted by UAF. The results are summarized and presented in Tables 4.1 to 4.2 and Figures 4.1 to 4.3.

The UAF research group collected HMA mixtures from four sublots in the AIA paving project during one day of production. The measured composition properties are summarized in Table 4.1. The testing results from ADOT&PF and the contractor (QAP) are also listed in the table. The mean and STDEV of material from four sublots were calculated for each sieve size and operator.

Generally, a higher variance of sieving analysis was observed on coarse aggregate. The STDEVs at sieve sizes ranging from ½″ to #4 were between 0.9 and 2.2 based on the results from three operators. The variance was less than the suggested values in AASHTO R42 (Table 2.2) and within the ranges indicated by the most recent national survey conducted during the NCHRP 9-48 project (Mohammad and Elseifi, 2010). The STDEVs of the fine aggregate passing sieve #4 (4.75 mm) were less than 1, except the UAF testing results at the #8 sieve. All results were within the ranges listed in AASHTO R42 and the national survey (Table 2.2).

Table 4.1 Sieving analysis testing results (AIA paving project)

	Sieve No.	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
	Design	100.0	86.0	73.0	52.0	37.0	27.0	20.0	13.0	9.0	5.8
ADOT&PF	A1	100.0	87.0	73.0	51.0	37.0	26.0	19.0	14.0	10.0	7.3
	A2	100.0	83.0	69.0	47.0	33.0	24.0	18.0	13.0	10.0	6.9
	A3	100.0	84.0	69.0	47.0	34.0	25.0	18.0	13.0	10.0	7.2
	A4	100.0	85.0	72.0	49.0	35.0	25.0	19.0	14.0	10.0	7.3
	Mean	100.0	84.8	70.8	48.5	34.8	25.0	18.5	13.5	10.0	7.2
	STDEV	0.0	1.7	2.1	1.9	1.7	0.8	0.6	0.6	0.0	0.2
QAP	A1	100.0	84.2	72.5	49.9	35.7	25.8	19.0	13.2	9.4	6.8
	A3	100.0	83.5	70.1	47.9	33.9	24.5	18.2	12.9	9.5	7.1
	A4	100.0	85.2	71.8	49.0	34.5	24.9	18.4	13.0	9.4	6.8
	Mean	100.0	84.3	71.5	48.9	34.7	25.1	18.5	13.0	9.4	6.9
	STDEV	0.0	0.9	1.2	1.0	0.9	0.7	0.4	0.2	0.1	0.2
UAF	A1	100.0	86.6	71.4	48.6	34.6	26.0	18.9	12.7	9.3	6.8
	A2	100.0	81.6	65.8	43.4	30.7	23.3	17.3	12.3	8.9	6.5
	A3	100.0	83.9	68.6	46.3	32.7	24.3	17.6	12.5	9.2	6.7
	A4	100.0	85.4	70.1	47.4	33.0	24.3	17.6	12.6	9.1	6.5
	Mean	100.0	84.4	69.0	46.4	32.7	24.5	17.8	12.5	9.1	6.6
	STDEV	0.0	2.2	2.4	2.2	1.6	1.1	0.7	0.2	0.2	0.2

The mean percentage passing at each sieve size was plotted in a gradation chart with JMF and the corresponding upper and lower limits (Figure 4.1). Note that the testing results from all three operators were similar to each other. The gradation curves of ADOT&PF and contractor testing results almost overlapped. Generally, the gradation curve of field HMA was lower than JMF in the range from sieve sizes #8 and ½″, which meant the HMA contained more coarse aggregate.

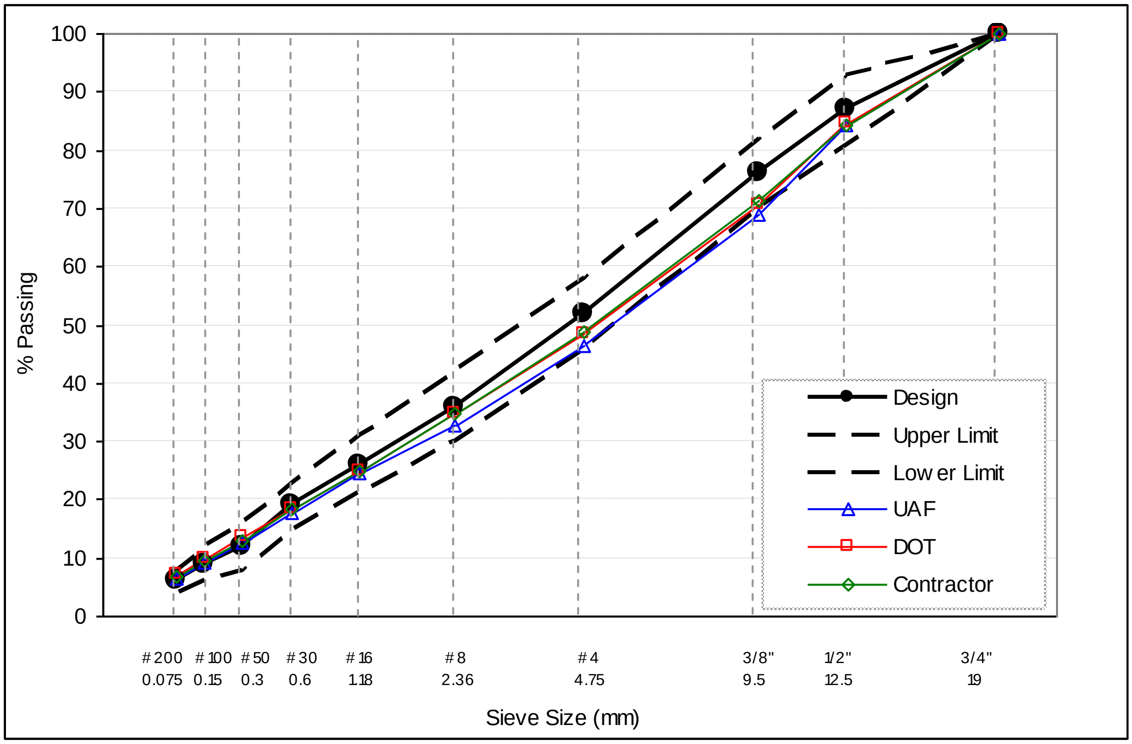


Figure 4.1 Gradation chart of AIA paving project

The sieving analysis results of the Nenana paving project are summarized in Table 4.2. The acceptance tests and third party tests conducted by UAF were performed on 9 sublots of HMA. The contractor performed sieving analysis on 3 of the 9 HMA sublots during the quality control process. The ratio between frequency of acceptance and quality control tests was 3:1. This ratio was between 1:1 and 1:10 (Table 2.1), similar to findings of Mohammad and Elseifi (2010).

The averaged gradation curves are plotted in Figure 4.2. The measurements from ADOT&PF (in figures and tables, also shown as DOT or AKDOT) almost overlap on the JMF. However, measurements from the contractor and UAF were quite different from the JMF, and the curves from these two operators deviated to opposite sides of the JMF. The results from the contractor indicated that the field mix contained more fine aggregate than the JMF, while the results from UAF indicated that the mix contained more coarse aggregate. The UAF testing results on sublots 8 and 9 show extremely low fines contents (passing #200 sieve), which might be due to material segregation during long distance shipping and material handling.

The testing results of binder contents are summarized in Figure 4.3. Generally, the measurements from all three operators were consistent.

Table 4.2 Sieving analysis testing results (Nenana paving project)

Operator	Design	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
		100.0	86.0	73.0	52.0	37.0	27.0	20.0	13.0	9.0	5.8
ADOT&PF	N1	100.0	88.0	72.0	51.0	36.0	26.0	19.0	12.0	8.0	5.1
	N2	100.0	83.0	71.0	52.0	37.0	27.0	19.0	12.0	8.0	5.4
	N3	100.0	86.0	73.0	53.0	37.0	27.0	19.0	12.0	8.0	5.5
	N4	100.0	87.0	72.0	52.0	36.0	26.0	18.0	12.0	8.0	5.2
	N5	100.0	86.0	72.0	51.0	36.0	26.0	19.0	12.0	8.0	5.5
	N6	100.0	89.0	74.0	52.0	37.0	27.0	20.0	13.0	8.0	5.7
	N7	100.0	87.0	72.0	50.0	35.0	25.0	18.0	11.0	7.0	5.0
	N8	100.0	87.0	73.0	51.0	35.0	25.0	18.0	12.0	8.0	5.2
	N9	100.0	87.0	73.0	53.0	37.0	27.0	19.0	12.0	8.0	5.3
	Mean	100.0	86.7	72.4	51.7	36.2	26.2	18.8	12.0	7.9	5.3
	STDEV	0.0	1.7	0.9	1.0	0.8	0.8	0.7	0.5	0.3	0.2
QAP	N1	100.0	82.0	68.3	56.4	49.3	36.1	26.5	19.2	12.0	7.2
	N6	100.0	83.0	66.0	53.0	45.4	32.0	22.6	16.0	9.2	6.0
	N9	100.0	83.0	69.0	54.1	46.1	34.0	24.0	17.1	11.0	7.0
	Mean	100.0	82.7	67.8	54.5	46.9	34.0	24.4	17.4	10.7	6.7
	STDEV	0.0	0.6	1.6	1.7	2.1	2.1	2.0	1.6	1.4	0.6
UAF	N1	100.0	86.9	74.9	51.6	36.2	27.0	17.8	11.0	7.2	4.7
	N2	100.0	85.7	70.0	49.2	34.9	25.8	18.6	11.4	7.4	5.1
	N3	100.0	85.8	70.0	49.5	35.3	25.9	18.7	11.7	7.1	5.4
	N4	100.0	86.2	70.1	49.7	34.9	25.5	18.4	11.7	7.2	5.1
	N5	100.0	85.7	69.4	47.3	32.7	24.7	15.7	11.5	7.3	5.0
	N6	100.0	85.5	68.9	46.9	32.4	25.0	15.8	11.1	6.9	4.8
	N7	100.0	82.6	65.6	38.9	30.8	23.1	17.0	12.0	8.6	6.3
	N8	100.0	81.2	64.7	41.7	28.0	19.4	12.4	7.3	4.0	1.5
	N9	100.0	83.5	65.9	41.2	27.3	19.2	12.5	7.4	4.0	1.4
	Mean	100.0	84.8	68.8	46.2	32.5	24.0	16.3	10.6	6.6	4.4
	STDEV	0.0	1.9	3.1	4.5	3.2	2.9	2.5	1.8	1.6	1.7

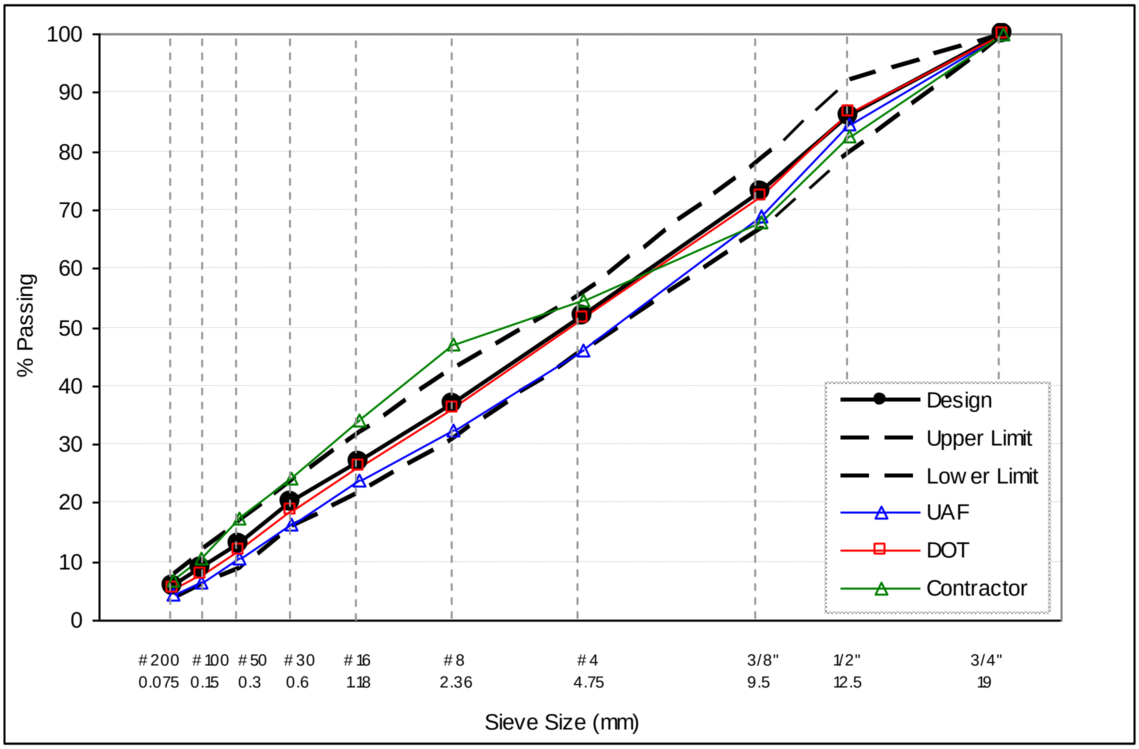


Figure 4.2 Gradation chart of Nenana paving project

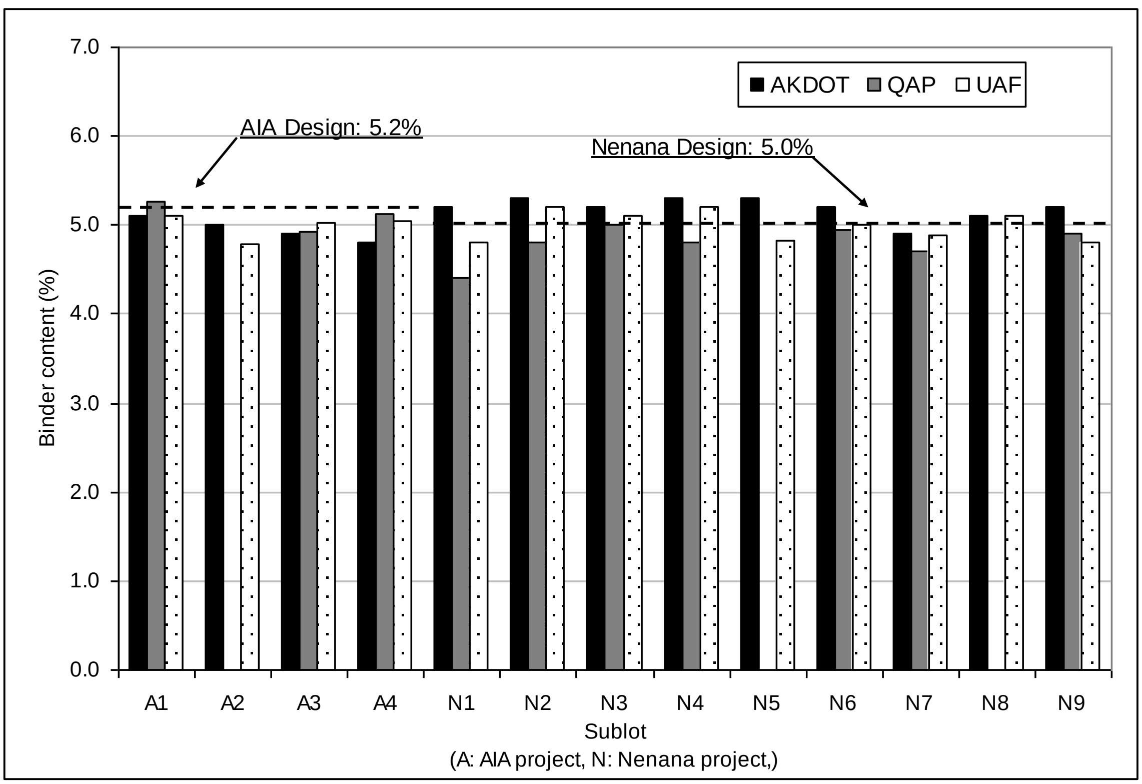


Figure 4.3 Binder content

4.1.2 Analysis of Variance

During the field production of HMA, the material exhibited variability, and this variability changed as production progressed. To identify the changes of variability along the production of HMA, the variances in aggregate gradation were obtained for each sublot by calculating the STDEV of percentage passing at each sieve size. The results are plotted in Figure 4.4. The calculations were based on the testing results conducted by UAF. Due to limited data collection by ADOT&PF and the contractor, their data were not used to check variance.

Figure 4.4 shows that variance changes greatly along sublot numbers and sieve sizes. For coarse aggregate, the STDEV varies between 0.5 and 5.5; generally, the STDEVs of fine aggregate are less than 1. A single-factor ANOVA test was performed at a significance level of 0.05 to evaluate statistically the significance of sublot on the variance of aggregate gradation. The results (Table 4.3) indicate that sublot is a very significant influencing factor for measured gradation variance. The possible sources of this variation include variance of material itself, sampling errors, and measurement errors.

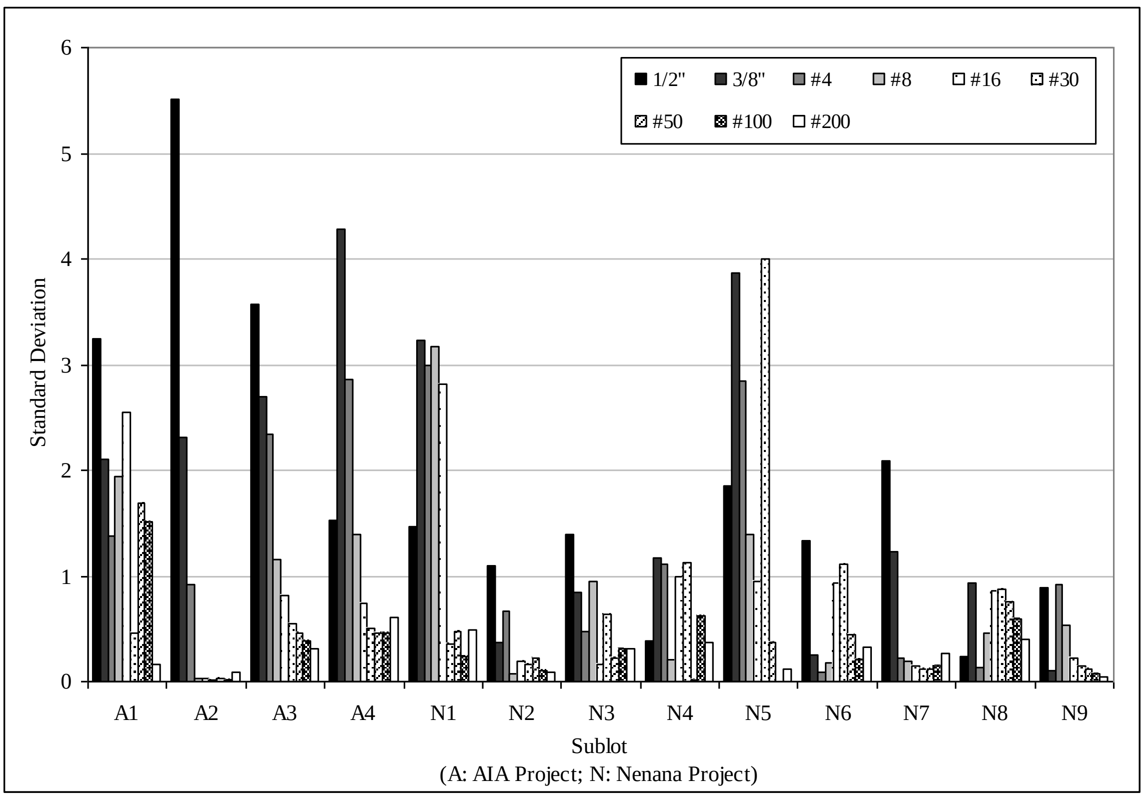


Figure 4.4 Variance of sieving analysis

Table 4.3 Single factor ANOVA analysis

Factor	Significance Level, α	Degrees of Freedom	P-value	Significance
Sublot	0.05	12	0.0090	Significant
Operator	0.05	2	0.0026	Significant

Measurement errors are inevitably introduced during testing. Operators are one of the most important factors relating to measurement error. In this study, the state agency, the contractor, and a third party were the operators. To identify the significance of the operator on the variance of aggregate gradation, the STDEVs of percentage passing were calculated for each sieve size based on overall samples collected from each paving project (AIA paving project: four sublots; Nenana paving project: nine sublots). It can be seen from Figure 4.5 that testing results from UAF always have the highest variance. Further statistical analysis, a single-factor ANOVA, was performed at a significance level of 0.05, and results indicate that the operator is a significant factor for measured variability of field HMA (Table 4.3).

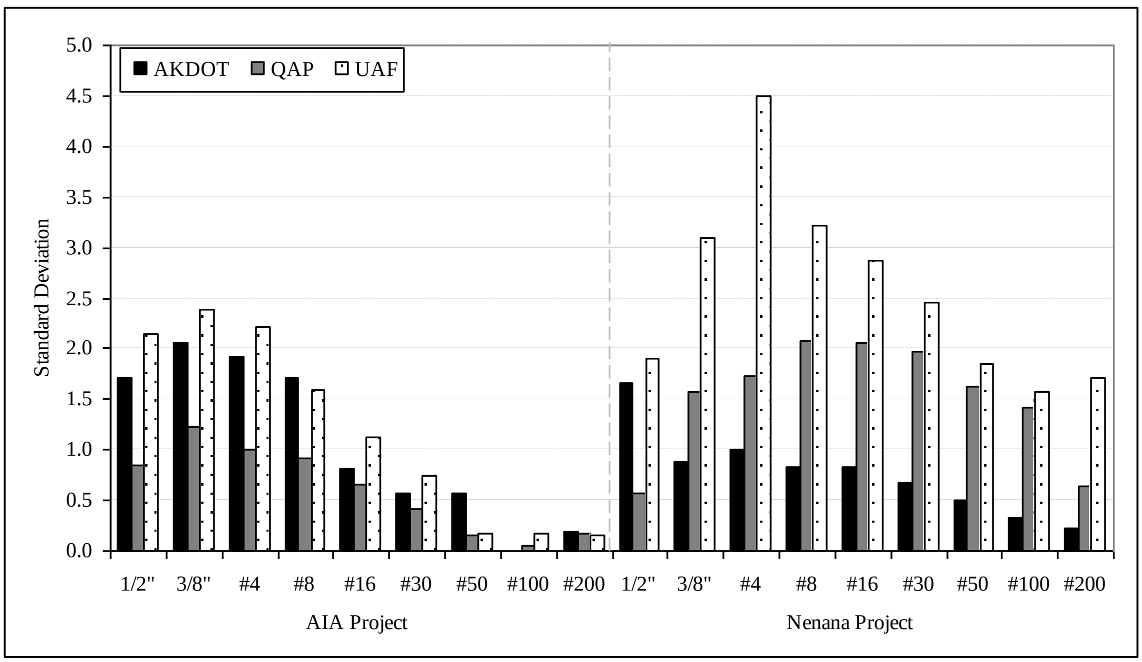


Figure 4.5 Standard deviation of sieving analysis from three operators

Based on UAF testing results, the STDEV of binder content was calculated for each sublot, and the values were found to be between 0.02 and 0.26 (Figure 4.6). The STDEVs were less than 0.2 in 9 of 13 sublots. As listed in Table 2.1, the average STDEV obtained from third party tests was 0.2; the AASHTO recommended limit for the ignition method is 0.21. The variability of binder content observed was within ranges of these typical values.

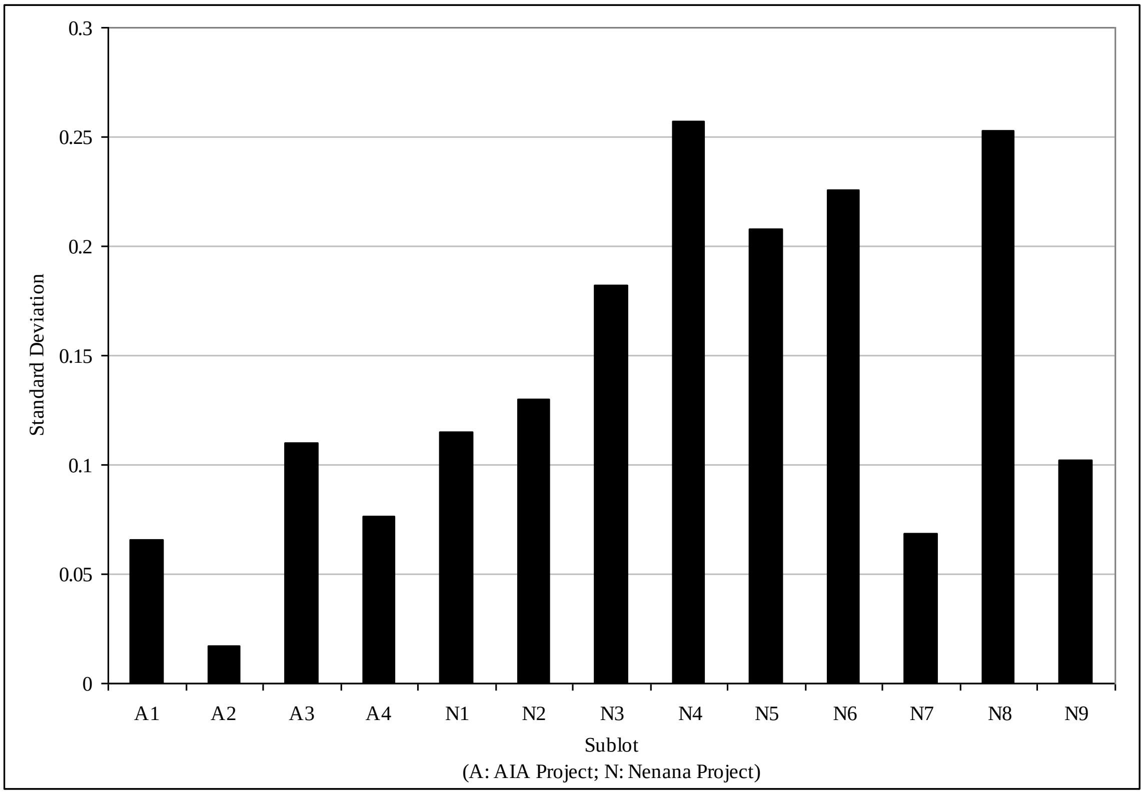


Figure 4.6 Variation of binder content

4.1.3 Analysis of Error

The differences between measured and design (target) values of material properties were quantitatively represented by errors, which is calculated as "$|Value_{measured} - Value_{design}|$." A negative error refers to a measured value that is less than the design value, and a positive error means the measured value is greater than the design value. Figures 4.7 to 4.16 illustrate the errors of percentage passing at each sieve size and the binder content. The errors were calculated based on the testing results from three operators.

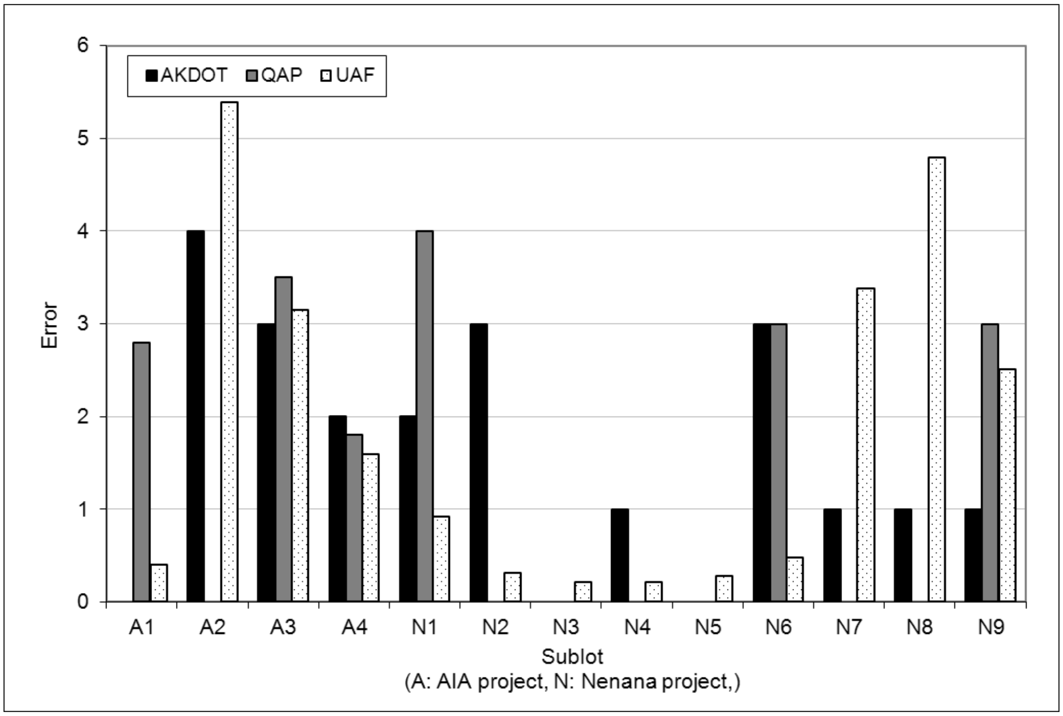


Figure 4.7 Difference between measured and design values (1/2″ sieve)

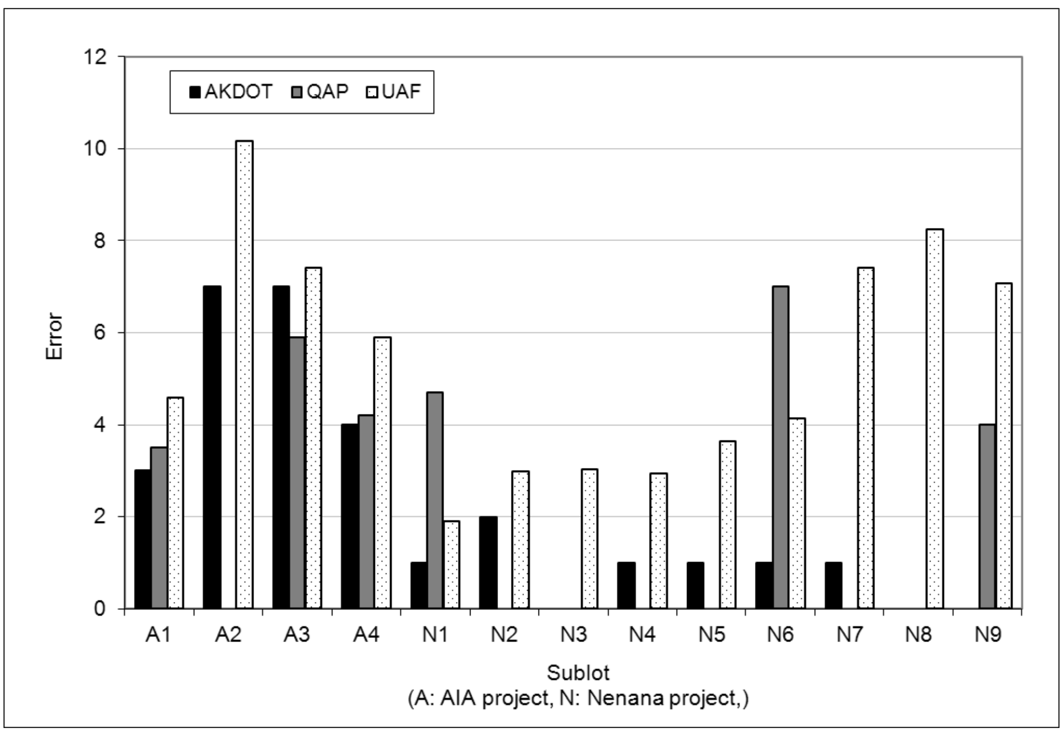


Figure 4.8 Difference between measured and design values (3/8″ sieve)

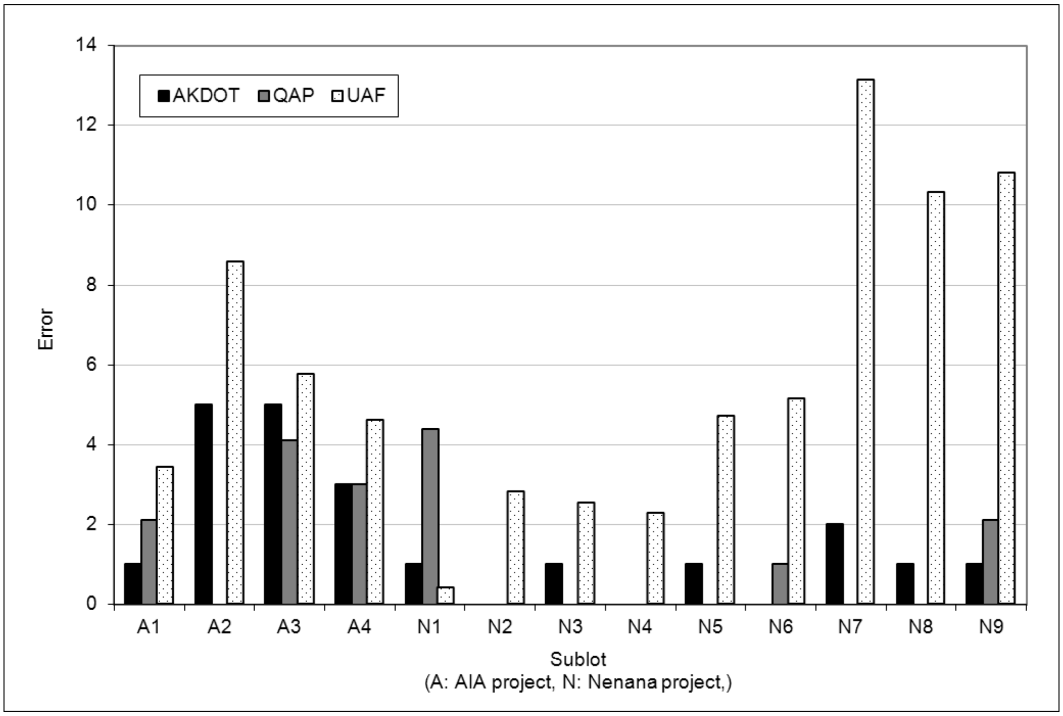


Figure 4.9 Difference between measured and design values (#4 sieve)

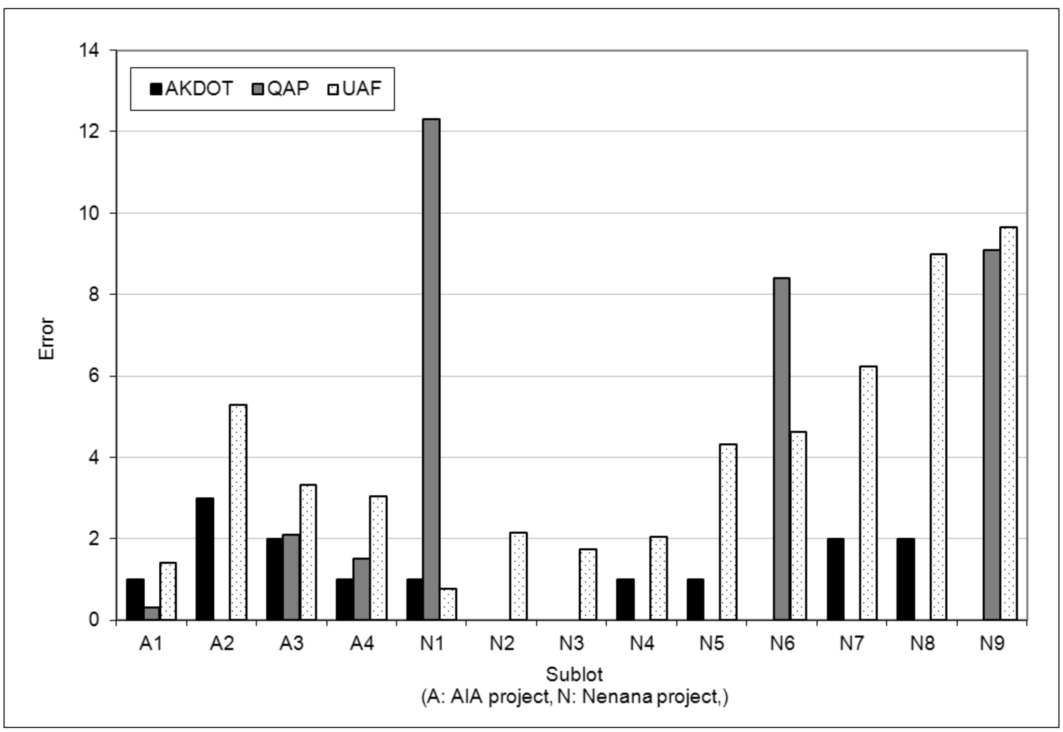


Figure 4.10 Difference between measured and design values (#8 sieve)

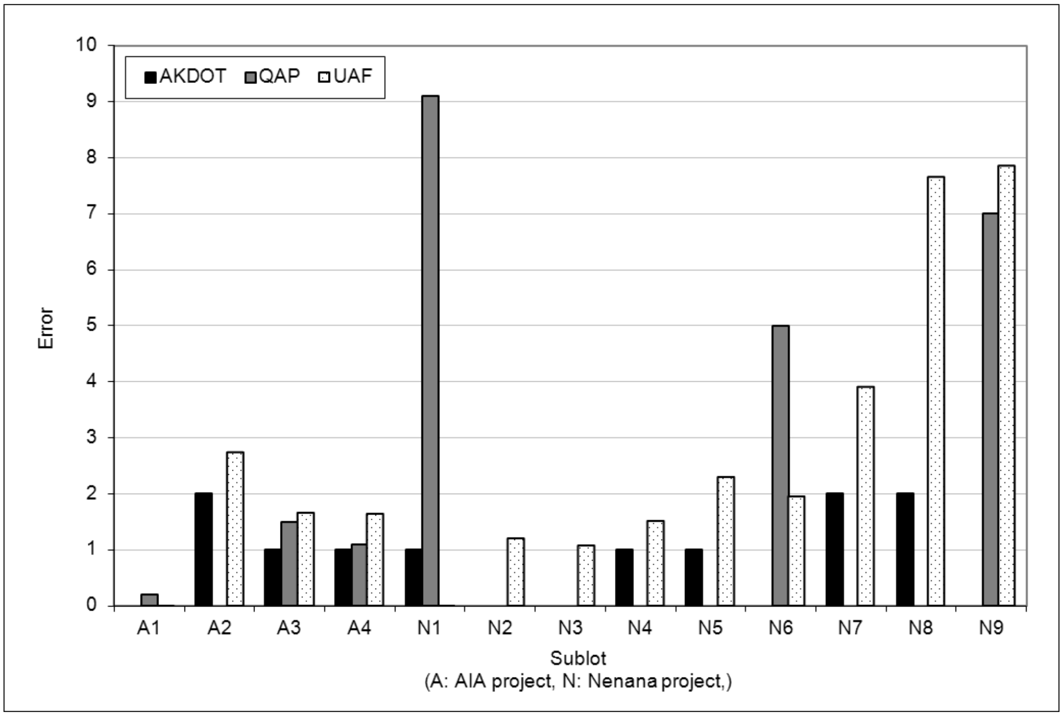


Figure 4.11 Difference between measured and design values (#16 sieve)

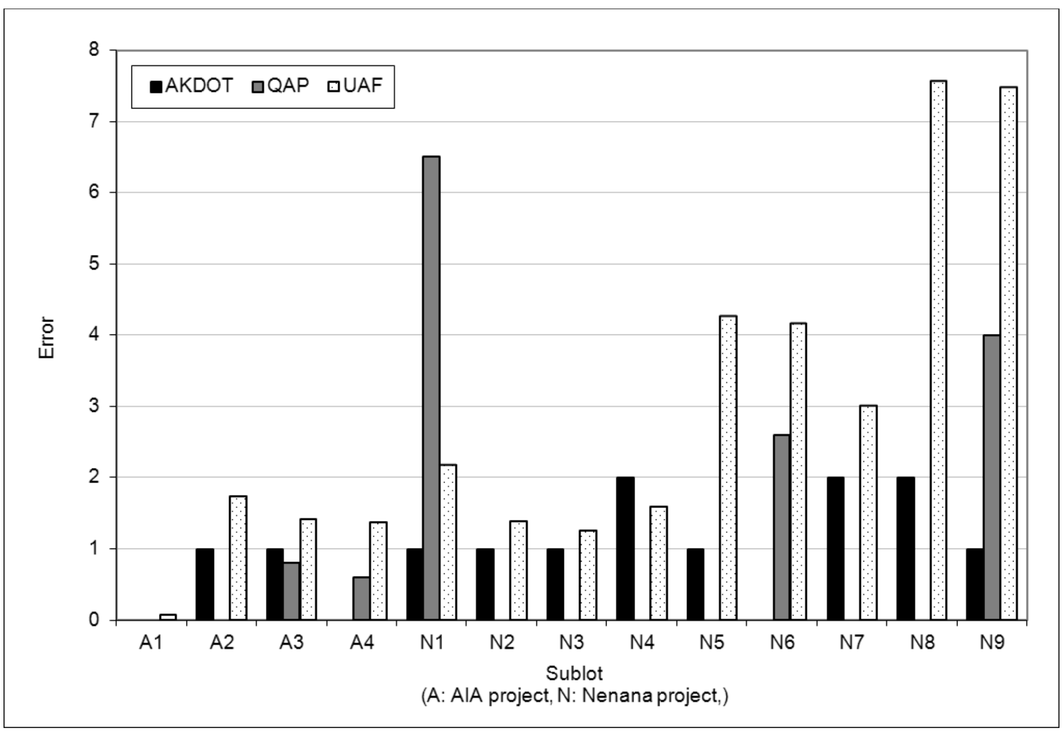


Figure 4.12 Difference between measured and design values (#30 sieve)

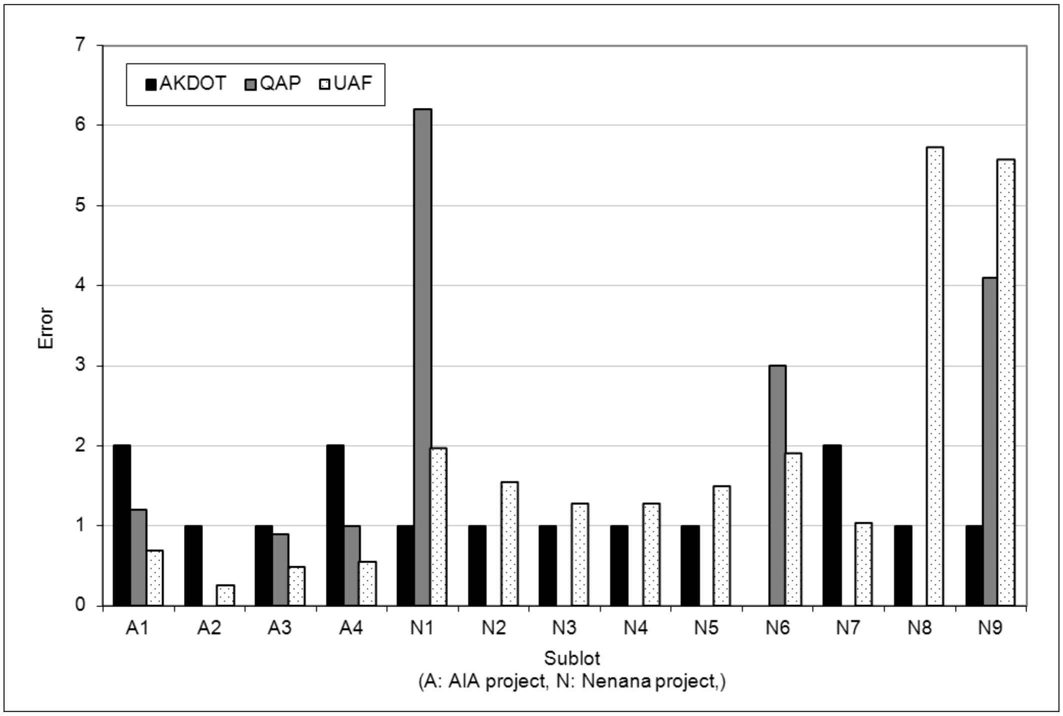


Figure 4.13 Difference between measured and design values (#50 sieve)

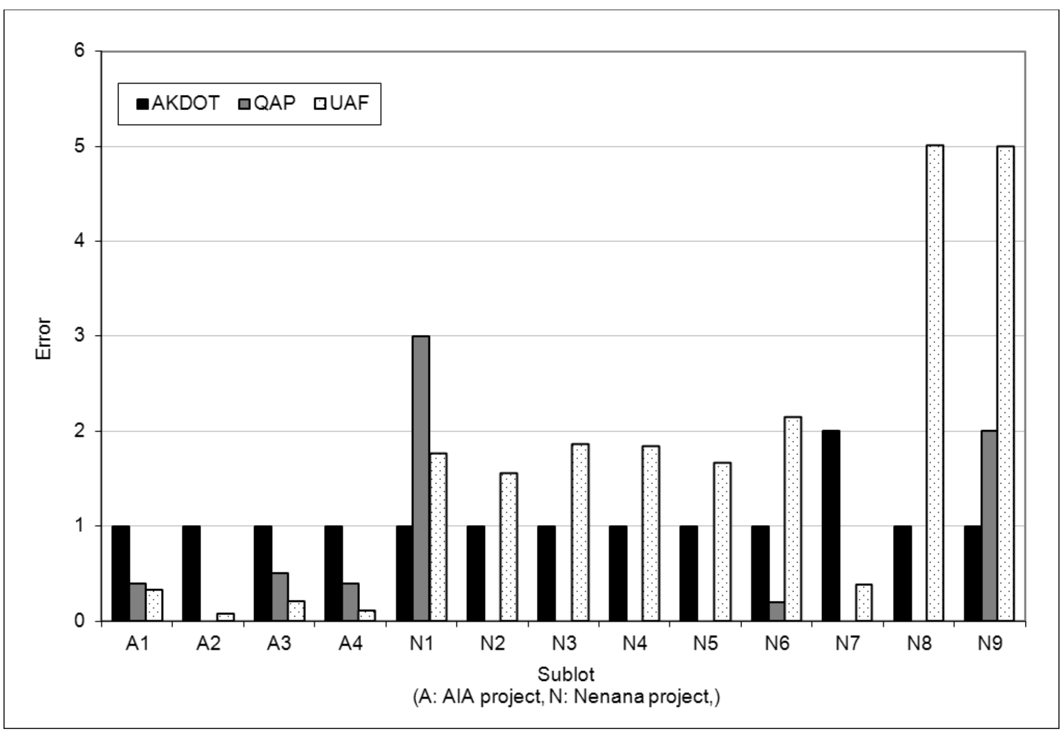


Figure 4.14 Difference between measured and design values (#100 sieve)

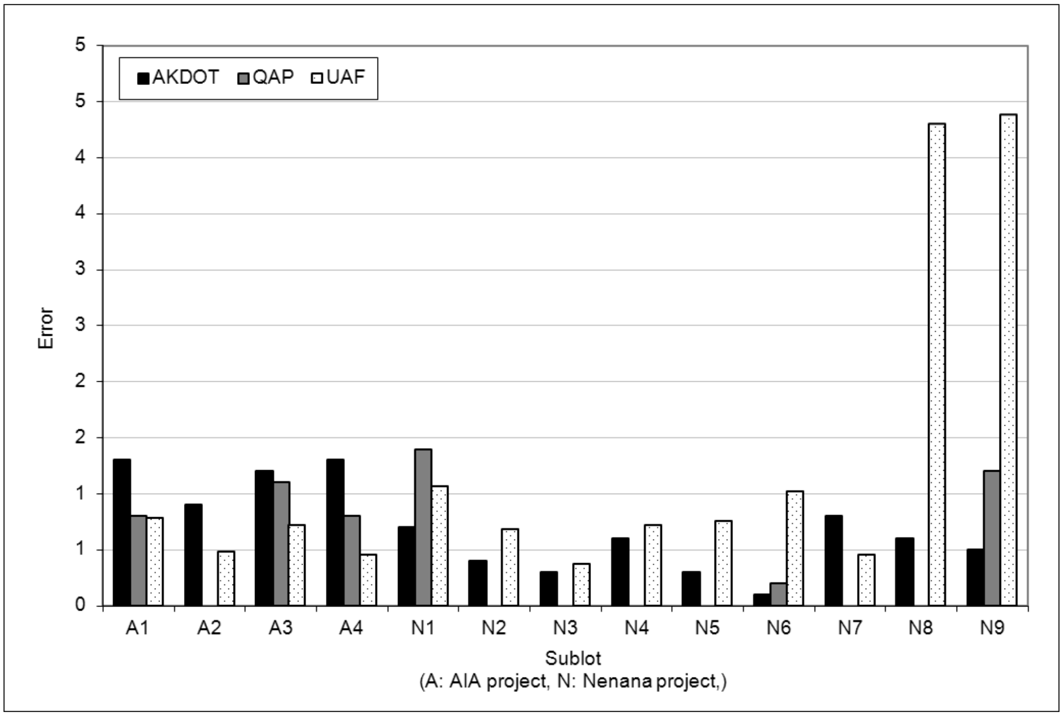


Figure 4.15 Difference between measured and design values (#200 sieve)

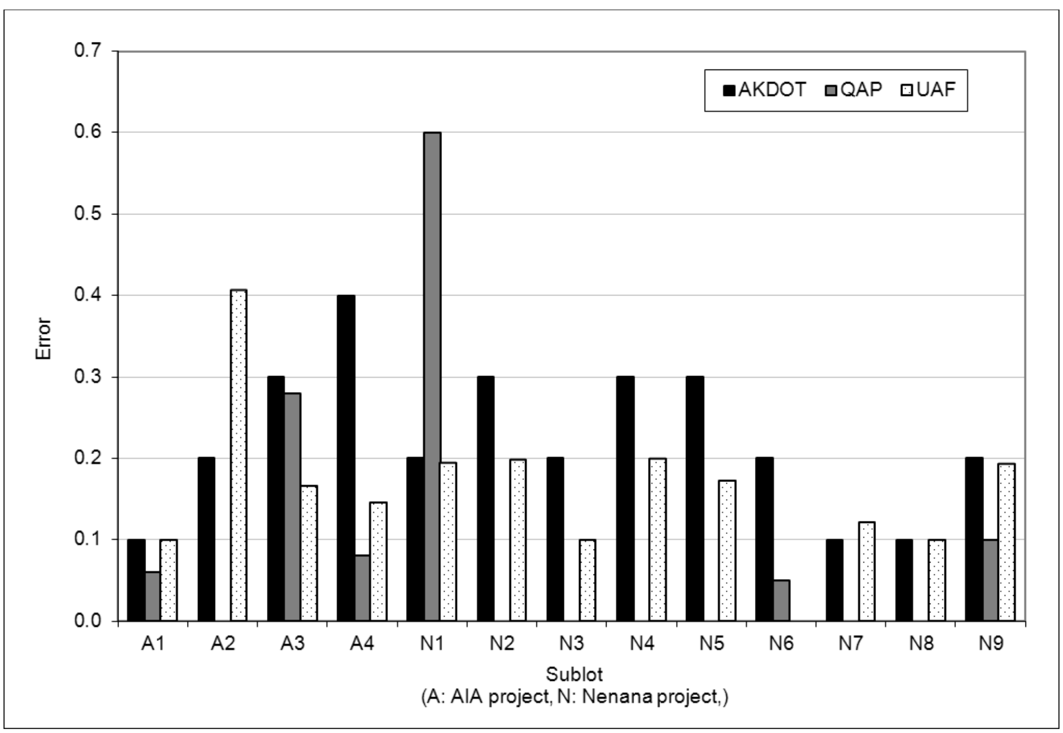


Figure 4.16 Difference between measured and design values (binder content)

Note in these figures that errors of composition properties greatly change along sublot number and that gaps are easily observed between the three operators. The average errors of composition properties are summarized in Table 4.4, which shows that the error of percentage passing obtained from ADOT&PF was lowest, but that the error of binder content for ADOT&PF was highest. The lowest error of binder content was obtained from the contractor, QAP. Note also that errors tended to decrease as sieve size decreased. Sublot, aggregate size, and operator were considered the three primary factors for error in composition properties. The effect of sublot could be interpreted as the errors mainly introduced by construction during the production and delivery of HMA, and the effects of operator were the errors mainly introduced by material testing during sampling, laboratory testing, and measuring of results. Further statistical analyses were performed to determine the significance of these two factors.

Table 4.4 Summary of errors of composition properties among three operators

Composition Properties		Error from Three Operators		
		AKDOT	QAP	UAF
Sieve size	1/2"	1.62	2.59	1.82
	3/8"	2.15	4.19	5.34
	#4	1.62	2.39	5.73
	#8	1.08	4.81	4.13
	#16	0.85	3.41	2.58
	#30	1.00	2.07	2.89
	#50	1.15	2.34	1.83
	#100	1.08	0.93	1.69
	#200	0.69	0.79	1.25
Binder Content		0.22	0.14	0.16

A three-factor ANOVA test was used to examine statistically whether the errors of percentage passing were significantly influenced by sublot and operator. In the analysis, it was assumed that no interaction among the three factors occurred. The results are summarized in Table 4.5. The *P*-values of these three factors are much smaller than the significance level 0.05, which indicates that errors of percentage passing were significantly affected by both sublot and operator. Therefore, based on the results of the statistical analysis, errors observed during the QA/QC process were caused by both construction and material testing.

Table 4.5 Two-factor ANOVA for error of gradation ($\alpha = 0.05$)

Factor	Degrees of Freedom	P-value	Significance
Sublot	12	9.68E-10	Significant
Sieve size	8	<2.20E-16	Significant
Operator	2	8.73E-15	Significant

A two-factor ANOVA test was also applied for errors of binder content, considering the factors of sublot and operator. Any interaction between sublot and operator was ignored as well. The analysis shows that neither of these two factors is significant.

Table 4.6 Two-factor ANOVA for error of binder content ($\alpha = 0.05$)

Factor	Degrees of Freedom	P-value	Significance
Sublot	12	0.2014	Not Significant
Operator	2	0.2892	Not Significant

4.2 Volumetric Properties

The volumetric properties presented in this section include VTM, VMA, and VFA. The results were collected from four testing scenarios: L&L, F&L, F&F, and field cores. The same analysis approach used for composition properties was used for the analysis of variance and error, considering factors such as sublot and scenario.

4.2.1 Testing Result

The testing results of VTM, VMA, and VFA from four scenarios are summarized in Figures 4.17 to 4.19. In these figures, the horizontal axis represents the sublot number, and the vertical axis represents the volumetric properties. In sum, samples were collected from 13 sublots, including 4 sublots from the AIA paving project marked through A1 to A4 and 9 sublots from the Nenana paving project marked through N1 to N9. Each sublot contains three data series representing F&F, F&L, and field core scenarios.

The sublot number could not be applied to L&L scenarios. Therefore, values of L&L samples were plotted along with 13 sublot samples and marked A_L&L and N_L&L for the AIA and Nenana paving projects, respectively. For the AIA paving project, L&L specimens were compacted according to the designed number of gyrations, and the differences between L&L and design values represented by the dotted line were found to be significant.

Due to different compaction methods used by JMF design and this research project, the number of gyrations applied to the Nenana loose mixture was set at the value at which the SGC compactor produced same VTM as the JMF. Therefore, the volumetric properties of the Nenana project in the L&L scenarios are the same as the design values. Variances of testing results are also illustrated in these figures with a variation bar. The half-length of the variation bar equals one STDEV.

Since field compaction effort is usually less than Superpave gyratory compaction and more influencing factors would be encountered in field construction, the field cores had the highest VTM and VMA. The L&L specimens showed the lowest values for these properties. For VFA, the ranking of field cores in the L&L scenario is reversed. The volumetric properties of

F&L and F&F scenarios are similar to each other and between the values of field cores and L&L. Generally, the differences of volumetric properties between sublots are less obvious then the differences between scenarios. Further statistical tests were applied to VTM, VMA, and VFA data to examine the influence on variance and error caused by sublot and scenario.

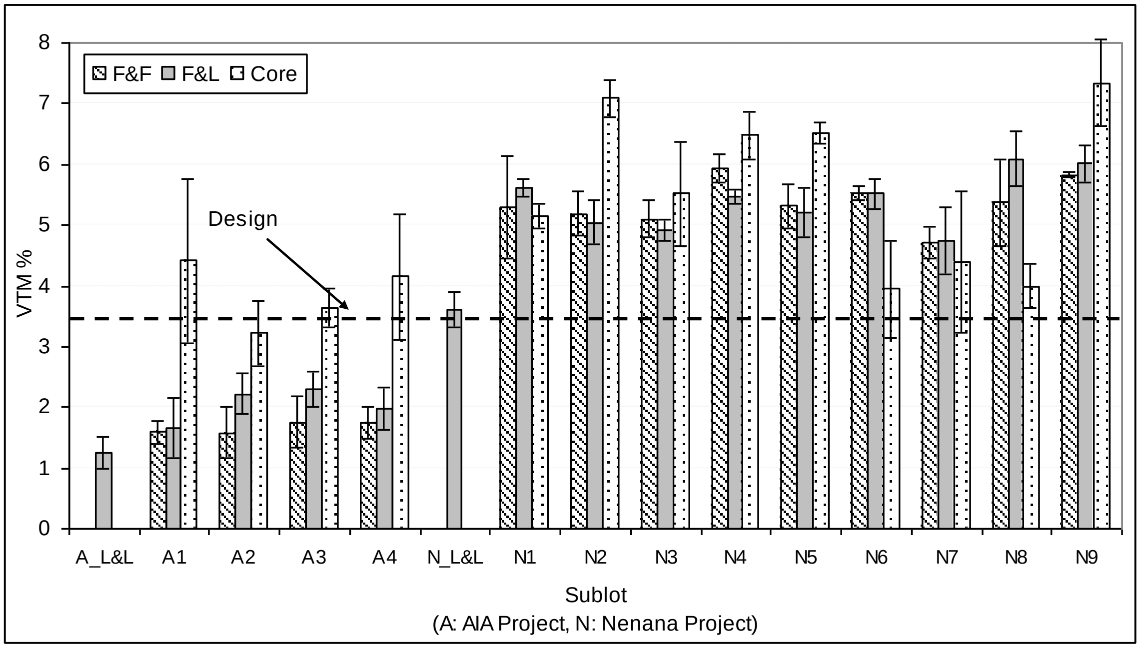


Figure 4.17 Summary of percent air voids of total mix

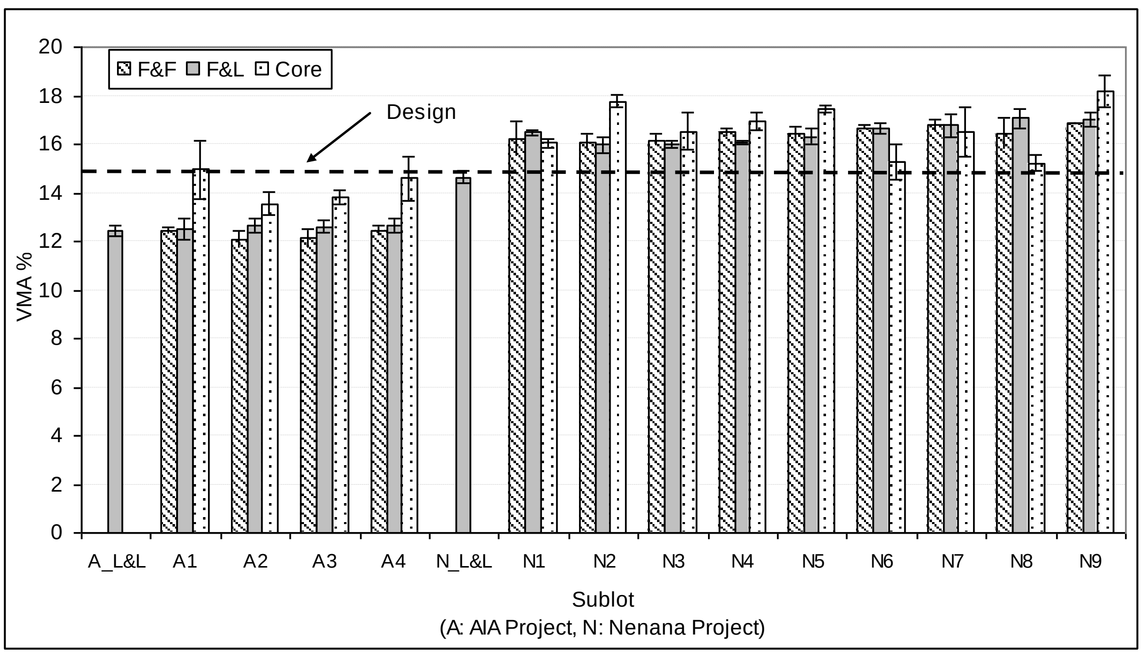


Figure 4.18 Summary of percent void in mineral aggregate

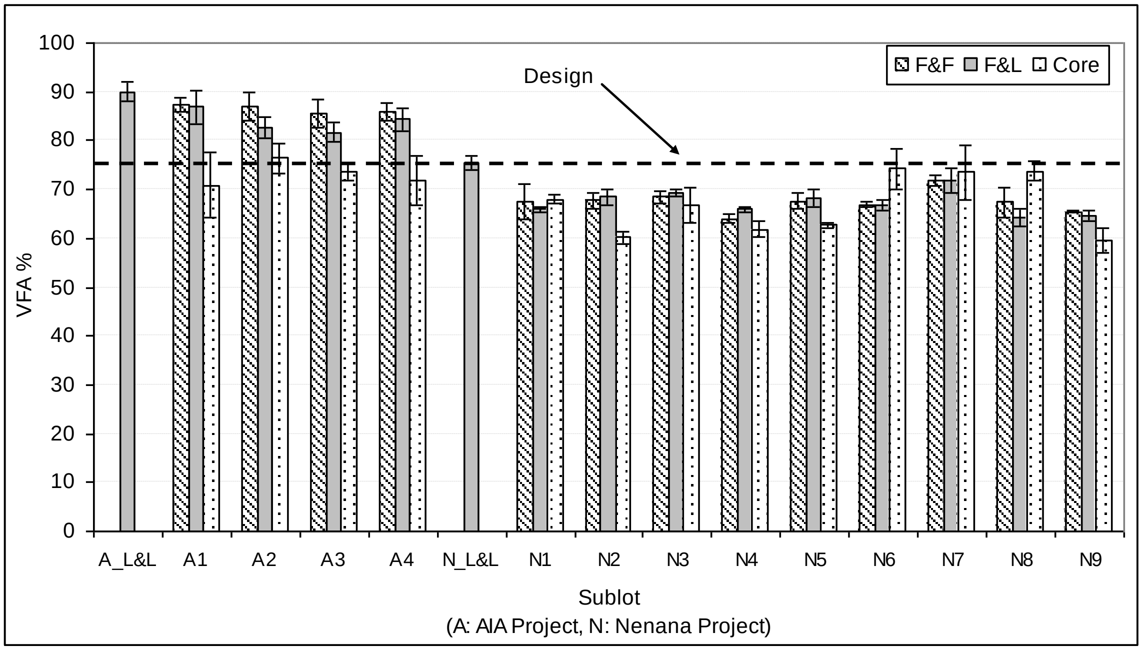


Figure 4.19 Summary of percent voids filled with asphalt binder

4.2.2 Analysis of Variance

The variances of volumetric properties determined from three scenarios are summarized in Figures 4.20 to 4.22. Since more influencing factors are involved in field construction than in laboratory specimen fabrication, the field cores always had the highest STDEV among the three scenarios.

The variances determined from the F&L and F&F scenarios are close to each other. The primary difference between these two scenarios was that no reheating and fewer disturbances were applied to F&F samples. Based on data analysis, these processes did not introduce significant variance to the volumetric properties. Generally, the variances of volumetric properties observed were lower than the STDEV limits suggested by AASHTO R42 (Table 2.3). The highest STDEVs of VTM and VMA were 1.4 and 1.2, respectively. The AASHTO recommended limit for VTM and VMA is 1.6. The highest STDEV of VFA was 6.7 in these two projects; the AASHTO recommended limit is 8.

A two-factor ANOVA was performed at a significance level of 0.05. The results (Table 4.7) indicate that scenario is a significant factor for measured variability of field HMA, but that sublot is not a significant factor.

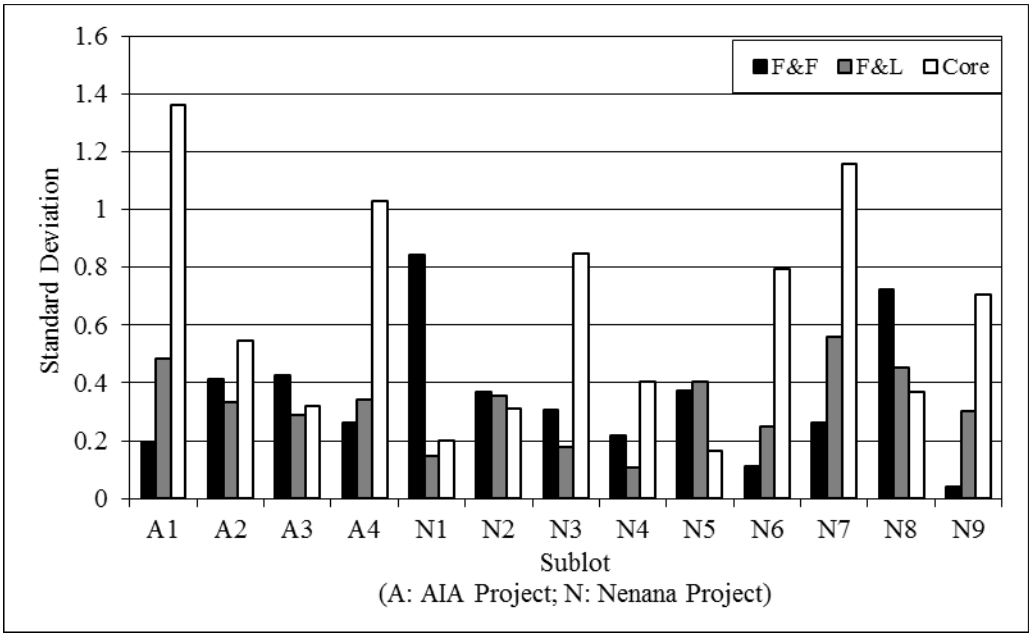


Figure 4.20 Standard deviation of VTM from three scenarios

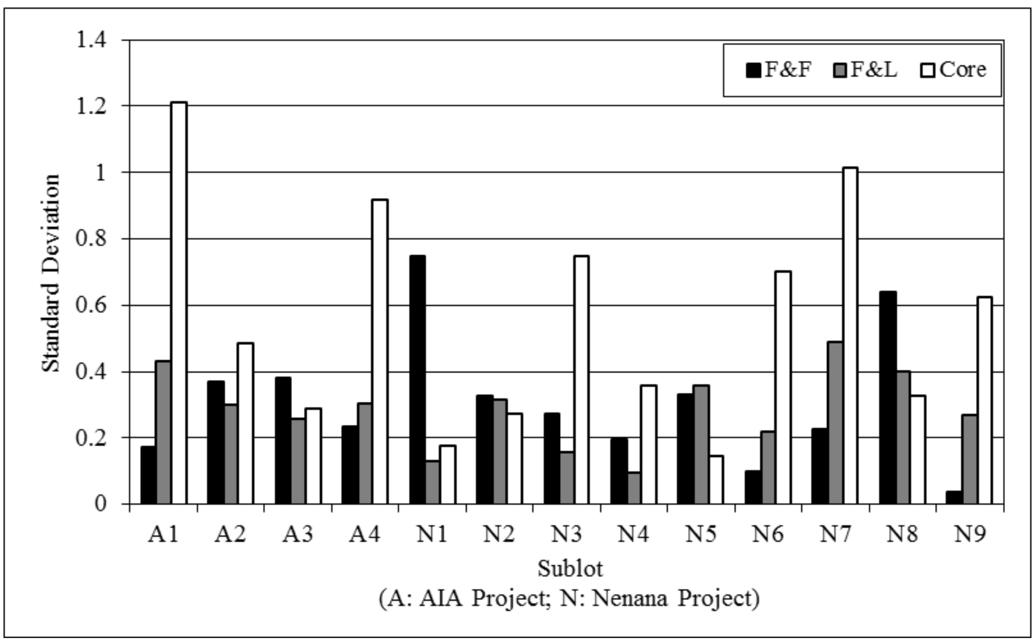


Figure 4.21 Standard deviation of VMA from three scenarios

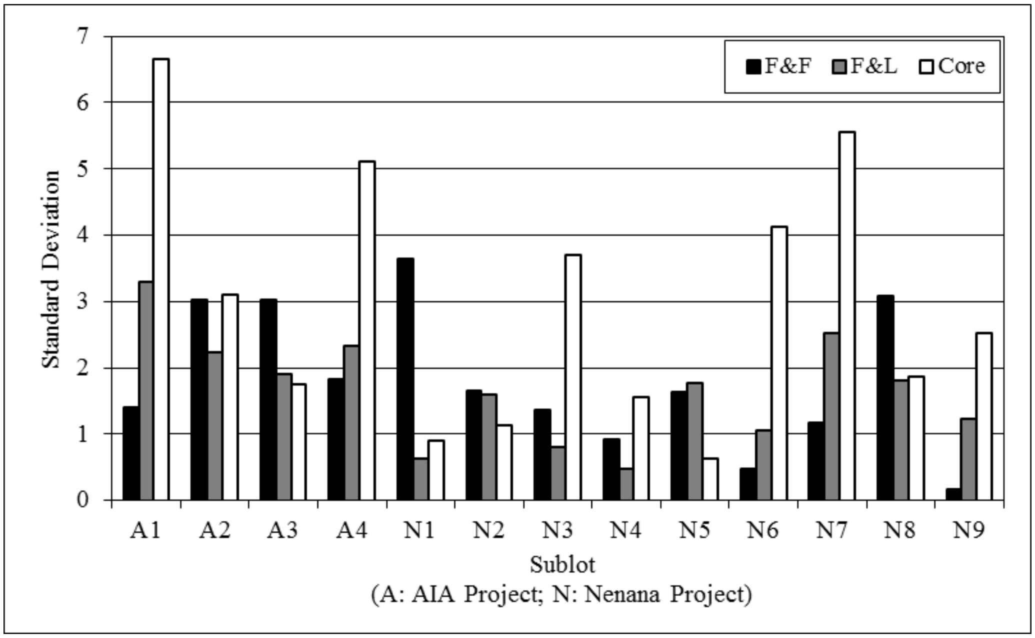


Figure 4.22 Standard deviation of VFA from three scenarios

Table 4.7 Multi-factor ANOVA for variance of volumetric properties

Properties	Factor	Degrees of Freedom	P-value	Significance
VTM	Sublot	12	0.796384	Not Significant
	Scenario	2	0.020336	Significant
VMA	Sublot	12	0.800627	Not Significant
	Scenario	2	0.020306	Significant
VFA	Sublot	12	0.340702	Not Significant
	Scenario	2	0.034847	Significant

4.2.3 Analysis of Error

The errors of volumetric properties (i.e., VTM, VMA, and VFA) are illustrated in Figures 4.23 to 4.25. In these figures, the vertical axis represents absolute error, which is the difference between measured volumetric property and design value. The horizontal axis represents sublot number. Each figure contains three data series: F&L, F&F, and cores.

Note that error varies significantly among sublots. The effect of sublot represents the errors introduced during material production and delivery. Errors also changed among scenarios. As suggested by Mohammad et al. (2004), changes in volumetric properties during field construction may be attributed to mixture composition properties and to non-homogeneous paving and compaction.

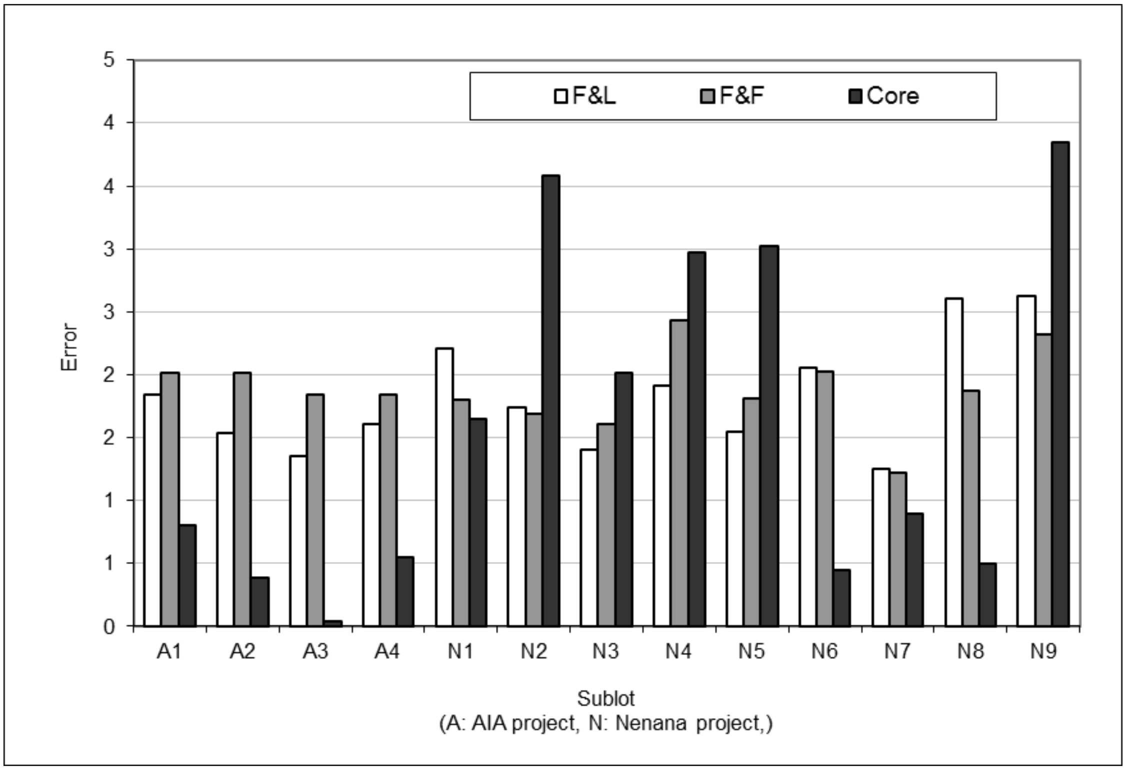


Figure 4.23 Difference between measured and design values (VTM)

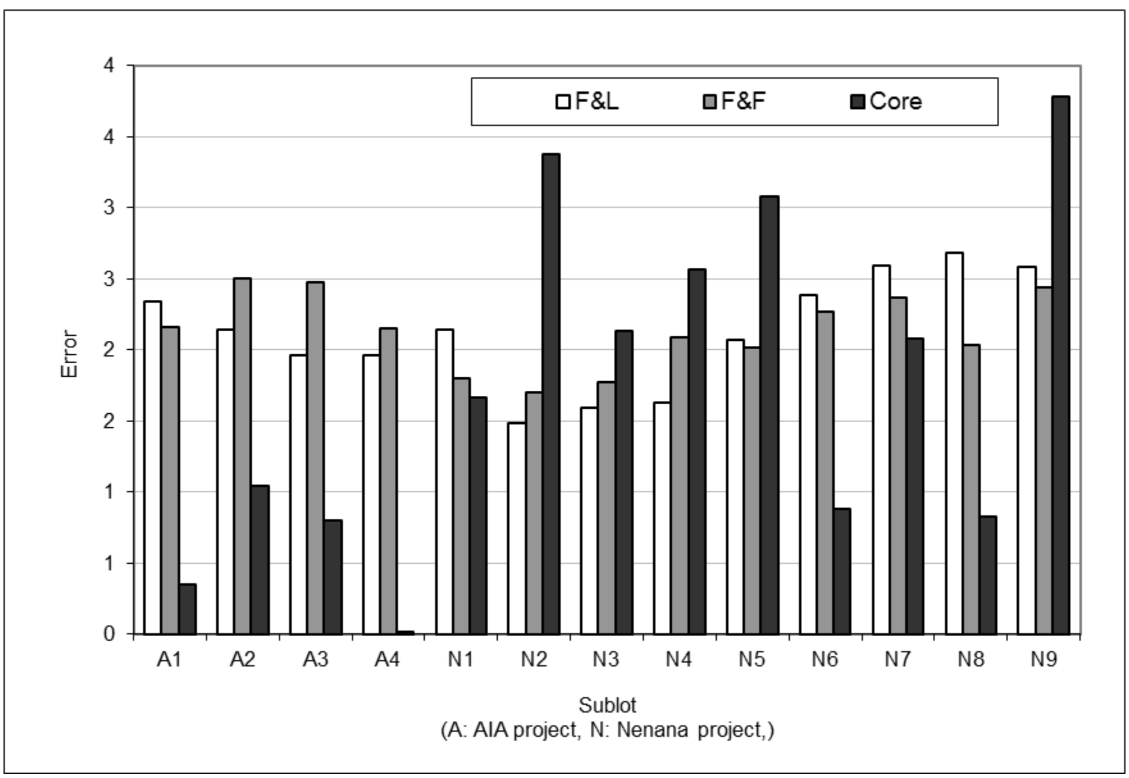


Figure 4.24 Difference between measured and design values (VMA)

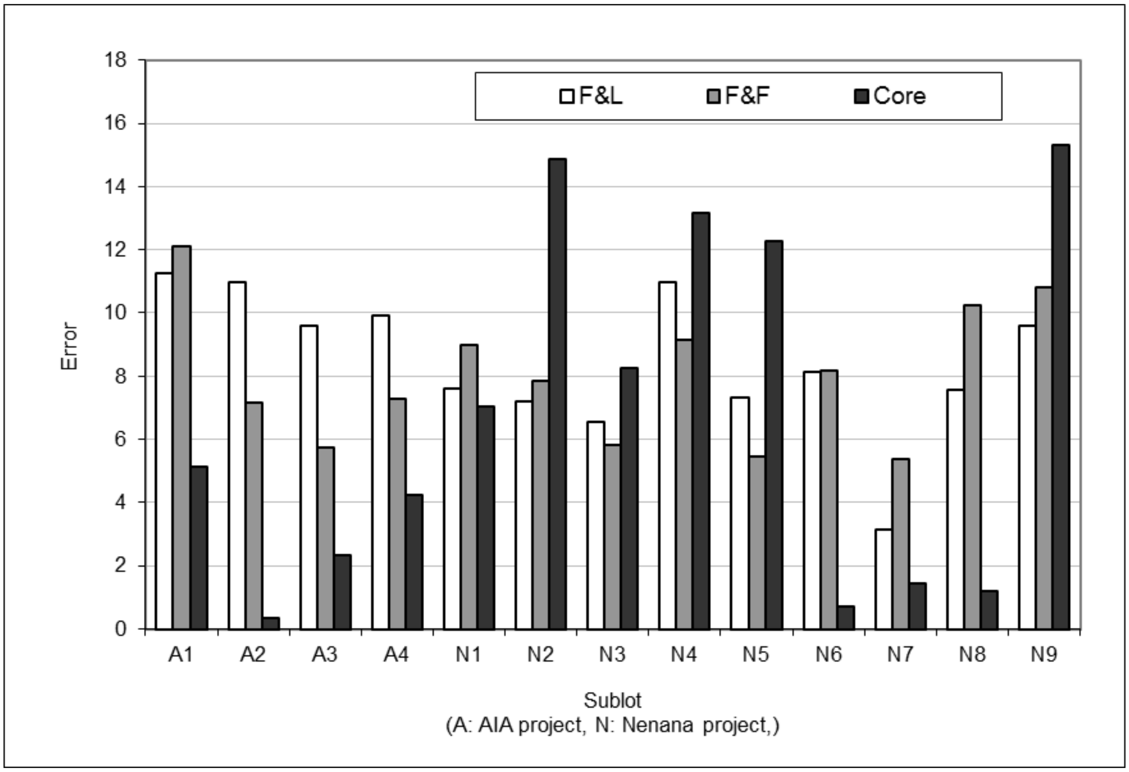


Figure 4.25 Difference between measured and design values (VFA)

Table 4.8 Summary of error of volumetric properties

Volumetrics	Scenarios PF	Scenarios PL	Scenarios Cores
VTM	1.88	1.82	1.59
VMA	2.14	2.12	1.74
VFA	8.45	8.01	6.63

Two-factor ANOVA tests were conducted to examine the effects of scenario and sublot on errors of volumetric properties. The *P*-values ($\alpha = 0.05$) of the two factors for VTM, VMA, and VFA are summarized in Table 4.9. The analysis indicated that neither sublot nor scenario were significant factors for volumetric properties.

Table 4.9 Two-factor ANOVA for error of volumetric properties

Properties	**Factor**	**Degrees of Freedom**	**P-value**	**Significance**
VTM	Sublot	12	0.1702	Not Significant
	Scenario	2	0.5997	Not Significant
VMA	Sublot	12	0.6627	Not Significant
	Scenario	2	0.3526	Not Significant
VFA	Sublot	12	0.2058	Not Significant
	Scenario	2	0.3899	Not Significant

4.3 Mechanical Properties

The mechanical properties presented here include │E*│, maximum strains at end of flow number, flow time test, creep stiffness, and indirect tensile strength (ITS). Instead of flow time and flow number, the maximum strains at the end of flow number and flow time tests were used in the analysis. Due to the confining pressure applied during flow testing, most specimens did not fail after 10,000 loading cycles, and some did not even pass the second zone of deformation. Therefore, the flow time or flow number values automatically calculated based on the machine built-in algorithm were meaningless. Dynamic modulus and flow tests were performed on specimens made from F&L and L&L scenarios. Indirect tensile tests were performed on specimens made from all four scenarios to measure creep stiffness and ITS. The mechanical properties measured on L&L specimens were used as target values during errors analysis.

4.3.1 Dynamic Modulus

4.3.1.1 Testing Results

Dynamic modulus tests were performed at four temperatures (4°C, 21°C, 37°C, and 54°C) and eight loading frequencies (25 Hz, 20 Hz, 10 Hz, 5 Hz, 2 Hz, 1 Hz, 0.5 Hz, and 0.1 Hz) on material from 14 sublots collected from two paving projects. The testing results are summarized in Figures 4.26 to 4.29. As illustrated in these figures, testing temperature and loading frequency greatly affected the │E*│ of HMA. Higher │E*│ values were measured at lower temperatures and higher loading frequencies. At 4°C, the │E*│ was over 16,000 MPa at loading frequencies of 25 Hz and 20 Hz; at 54°C, the │E*│ was as low as 50 MPa at a loading frequency of 0.1 Hz. Measured │E*│ exhibits great variability among sublots.

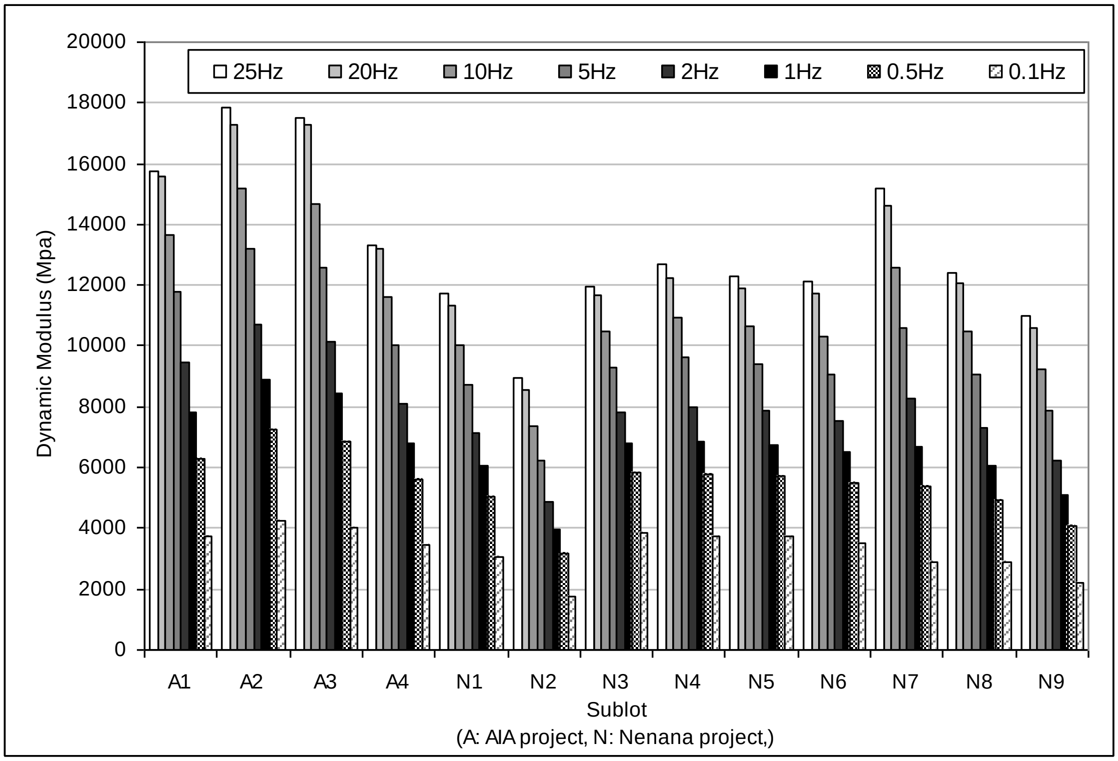


Figure 4.26 │E*│at 4°C

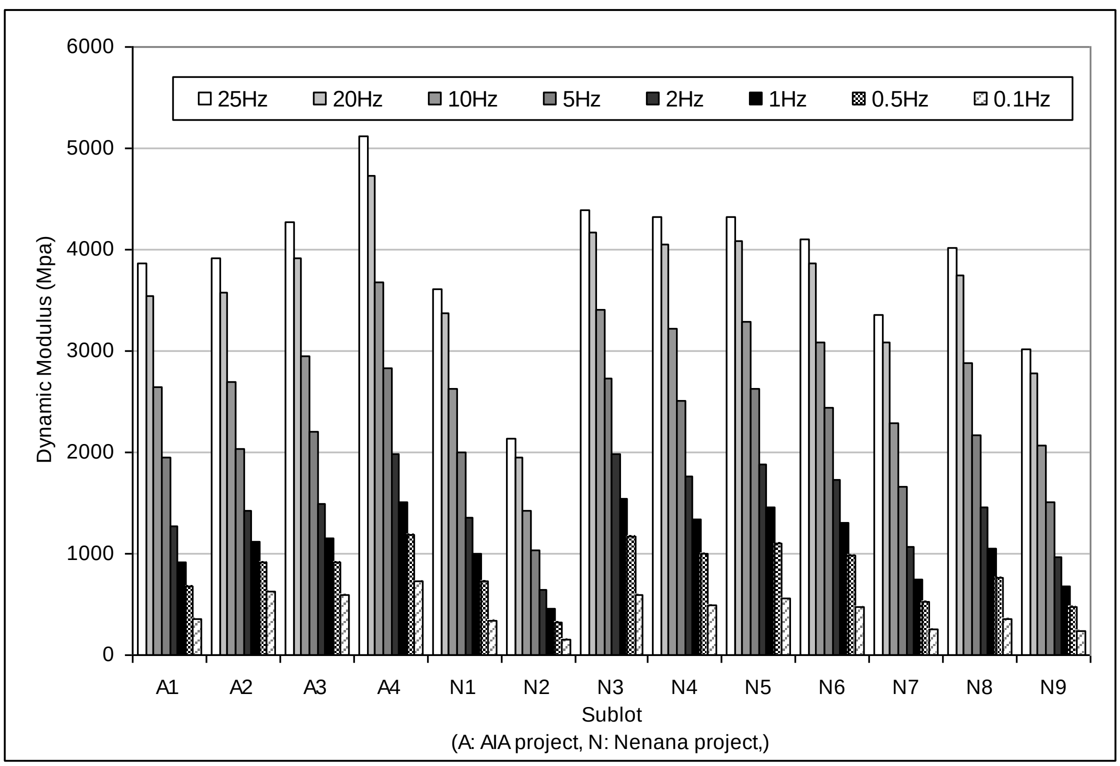


Figure 4.27 │E*│at 21°C

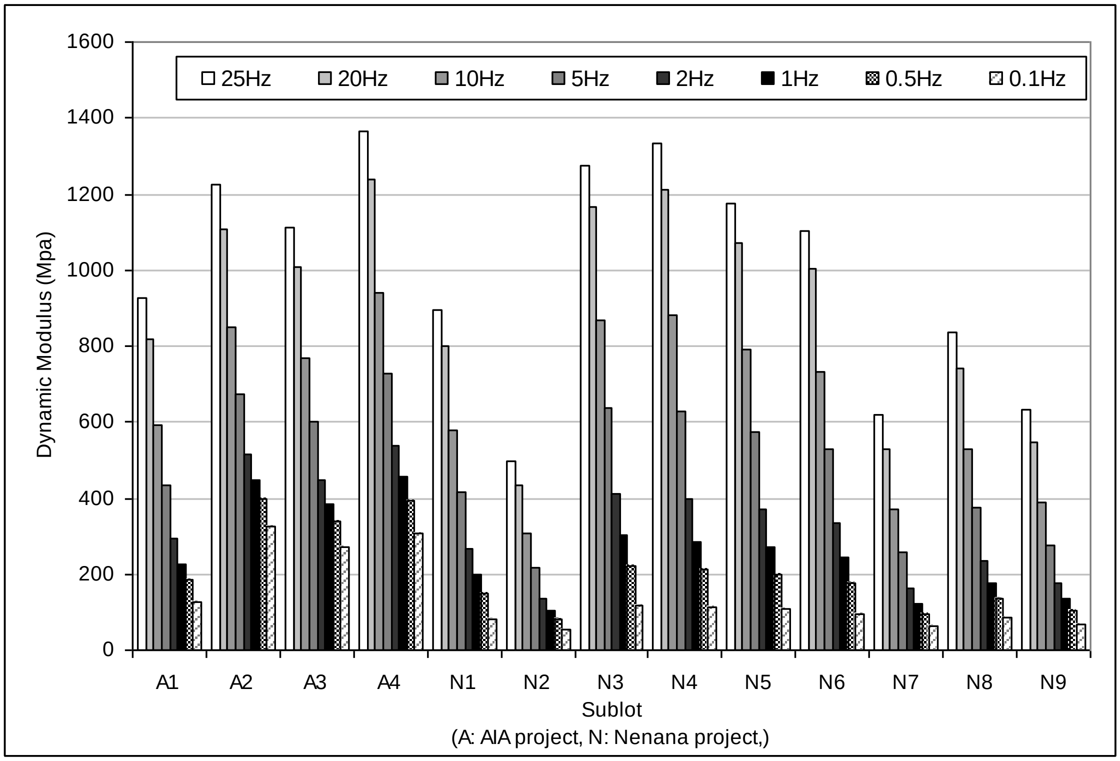


Figure 4.28 |E*| at 37°C

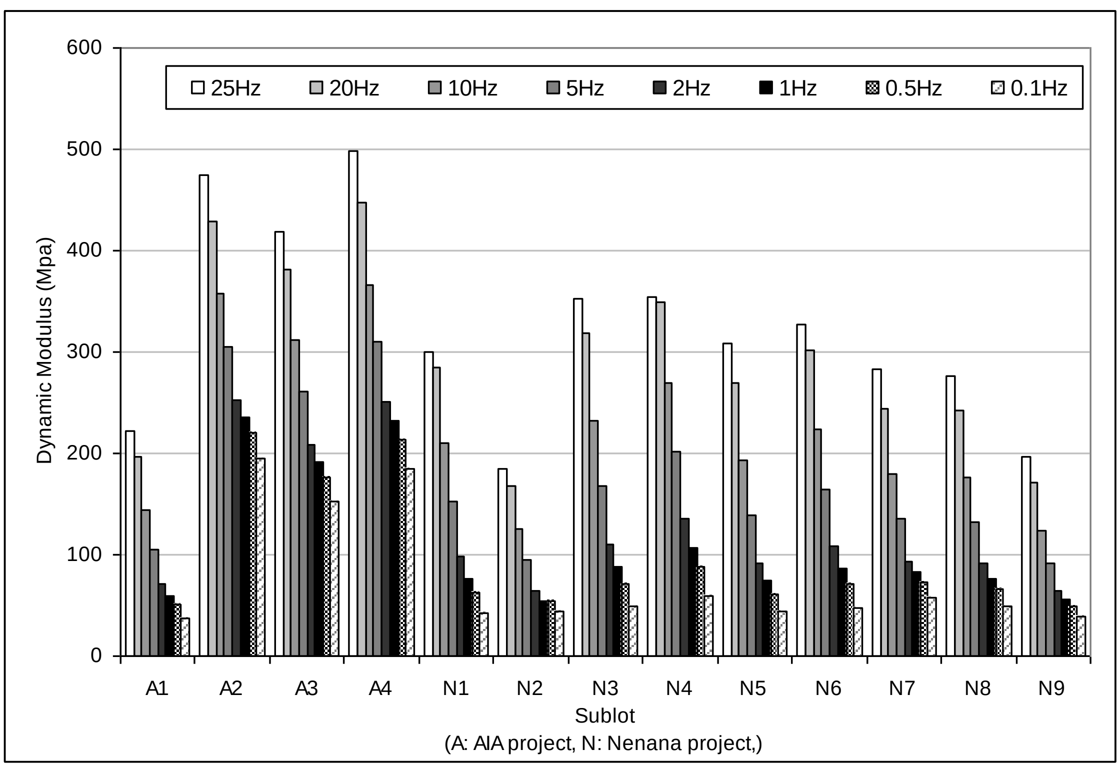


Figure 4.29 |E*| at 54°C

4.3.1.2 Analysis of Variance

The variability of │E*│ is represented by the COV, and the results are summarized in Figures 4.30 to 4.33. Generally, the COV ranges between 5% and 30%. In extreme conditions—for example, HMA collected from the AIA paving project and tested at 37°C and 0.1 Hz loading frequency—the COV reached 70%. Variance changes greatly among sublots and temperatures.

Multi-factor ANOVA tests were used to examine the significance of potential influencing factors such as sublot, temperature, and frequency. The analysis results, summarized in Table 4.10, indicate that temperature and sublot are significant factors for variance of │E*│. The effect of frequency on the COV of │E*│, however, is not significant. A similar analysis was performed by Mohammad and Elseifi (2010) on data collected from the University of Arkansas, MnROAD, and FHWA. The analysis of MnROAD and FHWA data showed that both temperature and frequency were significant factors. However, the analysis on data collected from the University of Arkansas showed that the effect of temperature was significant, but frequency was not.

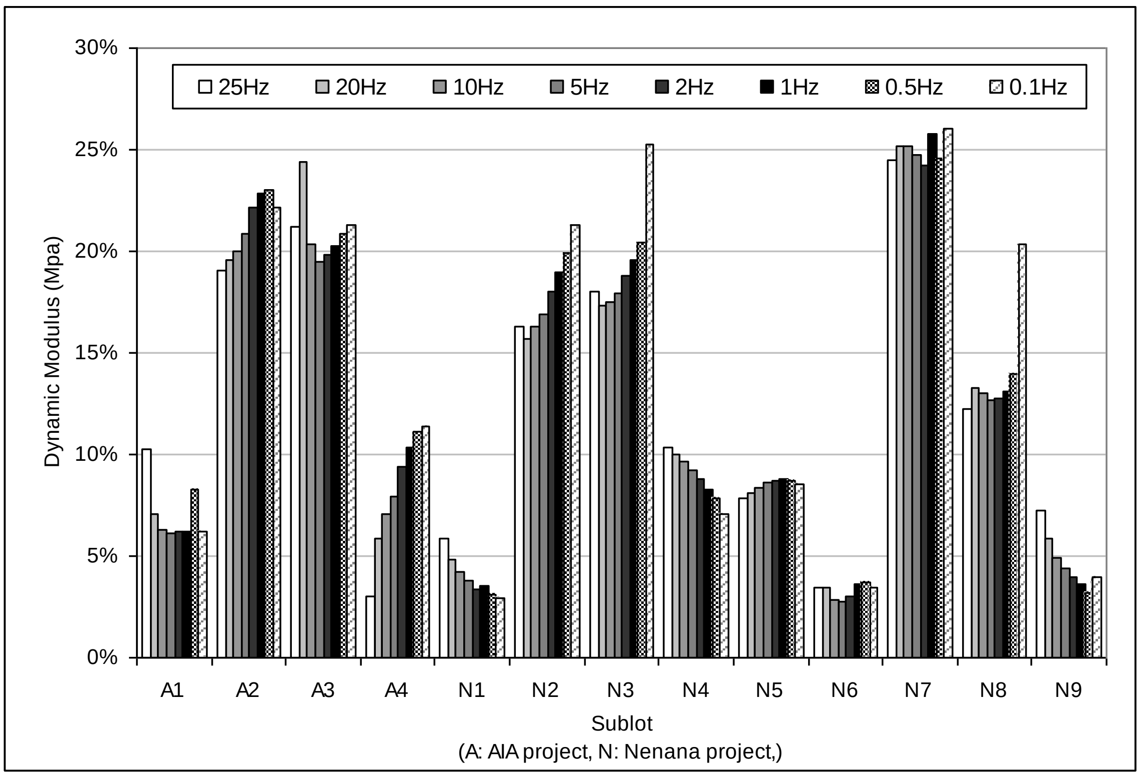


Figure 4.30 COV of │E*│ at 4°C

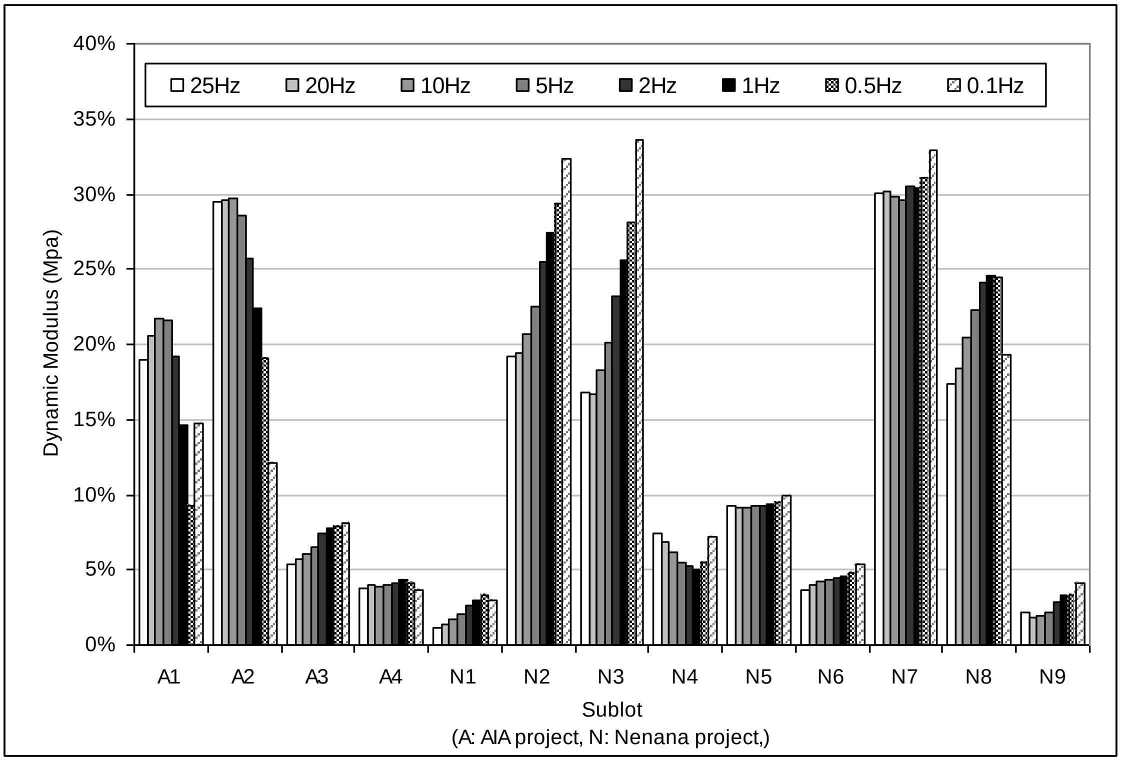


Figure 4.31 COV of │E*│ at 21°C

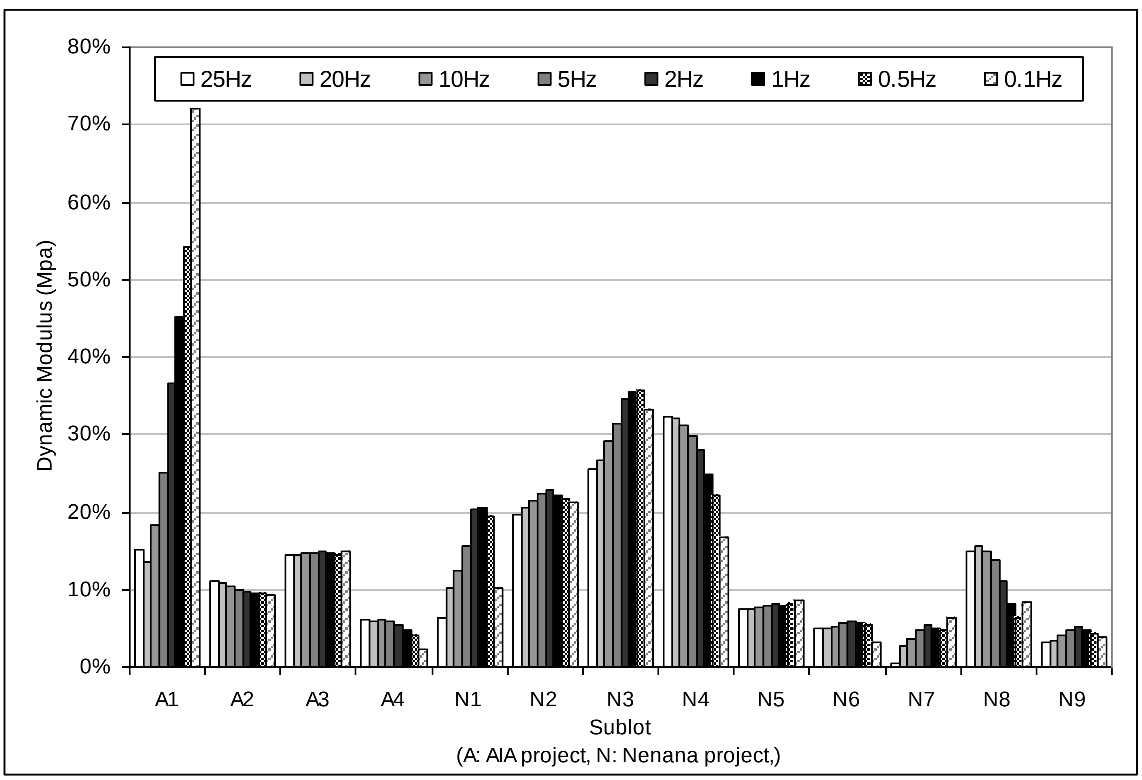


Figure 4.32 COV of │E*│ at 37°C

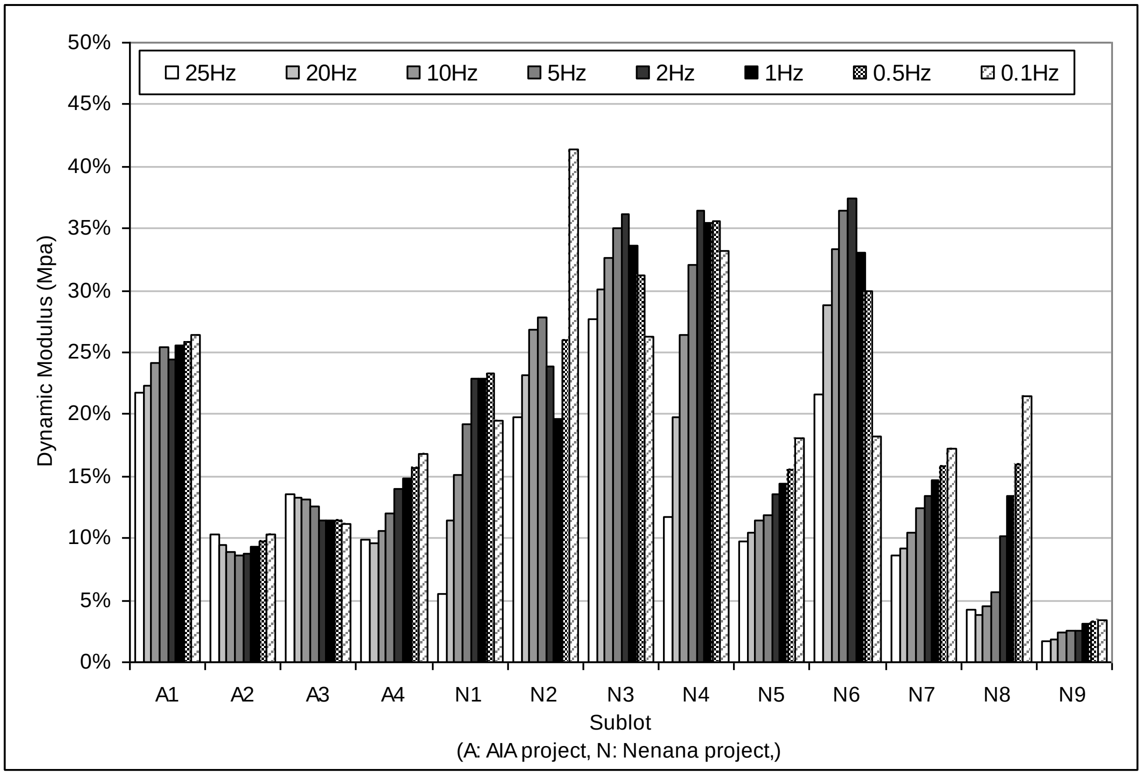


Figure 4.33 COV of │E*│ at 54°C

Table 4.10 Multi-factor ANOVA for COV of │E*│

Factor	Degrees of Freedom	P-value	Significance
Temperature	3	1.952E-5	Significant
Frequency	7	0.2142	Not Significant
Sublot	12	<2.2E-16	Significant

4.3.1.3 Analysis of Percentage Error

Mechanical properties were measured at different testing conditions, and the values changed greatly as testing conditions changed. As presented above, │E*│ could vary from 16,000 MPa to 50 MPa. To perform the error analysis and make the errors obtained at different testing conditions comparable, percentage errors were used to represent the absolute values of differences between measured mechanical properties of field-produced HMA and target values. Target values were measured on L&L specimens.

The percentage errors of │E*│ are summarized in Figures 4.34 to 4.37 for different testing temperatures. Each figure contains data from 13 sublots and 8 testing frequencies. Note that percentage error changes with sublot numbers, and generally, higher testing frequencies lead to higher errors. Comparing the data presented in the four figures reveals that percentage errors are also influenced by temperature. At 54°C, the errors of 7 sublots exceed 100%, and maximum error reaches 500%. The findings indicate that │E*│ of field-produced HMA is greatly affected by material production and testing conditions.

The study conducted by Mohammad et al. (2005) concluded that at the daily production level, which approximately equals one lot of HMA, no significant difference of │E*│ exists among the plant-produced mixtures based on data collected in three-day production. The present study reached a different conclusion. It is possible that since the two studies focused on different production levels, the size of samples obtained for this study from three-day production may be too small to reveal any variation during the field HMA production.

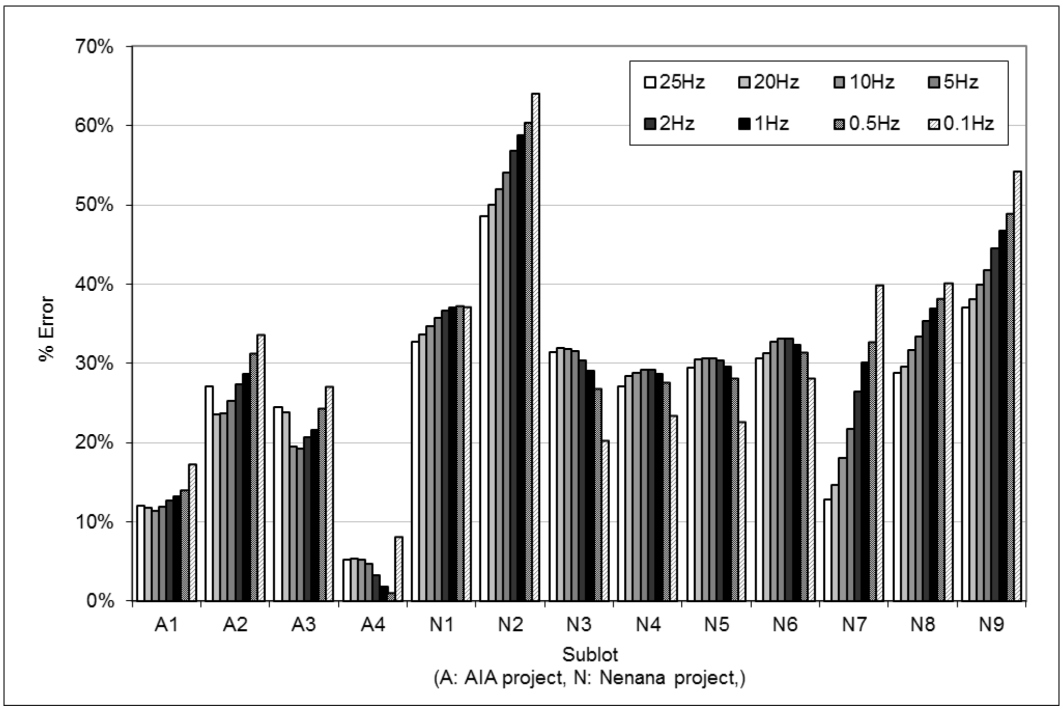


Figure 4.34 Percentage error of E* (4°C)

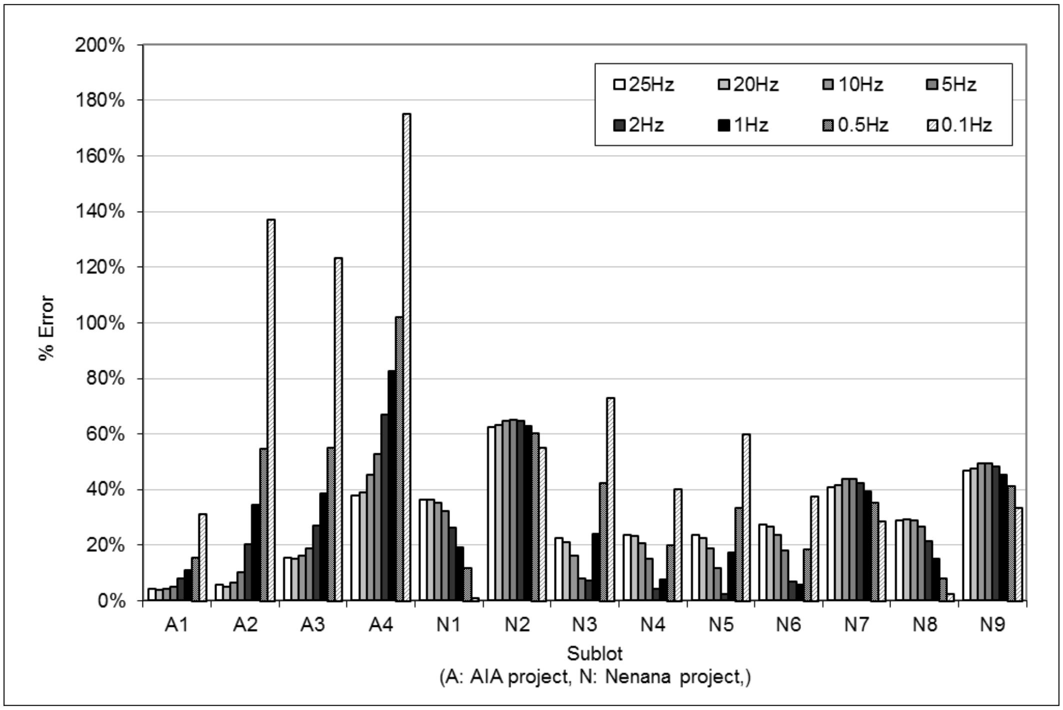


Figure 4.35 Percentage error of E* (21°C)

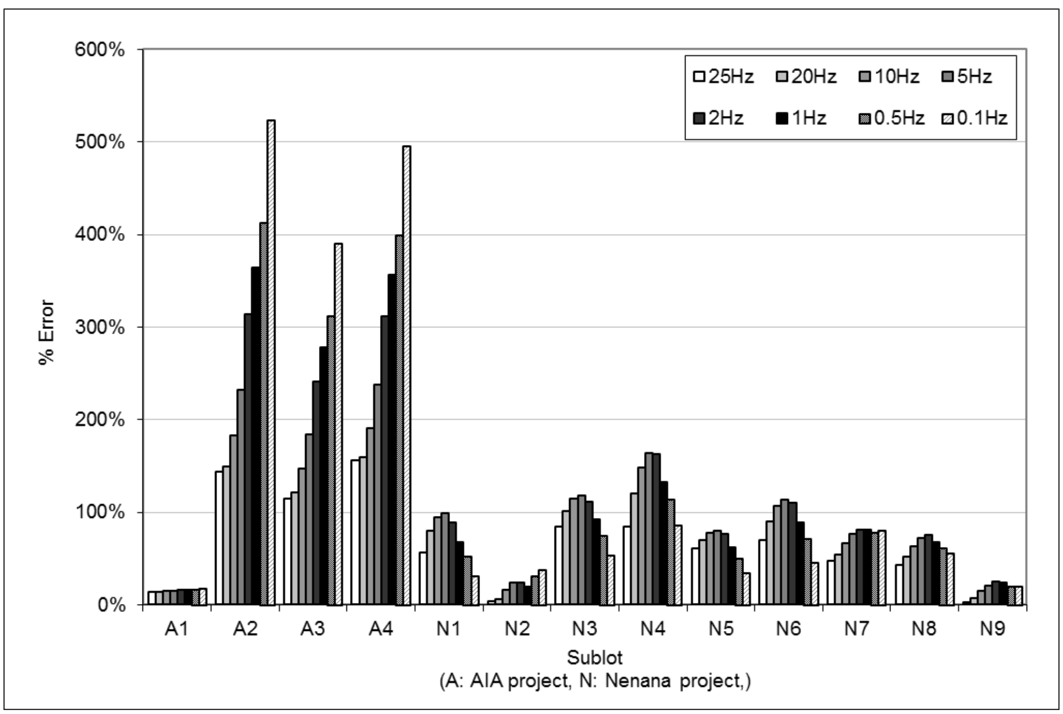


Figure 4.36 Percentage error of E* (37°C)

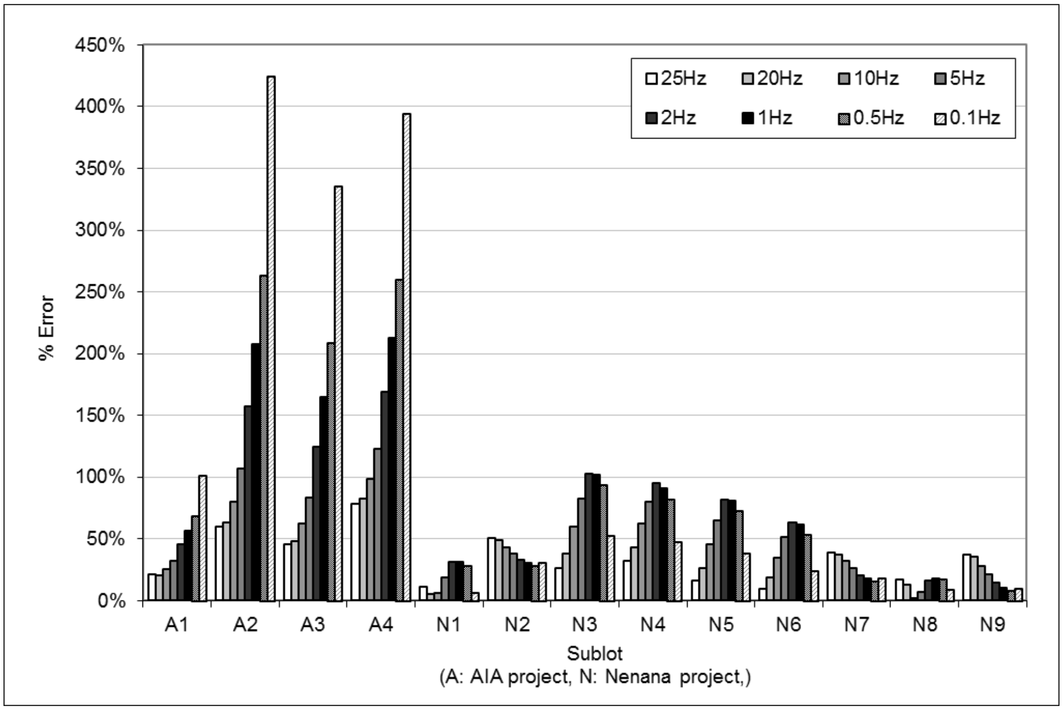


Figure 4.37 Percentage error of E* (54°C)

The average percentage errors of │E*│ of HMA from 13 sublots are summarized in Table 4.11. As temperature increased, the percentage errors increased significantly. The maximum average percentage error was observed at 54°C with 0.1 Hz loading frequency. At high temperatures and low loading frequencies, the asphalt binder became soft, and the errors induced by aggregate gradation were revealed.

Table 4.11 Summary of percentage error of │E*│

Temp (°C)	Percentage Error at Different Frequencies (%) 25 Hz	20 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.1 Hz
4	26.7	27.1	27.7	28.6	29.8	30.3	30.9	32.0
21	28.9	28.8	28.7	27.5	26.6	31.0	38.5	61.6
37	34.3	36.9	44.8	56.6	73.5	83.5	92.7	115.2
54	67.8	79.0	95.1	110.5	126.0	126.8	130.7	144.2

A multi-factor ANOVA test was conducted to examine statistically the significance of influencing factors such as frequency, sublot, and temperature. The results are summarized in Table 4.12. The analysis indicates that frequency, sublot, and temperature were significant factors for the percentage errors of │E*│.

Table 4.12 Multi-factor ANOVA for percentage error of $|E^*|$

Factor	Degrees of Freedom	P-value	Significance
Frequency	7	0.0001031	Significant
Sublot	12	<2.20E-16	Significant
Temperature	3	<2.20E-16	Significant

4.3.2 Flow Test

4.3.2.1 Testing Results

Due to the confining pressure (137 kPa) applied during flow testing, most specimens did not fail after 10,000 loading cycles; some did not even pass the second zone of deformation. Therefore, the flow time and flow number values automatically calculated based on the built-in machine algorithms were meaningless. Lower confining pressure should be used in future testing. The final test strain was used as an indicator of resistance to permanent deformation.

Figure 4.38 presents the microstrains at the end of the flow time and flow number tests. The bar chart clearly shows that HMA obtained from the AIA paving project had a substantially lower microstrain at the end of testing. This result would be mainly due to the greater compaction effort applied to the AIA HMA. During specimen fabrication, 75 gyrations were applied to AIA mixtures according to the JMF. Only 20 gyrations were applied to the Nenana mixtures to reproduce the target air voids specified in the JMF, which was based on the Marshall mix design method.

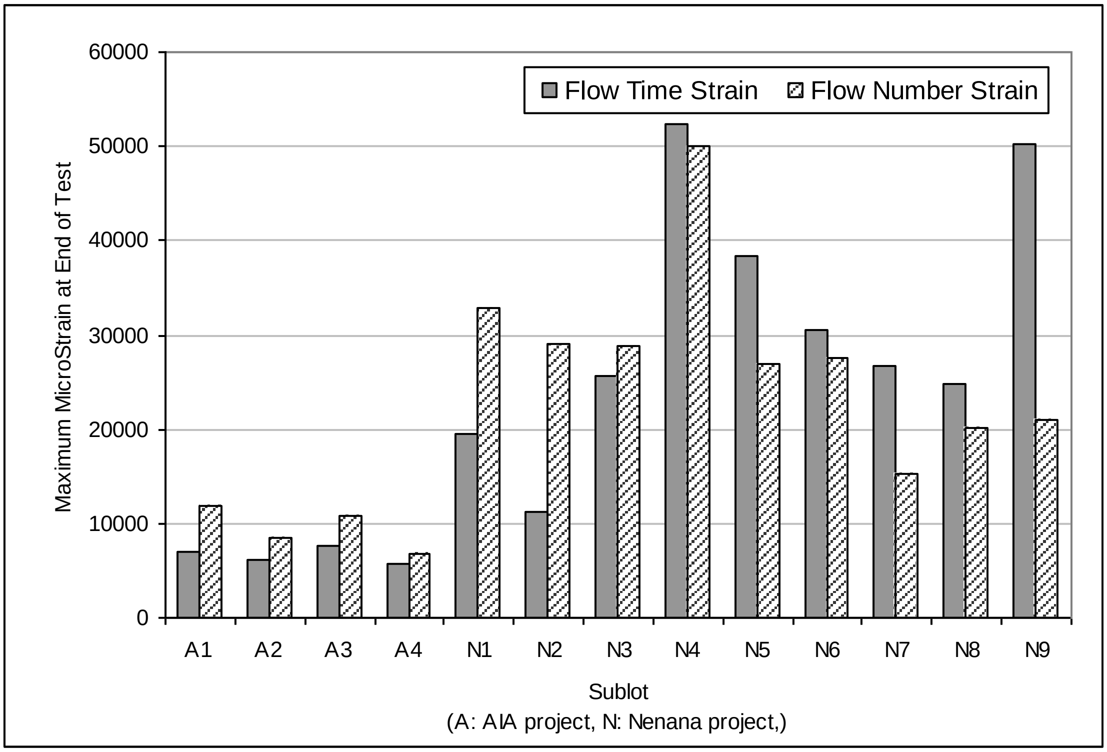


Figure 4.38 Microstrains at the end of flow tests

4.3.2.2 Analysis of Variance

The variances in microstrains at the end of the flow tests are summarized in Figure 4.39. Hot mix asphalt obtained from the AIA project not only had lower microstrains, but also had lower COVs than the Nenana paving project. The HMA of the AIA paving project was designed by the Superpave mix design method. More compaction efforts were applied on specimens during the Superpave mix design phase than with the Marshall mix design method. Such high compaction efforts improve the internal structure of HMA and reduce the variance of performance induced by the variance of material composition. The variance also changed greatly along the HMA production indicated by sublot number.

Two-factor ANOVA tests were performed to evaluate the significance of sublot and type of flow tests on the variance. The results (Table 4.13) show that sublot is a significant factor, but the type of flow test is not. The procedures of the flow time and flow number tests were similar, except for a different loading pattern (i.e., static load was used in flow time tests, while dynamic load was used in flow number tests). The loads used in both tests had the same amplitude (600 kPa). Therefore, the errors included by different types of flow tests were similar.

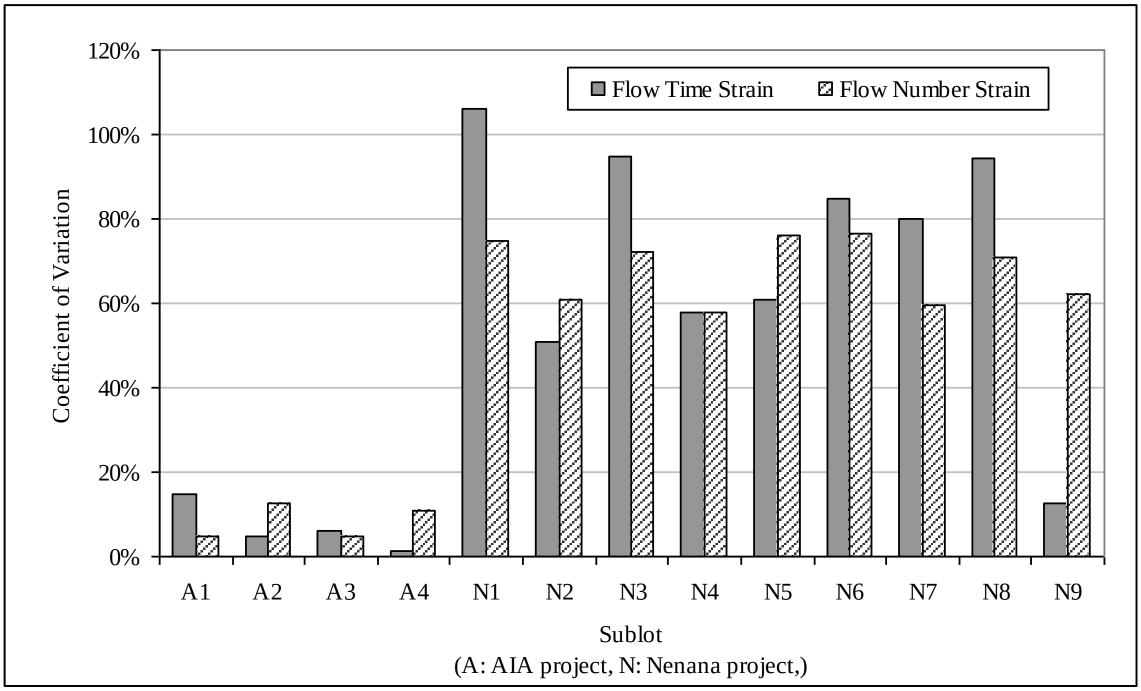


Figure 4.39 COV of flow tests

Table 4.13 Two-factor ANOVA for variance of microstrain at end of flow test

Factor	Degrees of Freedom	P-value	Significance
Type of Flow Test	1	0.7460	Not Significant
Sublot	12	0.0002	Significant

4.3.2.3 Analysis of Percentage Error

The percentage errors of microstrain at the end of the flow test are summarized in Figure 4.40. A random pattern was observed on the distribution of percentage error. By performing the two-factor ANOVA test (Table 4.14), the calculated *P*-values indicate that percentage error was not significantly affected by either type of flow test or sublot.

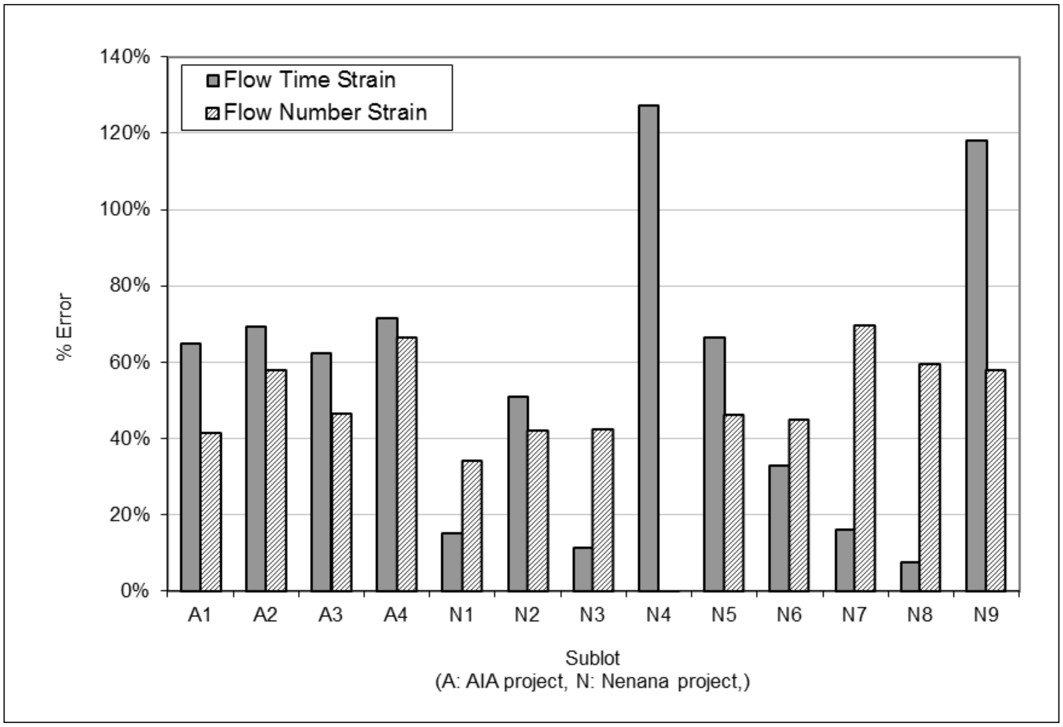


Figure 4.40 Difference between measured and design value

Table 4.14 Two-factor ANOVA for percentage error of microstrain at end of flow test

Factor	Degrees of Freedom	P-value	Significance
Type of Flow Test	1	0.5561	Not Significant
Sublot	12	0.8329	Not Significant

4.3.3 Creep Stiffness

4.3.3.1 Testing Results

Indirect tensile creep tests were performed on specimens produced from all four scenarios (L&L, F&F, F&L, and field cores) at three temperatures: -10°C, -20°C, and -30°C. Creep stiffness was calculated at 50s and 500s at each temperature. The results are summarized in Figures 4.41 to 4.46. Generally, at all temperatures and testing times, the specimens produced from F&L scenarios have the highest creep stiffness, and field cores have the lowest stiffness. Based on the volumetric properties of specimens obtained from four scenarios, field cores always have the highest VTM, leading to the lowest creep stiffness. However, information obtained from the study conducted by Marasteanu et al. (2007) shows field cores having higher stiffness than laboratory-produced specimens, and for laboratory-produced specimens, higher VTM correlated with higher creep stiffness.

As a viscoelastic material, lower stiffness is expected at higher temperatures and longer loading times. The testing results varied along the sublot numbers, but no trend could be observed.

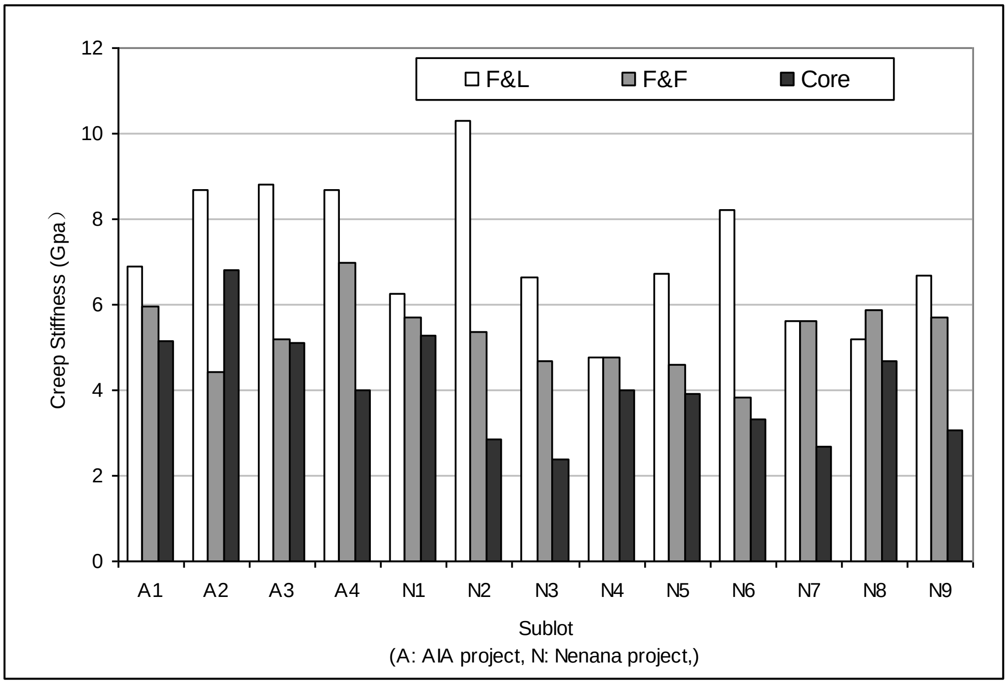


Figure 4.41 Creep stiffness at 50s (-10°C)

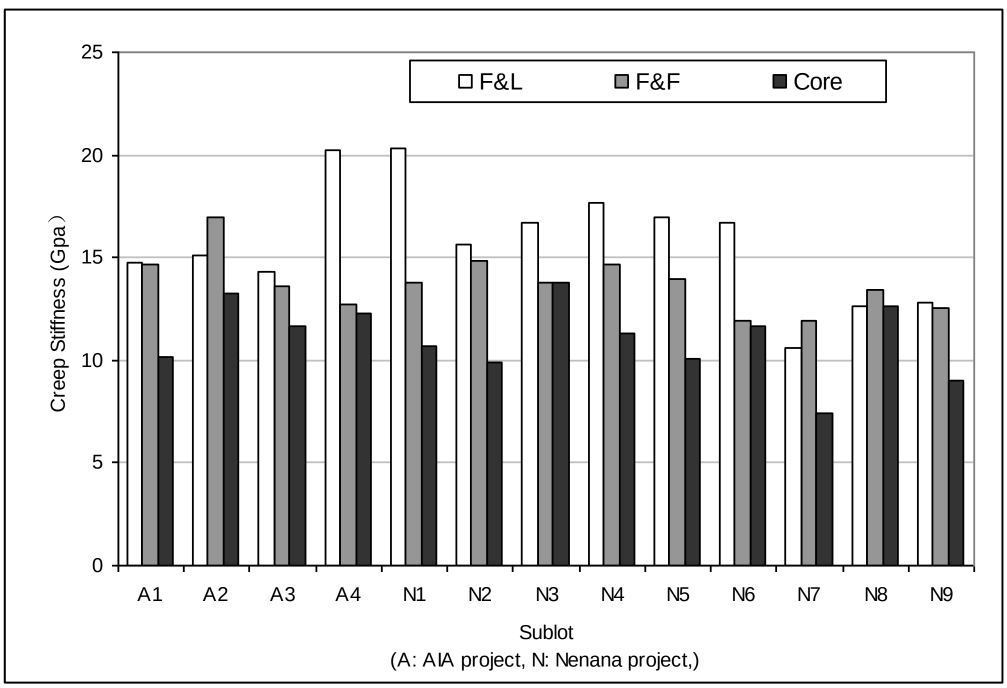


Figure 4.42 Creep stiffness at 50s (-20°C)

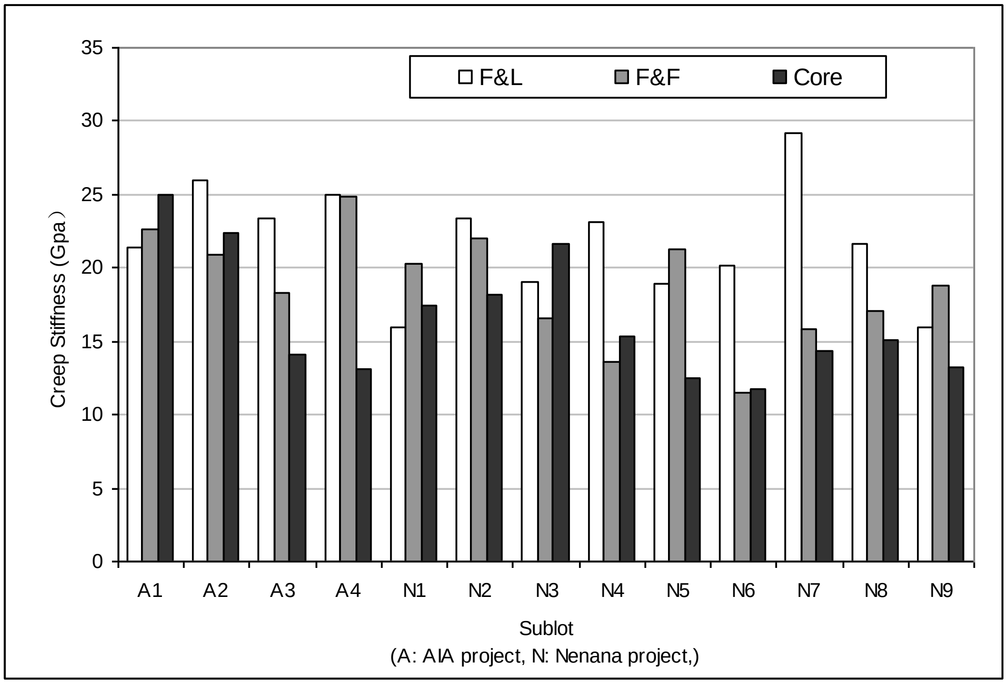


Figure 4.43 Creep stiffness at 50s (-30°C)

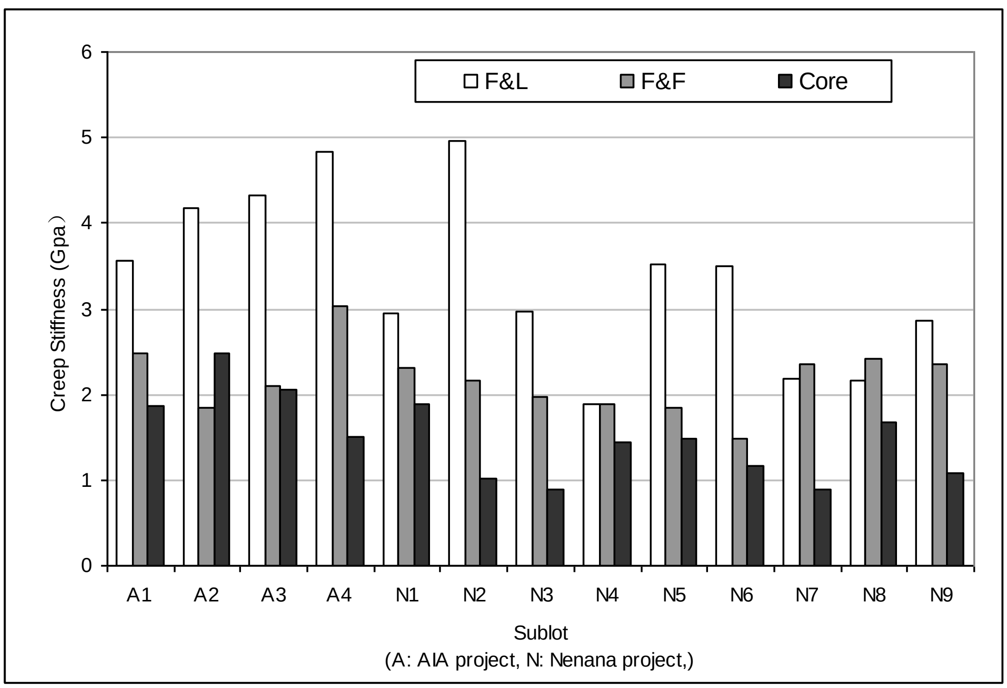


Figure 4.44 Creep stiffness at 500s (-10°C)

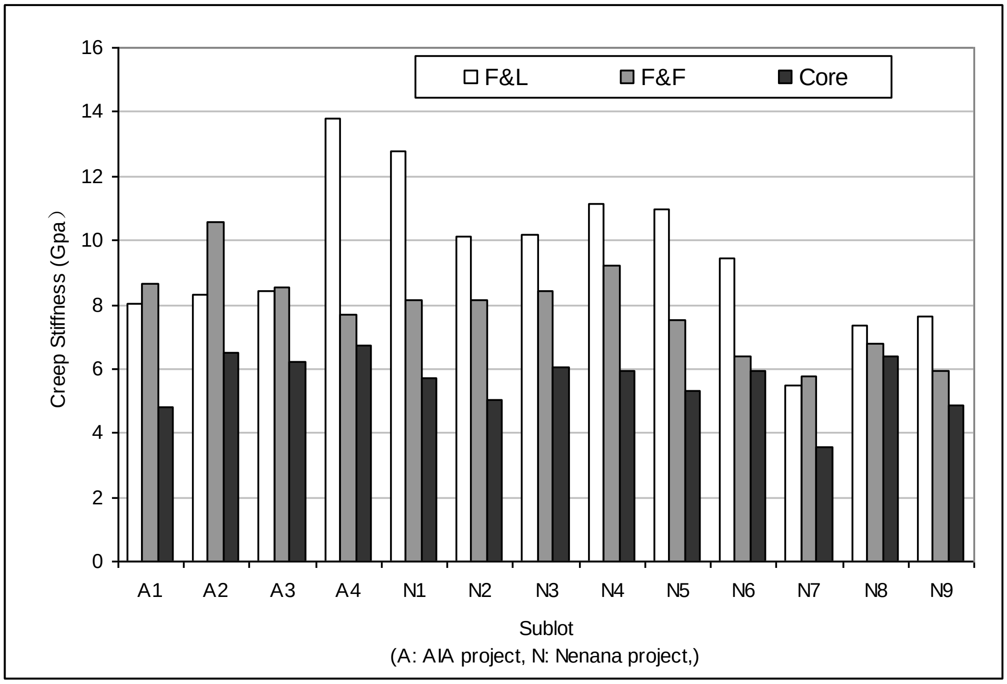


Figure 4.45 Creep stiffness at 500s (-20°C)

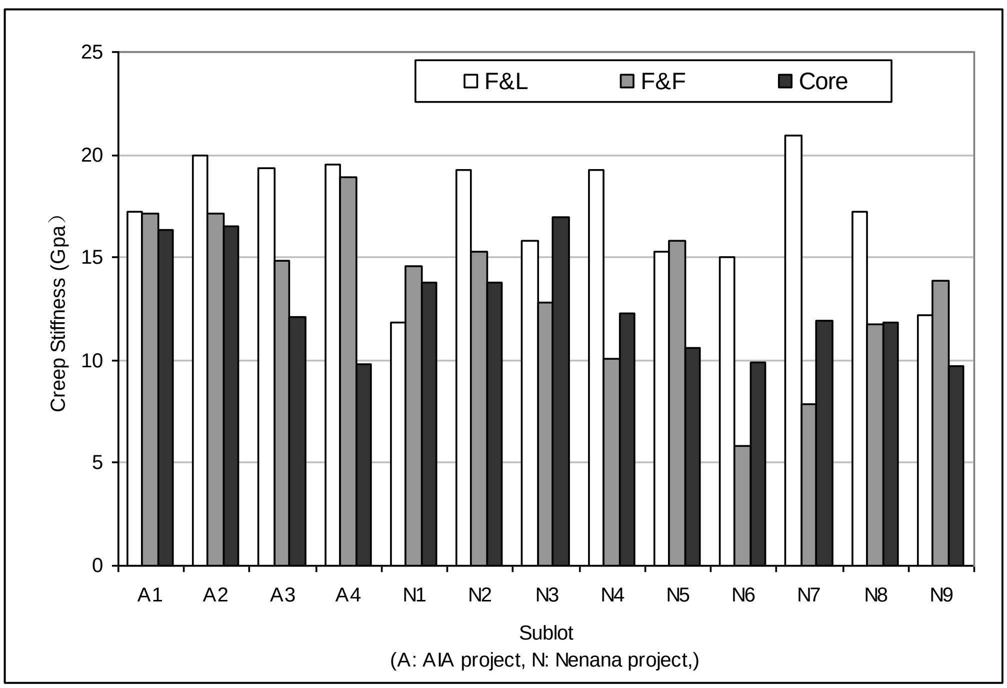


Figure 4.46 Creep stiffness at 50s (-30°C)

4.3.3.2 Analysis of Variance

Variation analysis was conducted to identify the significance of potential influencing factors. According to calculation methods provided in AASHTO T322, creep stiffness is obtained by stress over mean of strain of three specimens (six sides). Creep can be calculated for each specimen. Therefore, variance of creep stiffness for HMA obtained in each sublot could be calculated. The COV of creep stiffness was calculated for three scenarios at each temperature and loading time. The results are summarized in Figures 4.47 and 4.48. For testing results at 50s, the maximum variation was obtained on field cores at -30°C with the value of 26%, and minimum variation was obtained on F&F specimens at -20°C with the value of 10%. The variance of creep stiffness obtained at 500s is similar to results obtained at 50s. Generally, field cores possessed the highest variance due to influencing factors encountered during construction, such as non-homogenous paving and compaction.

A multi-factor ANOVA test was performed to evaluate the significance of influencing factors. The results (Table 4.15) reveal that the scenario, temperature, or loading time did not significantly affect the variance of creep stiffness.

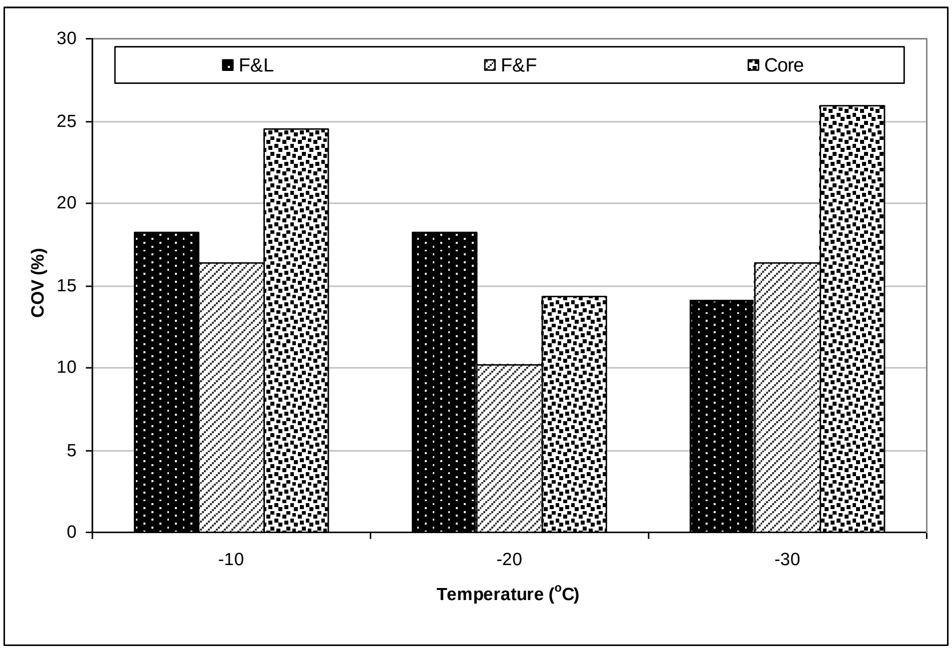


Figure 4.47 COV of creep stiffness at 50s

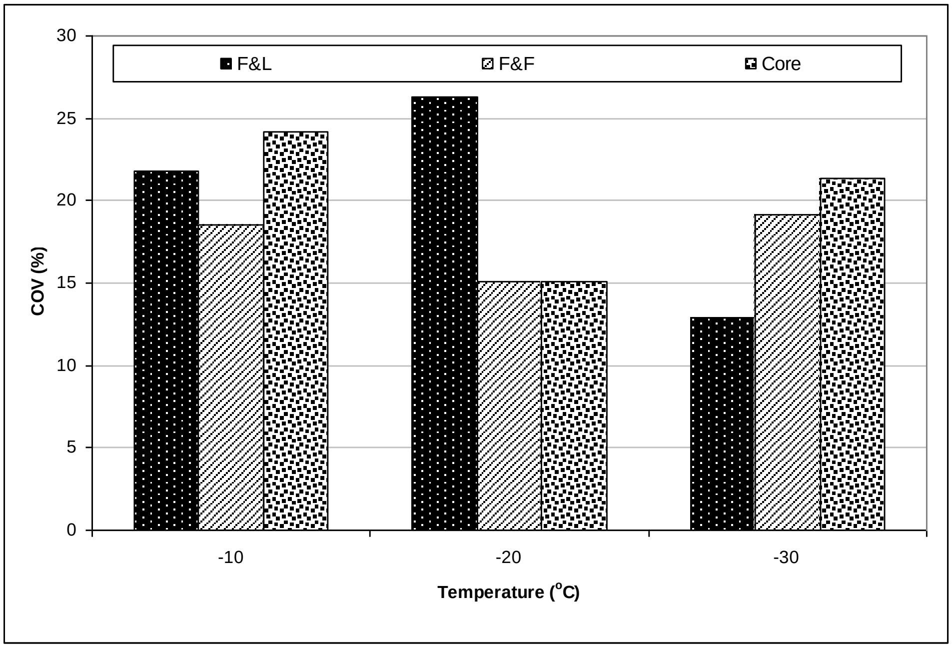


Figure 4.48 COV of creep stiffness at 50s

Table 4.15 Multi-factor ANOVA for COV of creep stiffness

Factor	Degrees of Freedom	P-value	Significance
Scenario	2	0.2	Not Significant
Temperature	2	0.322	Not Significant
Loading Time	1	0.412	Not Significant

4.3.3.3 Analysis of Percentage Error

Figures 4.49 to 4.54 present the percentage errors of creep stiffness at six different testing conditions (i.e., three temperatures and two loading periods). Negative errors were observed in most conditions, indicating generally that specimens made from field-produced HMA possess lower creep stiffness compared with L&L specimens, especially for the Nenana paving project.

Error varies greatly along sublot and testing scenarios. Multi-factor ANOVA tests were used to evaluate the significance of factors including sublot, temperature, loading time, and scenario. The results (Table 4.16) indicate that all of these factors significantly influenced the percentage error of creep stiffness.

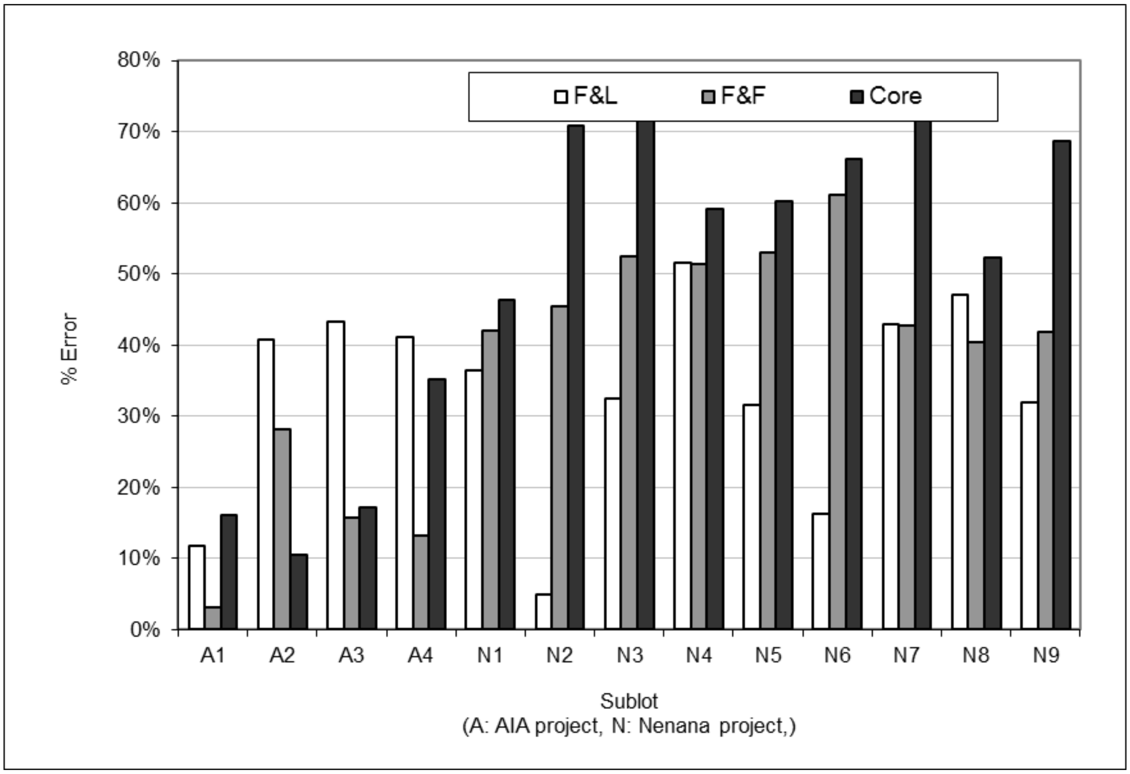


Figure 4.49 Difference between measured and design value (-10°C, 50s)

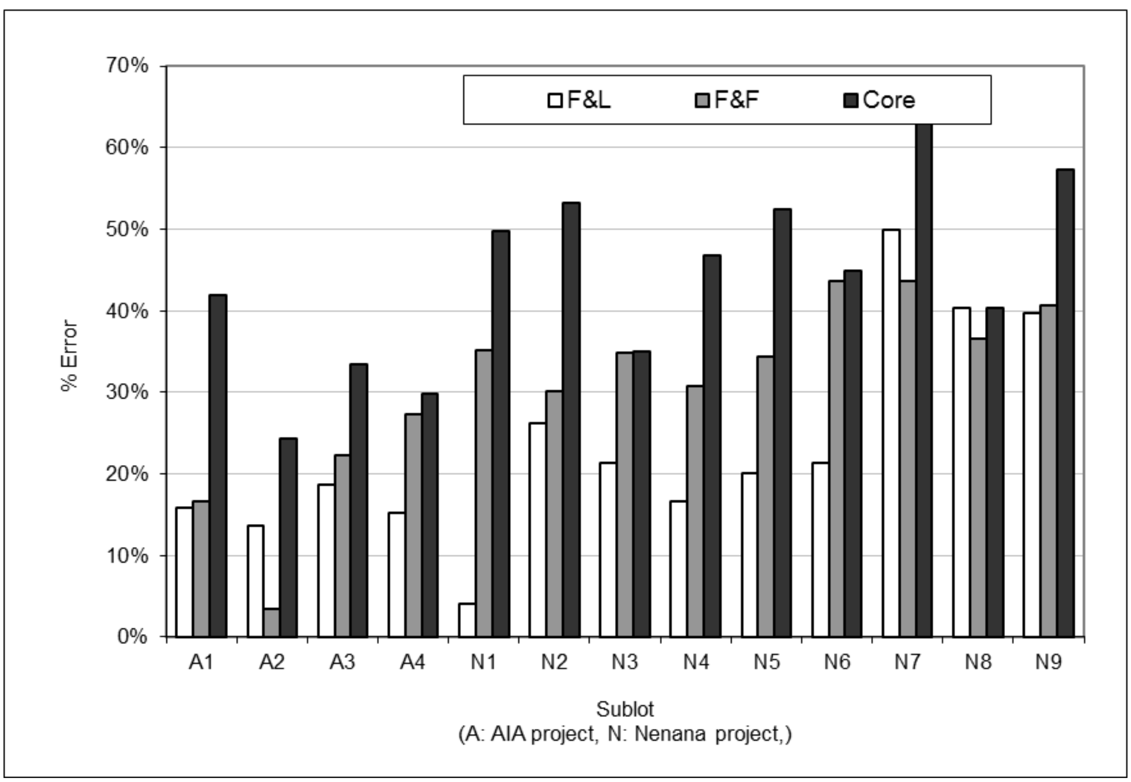


Figure 4.50 Difference between measured and design value (-20°C, 50s)

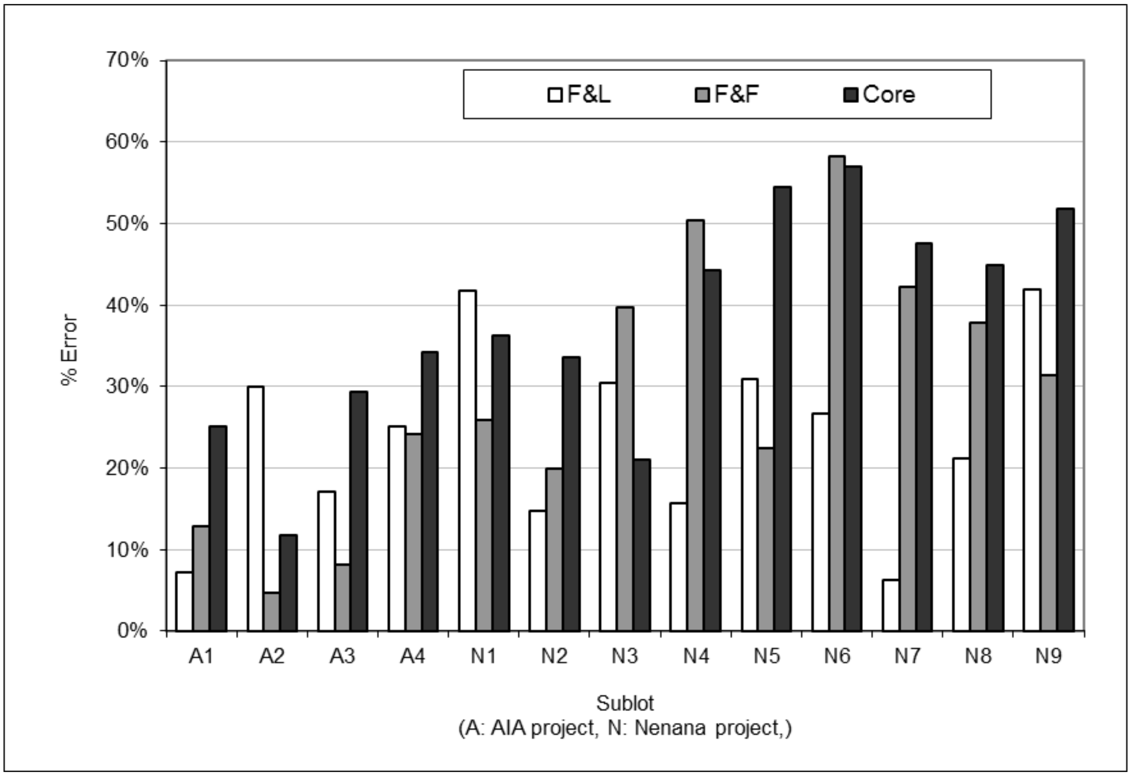


Figure 4.51 Difference between measured and design value (-30°C, 50s)

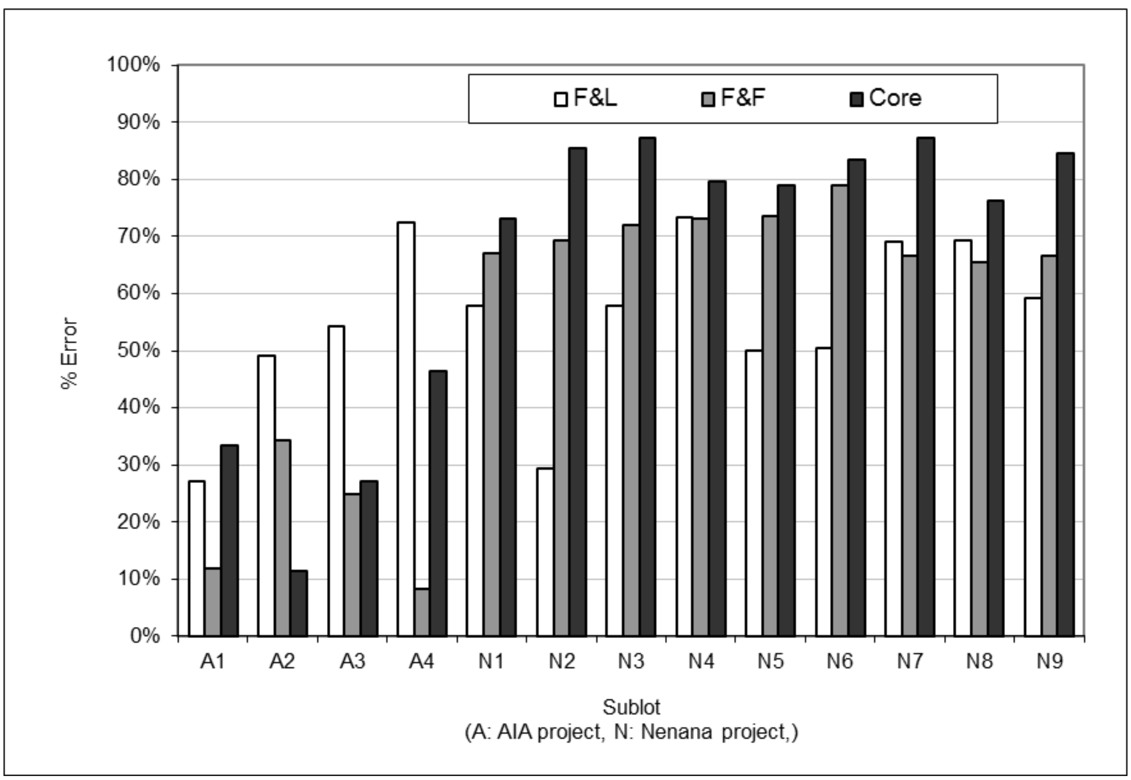


Figure 4.52 Difference between measured and design value (-10°C, 500s)

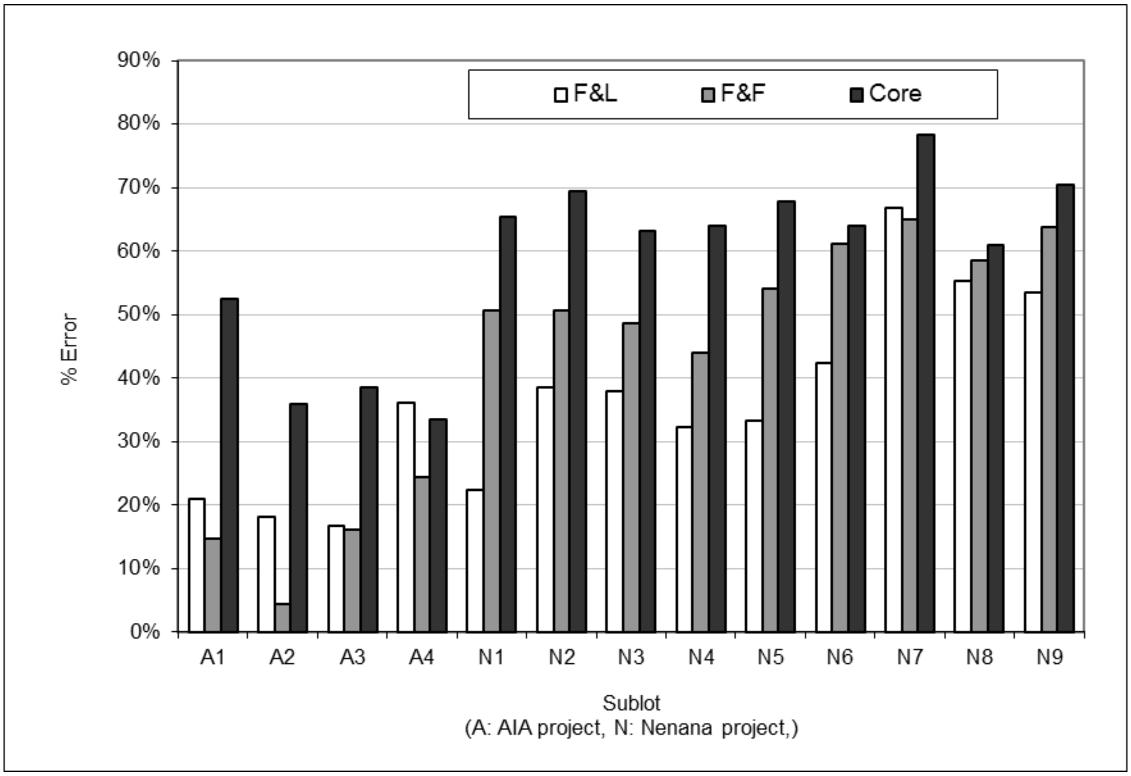


Figure 4.53 Difference between measured and design value (-20°C, 500s)

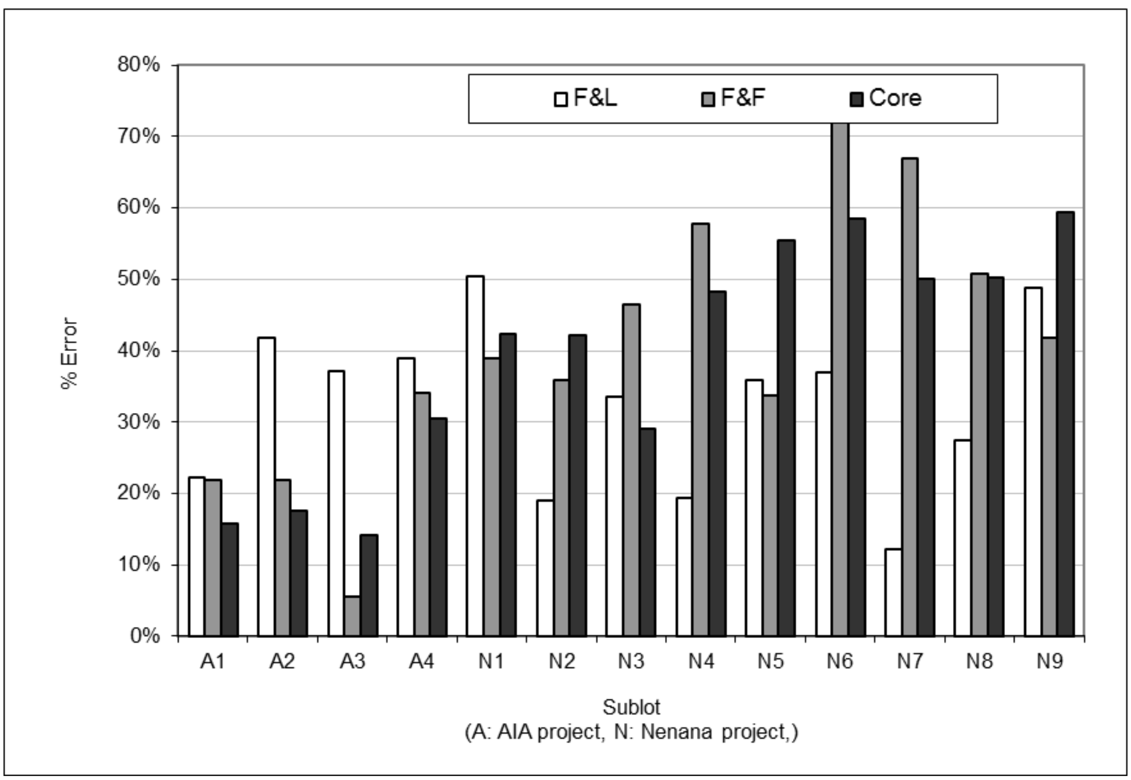


Figure 4.54 Difference between measured and design value (-30°C, 500s)

Table 4.16 Multi-factor ANOVA for % error of creep stiffness

Factor	Degrees of Freedom	F value	Pr(>F)	Significance
Sublot	12	29.3	5.41E-12	Significant
Scenario	2	16.4	2.20E-16	Significant
Temperature	2	304.92	2.17E-12	Significant
Loading Time	1	619.62	1.68E-13	Significant

4.3.4 Indirect Tensile Strength

4.3.4.1 Testing Results

After the IDT creep test, the specimens were subjected to vertical load at a constant crosshead rate of 12.5 mm/min until failure. Indirect tensile strength (ITS) was calculated based on measured maximum load. The L&L and F&L specimens were tested at -10°C, -20°C, and -30°C. The F&F specimens were tested at -10°C and -30°C, because only three standard Superpave specimens (150 mm in diameter and 115 mm in height) were compacted in the field for each sublot mixture, and each specimen was cut into two IDT specimens. Field cores were only tested at -20°C, due to the limited number of samples.

Figures 4.55 to 4.57 present the ITS measured at three temperatures. The results from Figures 4.55 and 4.66 show that the ITS of F&L and F&F is similar, and as the temperature drops, ITS increases. At -20°C, a comparison of F&L and core results reveals that the ITS of laboratory-produced specimens is higher than the ITS of field cores. The same observation was made by Mohammad et al. (2004). However, the study conducted by Marasteanu et al. (2007) showed that field cores possess higher ITS.

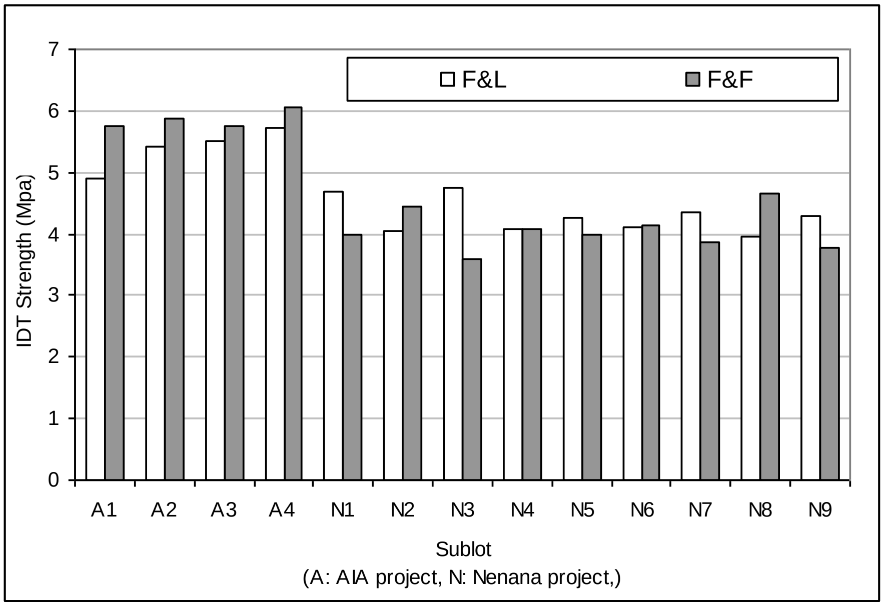


Figure 4.55 IDT strength at -10°C

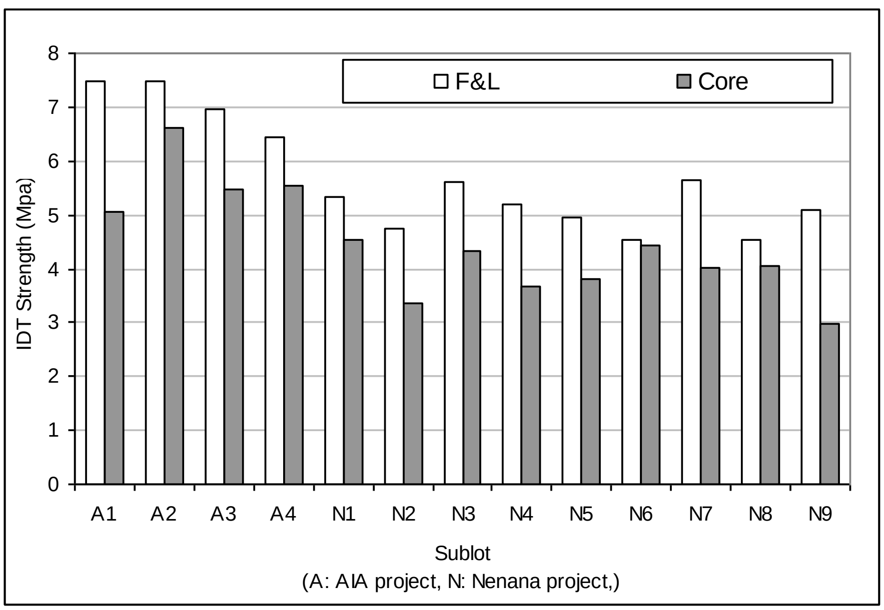


Figure 4.56 IDT strength at -20°C

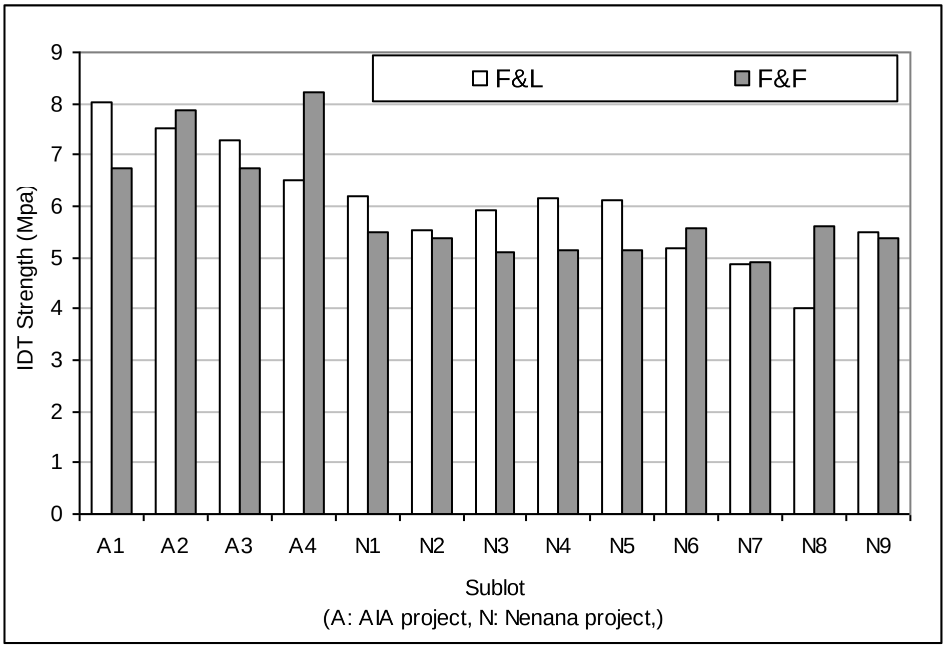


Figure 4.57 IDT strength at -30°C

4.3.4.2 Analysis of Variance

The COV for each sublot of HMA was calculated based on testing results. These COVs are summarized in Figures 4.58 to 4.60. Compared with $|E^*|$, microstrains at the end of flow tests, and creep stiffness, ITS variances were found to be lower. The COVs are in line with the results from the study performed by Mohammad et al. (2004, 2010). Coefficients of variance vary with changes of temperature, testing scenario, and sublot. However, particular trends could not be articulated based on visual examination of graphs. A multi-factor ANOVA test was performed, and the results (Table 4.17) imply that neither temperature, sublot, nor scenario significantly affects the variance of ITS.

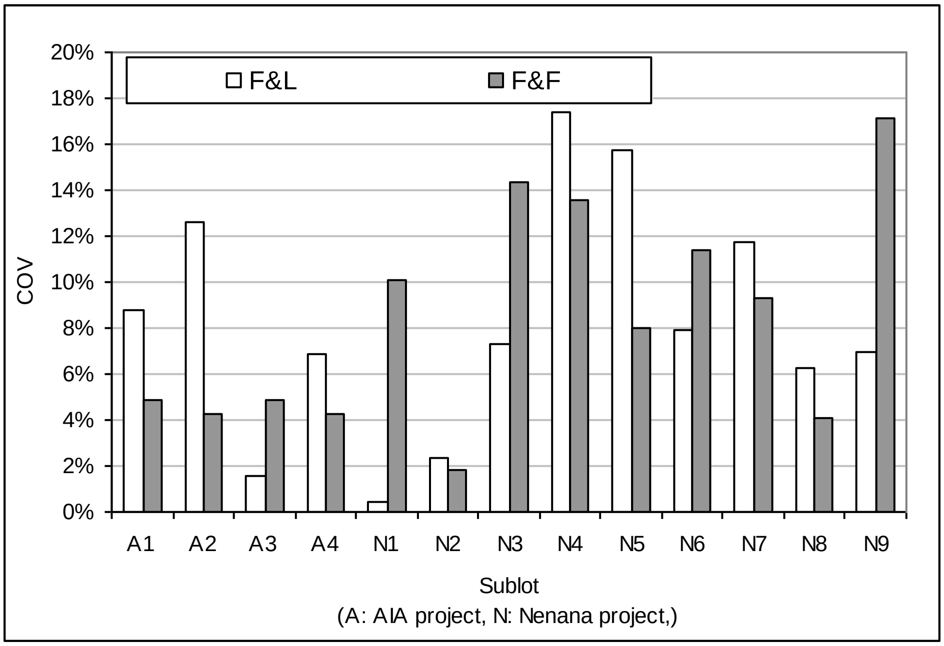


Figure 4.58 COV of IDT strength

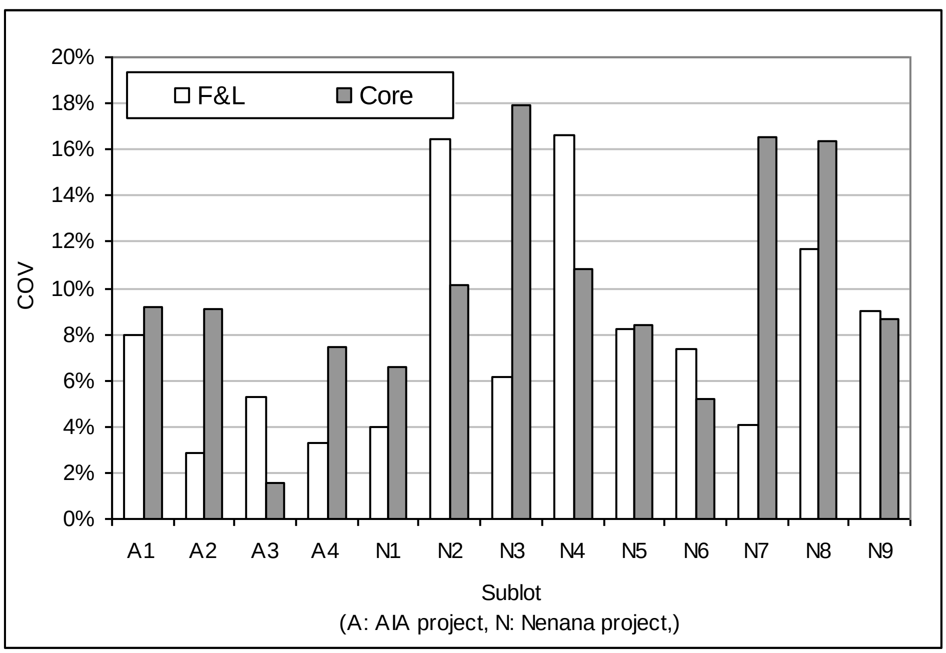


Figure 4.59 COV of IDT strength

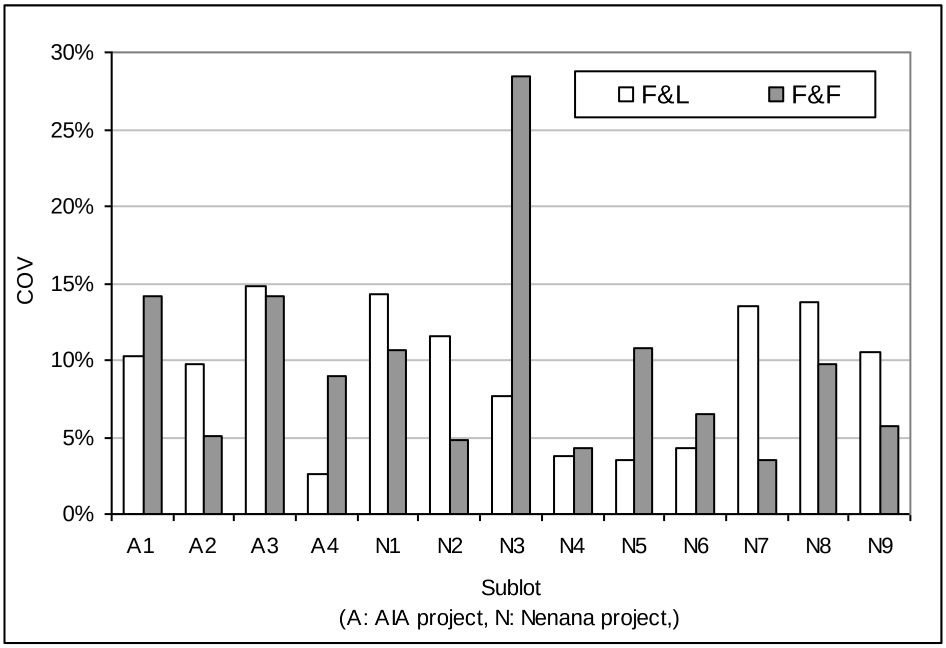


Figure 4.60 COV of IDT strength

Table 4.17 Multi-factor ANOVA for COV of IDT strength

Factor	Degrees of Freedom	P-value	Significance
Temperature	2	0.6631	Not Significant
Sublot	12	0.4181	Not Significant
Scenario	2	0.6095	Not Significant

4.3.4.3 Analysis of Percentage Error

Error analyses were also conducted for ITS. The percentage errors of IDT strength are summarized in Figures 4.61 to 4.63. Note that at -10°C and -20°C, specimens obtained from F&L had higher errors than specimens obtained from the F&F scenario. The errors of field cores were higher than the errors of specimens of the F&L scenario. To evaluate the effect of sublot, temperature, and scenario, a multi-factor ANOVA test was performed. The results (Table 4.18) show that scenario and temperature are significant factors in the percentage errors of IDT strength, but the effort of sublot was not significant.

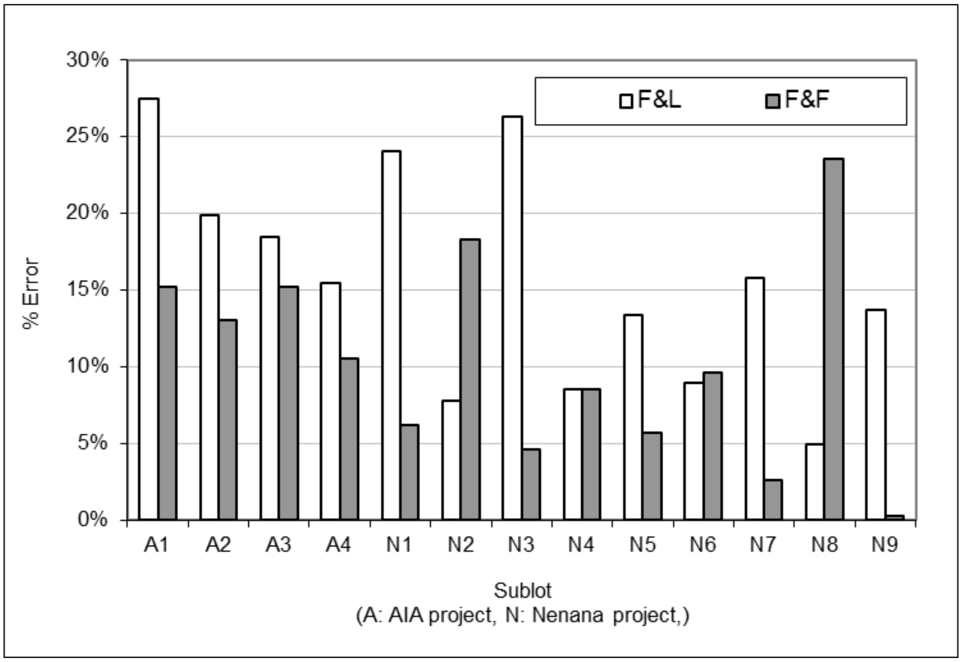


Figure 4.61 Difference between measured and design value (-10°C)

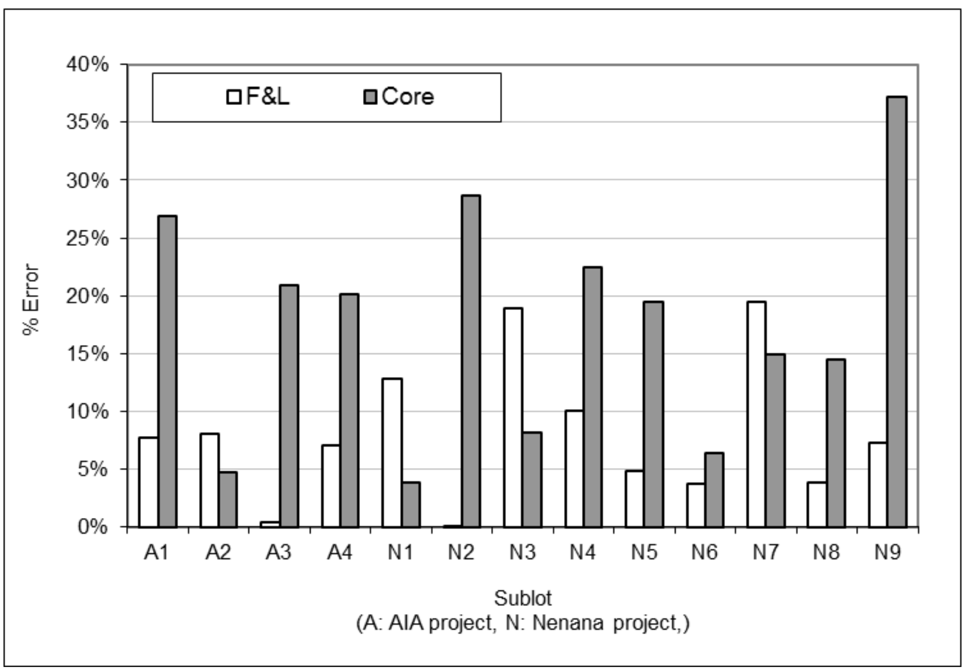


Figure 4.62 Difference between measured and design value (-20°C)

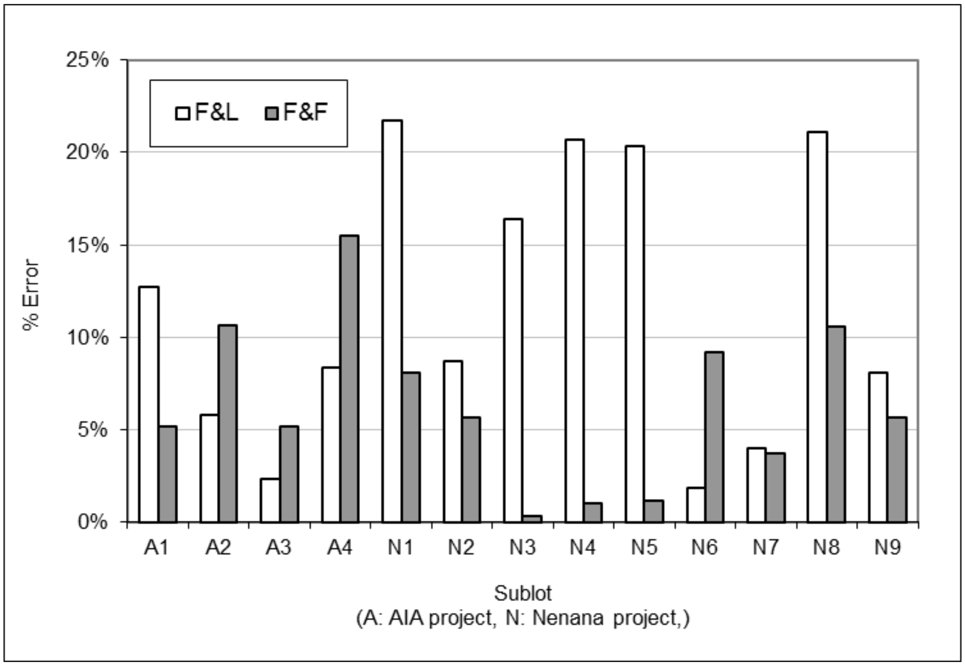


Figure 4.63 Difference between measured and design value (-30°C)

Table 4.18 Multi-factor ANOVA for % error of IDT strength

Factor	Degrees of Freedom	F value	Pr(>F)	Significance
Sublot	12	0.4925	0.9114	Not Significant
Scenario	2	6.7301	0.0023	Significant
Temperature	2	4.3569	0.0170	Significant

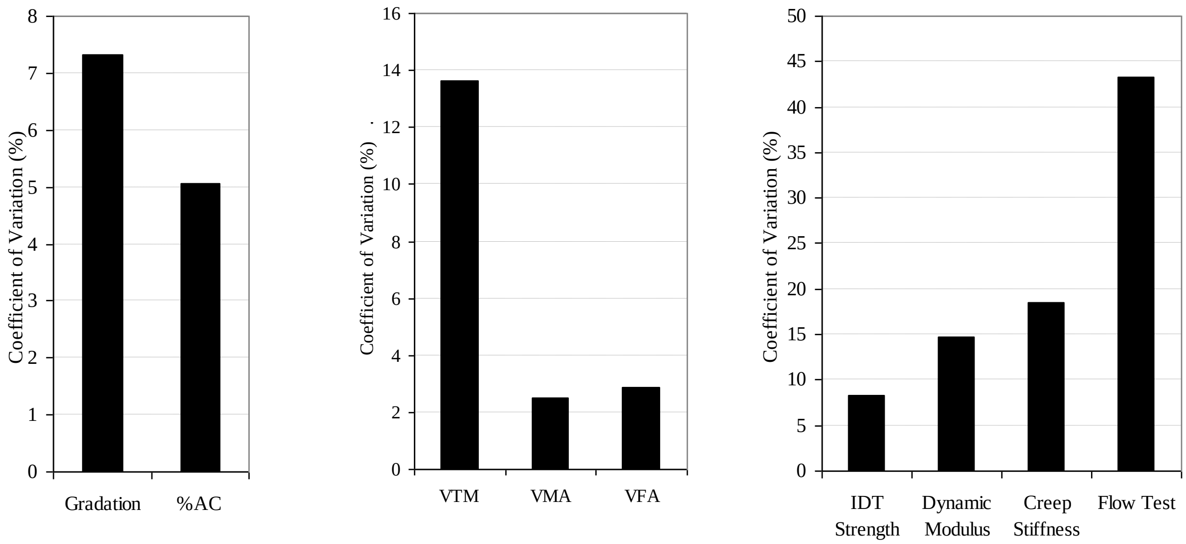
4.4 Correlation

Figure 4.64 summarizes and compares the variability of quality, represented by coefficient of variation (COV). The COV presented for each quality characteristic is the average value of all testing results from both projects. The COV of composition properties was found to be approximately 5%. The COVs of volumetric properties ranged from 2% to 14%.

The COV is calculated as the standard deviation divided by mean value of testing results. Therefore, with a similar level of standard deviation, a higher COV would be obtained on variables with small mean values, such as VTM, and a lower COV would be obtained on variables with greater mean values, such as VFA.

The variances of performance properties are higher than both composition and volumetric properties. The reason could be that additional errors were introduced during specimen cutting, sensor installation, and loading, activities not required for composition and volumetric properties. The sensitivity of performance tests also contributed to the higher variance. Previous studies have indicated that flow number and flow time have an extremely high level of variation

(Bonaquist, 2008). The results from this study confirmed this observation. The flow test results were represented by the final permanent deformation; the result still exhibited a high COV, reaching 43%.



a) Composition Properties b) Volumetric Properties c) Mechanical Properties

Figure 4.64 Summary of COV by quality characteristic

The purpose of a quality assurance (QA) program is to improve the quality of HMA mixtures and to make the best effort in ensuring that the performance of installed HMA mixtures reaches the levels specified in the design. Rather than measuring mechanical properties, which are considered directly related to pavement performance, composition and/or volumetric properties are measured in most QA programs. This approach relies on the assumption that composition and volumetric properties correlate well with mechanical properties; they are preferred because composition and volumetric properties can be measured easier and faster than mechanical properties.

Figure 4.65 presents the correlation between composition and mechanical properties based on data collected from both projects. Generally, correlations between these two types of properties are less than 0.25, indicating a poor correlation. The percentage passing the #200 sieve shows the best correlation among the composition properties; however, this value was still less than 0.4.

Better correlations were observed between volumetric properties and mechanical properties (Figure 4.66). The mechanical properties of HMA are related to volumetric properties in nature. The VTM, VMA, and VFA correlate to each other, and the results showed that these three material properties had a similarly strong relationship with mechanical properties. A strong correlation between IDT strength and volumetric properties is observed, indicated by correlation values over 0.8. The correlation between creep stiffness and dynamic modulus is not as strong as the correlation between creep stiffness and IDT strength. For QC and QA purposes, volumetric properties need to be measured, because they delivered more reliable information on material strength than composition properties.

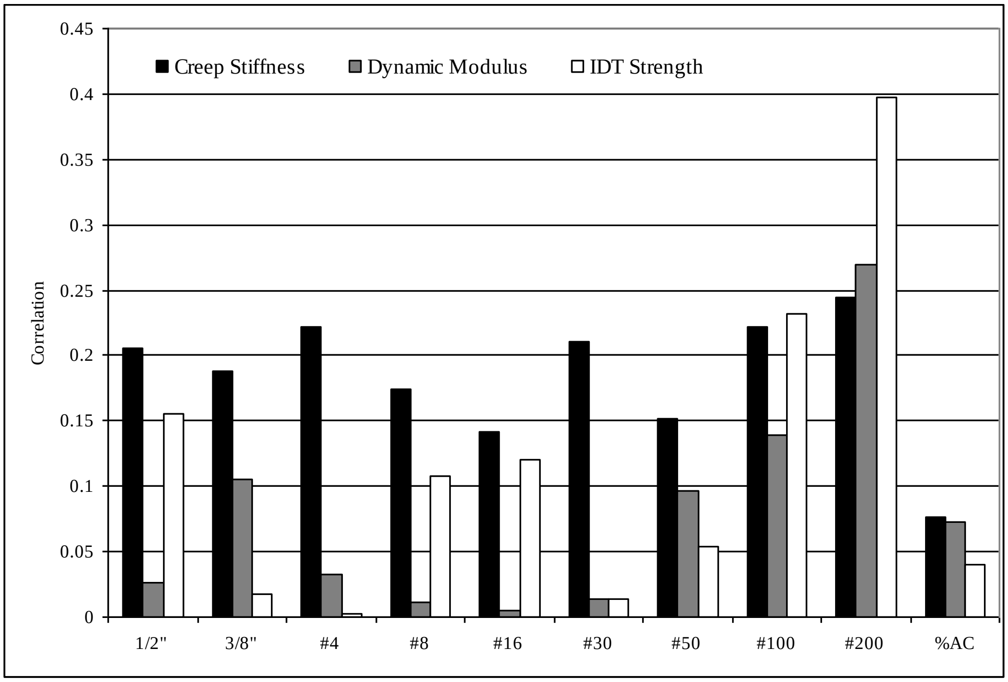


Figure 4.65 Correlations between composition and mechanical properties

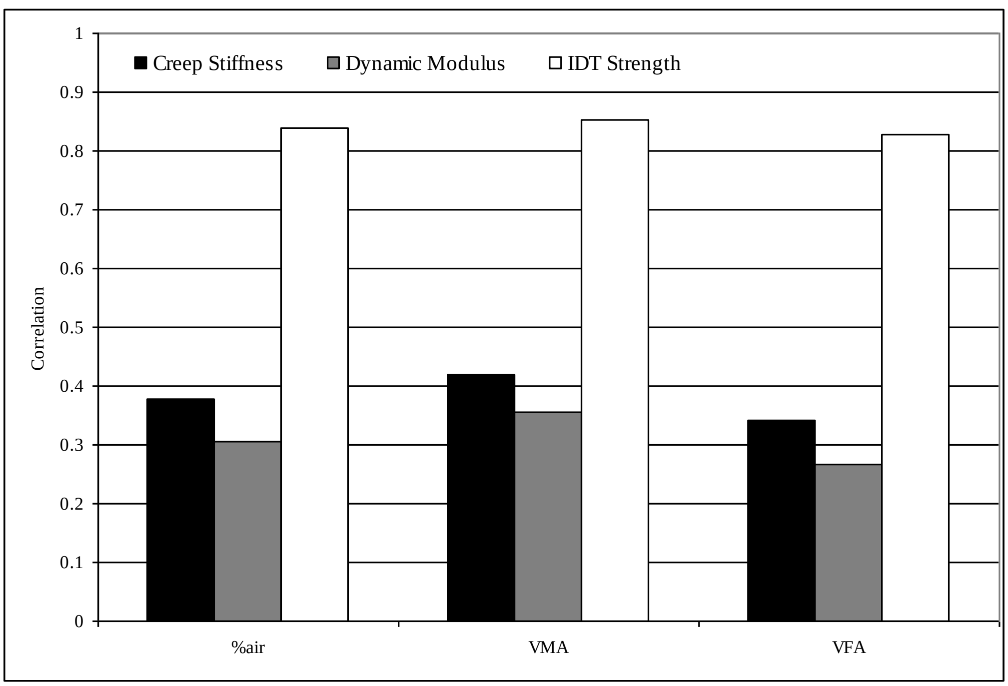


Figure 4.66 Correlation between volumetric and mechanical properties

CHAPTER 5 CONCLUSIONS

Efforts were made to identify the differences in material properties between expected and as-built hot mix asphalts (HMAs) based on the same job mix formula (JMF). Through fieldwork and laboratory testing, the variances and errors of HMA quality characteristics during field production and construction were measured, and the significances of associated influencing factors were examined using statistical analysis. This chapter presents a summary of research findings.

Based on testing results and data analyses presented in the previous chapters, the following conclusions can be drawn:

- The measurements of aggregate gradation and binder content obtained from the contractor, the state highway agency, and third parties are not always consistent with each other. Variances of composition properties were observed. Generally, the variance of percentage passing of aggregate at different sieve sizes was less than 2.5%, and the extreme value reached 4.5%. The variance of binder contents was less than 0.25%. The variance of aggregate gradation was significantly affected by operator and sublot number. Statistical analysis indicates that binder content was stable along material production, but data obtained using the ignition method varied among operators.

- Differences were observed in volumetric properties between JMF and specimens prepared from four scenarios. The differences are significantly affected by sublot and scenario. The variance of volumetric properties is only affected by testing scenario, that is, L&L, F&L, F&F, and field cores. The highest STDEVs of VTM, VMA, and VFA were 1.4, 1.2, and 6.7, respectively.

- The COV of mechanical properties was much higher than composition and volumetric properties. Among all mechanical properties investigated, ITS had the lowest COV at 7%, and flow tests had the highest COV with values up to 43%.

- The $|E^*|$ of field-produced HMA was greatly affected by material production and testing conditions. The results of multi-factor ANOVA analysis indicate that frequency, sublot, and temperature are significant factors. The variance of $|E^*|$ is affected by sublot and temperature.

- The permanent deformation at end of each test was used as a measurement of rutting resistance. A great variance was observed, and COV could reach 100%. The variance is affected by sublot number.

- Generally, creep stiffness obtained from three field scenarios—F&L, F&F, and field cores—does not agree with the value of L&L specimens. The percentage errors were significantly affected by scenario, sublot, temperature, and loading time. The variance of creep stiffness is not influenced by these factors.

- The results of indirect tensile strength (ITS) tests reveal a difference between field and L&L scenarios, and the difference changed along the production of HMA. The results of ITS testing have the lowest variance among all mechanical properties.
- Among the three types of property tested, mechanical properties have the greatest sublot-wise variance. Generally, the observed variance is close to that of previous studies and within the limits recommended by AASHTO R42.
- The correlations between composition and mechanical properties and between volumetric and mechanical properties were evaluated. Although the volumetric properties provide a better correlation with mechanical properties than with composition properties, as indicated by higher R^2 values, the correlation was generally found to be weak. Therefore, using volumetric properties would barely provide reliable estimates of future pavement performance.

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Appendix A Summary of Volumetric Properties Results

Scenario	ID	Air Voids (%)	VMA (%)	VFA (%)
L&L	A	1.2	12.4	90.0
	N	3.6	14.6	75.4
F&F	A1	1.6	12.4	87.3
	A2	1.6	12.1	87.0
	A3	1.8	12.1	85.6
	A4	1.8	12.5	85.9
	N1	5.3	16.2	67.4
	N2	5.2	16.1	67.8
	N3	5.1	16.2	68.4
	N4	5.9	16.5	64.0
	N5	5.3	16.4	67.7
	N6	5.5	16.7	66.9
	N7	4.7	16.8	71.8
	N8	5.4	16.4	67.4
	N9	5.8	16.8	65.4
F&L	A1	1.7	12.5	86.8
	A2	2.2	12.7	82.6
	A3	2.3	12.6	81.8
	A4	2.0	12.7	84.4
	N1	5.6	16.5	66.0
	N2	5.0	16.0	68.5
	N3	4.9	16.0	69.3
	N4	5.5	16.1	66.0
	N5	5.2	16.3	68.1
	N6	5.5	16.7	66.9
	N7	4.7	16.8	71.8
	N8	6.1	17.1	64.4
	N9	6.0	17.0	64.6
Core	A1	4.4	15.0	70.9
	A2	3.2	13.6	76.4
	A3	3.6	13.8	73.7
	A4	4.1	14.6	71.8
	N1	5.1	16.1	68.0
	N2	7.1	17.8	60.2
	N3	5.5	16.5	66.8
	N4	6.5	17.0	61.9
	N5	6.5	17.5	62.7
	N6	3.9	15.3	74.3
	N7	4.4	16.5	73.6
	N8	4.0	15.2	73.8
	N9	7.3	18.2	59.7

Appendix B Summary of Dynamic Modulus Results

Temp (ºC)	Scenario	ID	Dynamic Modulus (MPa)							
			25 Hz	20 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.1 Hz
4ºC	L&L	A	14042	13963	12263	10533	8388	6927	5529	3174
		N	17435	17106	15341	13574	11271	9603	7997	4854
	F&L	A1	15738	15604	13662	11785	9451	7847	6299	3721
		A2	17854	17253	15166	13189	10686	8912	7259	4240
		A3	17482	17285	14650	12552	10119	8419	6874	4032
		A4	13308	13214	11621	10042	8111	6798	5585	3430
		N1	11741	11353	10013	8726	7135	6042	5018	3054
		N2	8960	8559	7360	6229	4872	3963	3166	1741
		N3	11947	11647	10461	9300	7844	6816	5858	3869
		N4	12703	12257	10916	9612	7981	6846	5793	3720
		N5	12292	11897	10636	9418	7856	6767	5749	3760
		N6	12099	11747	10330	9087	7537	6502	5492	3488
		N7	15197	14607	12570	10618	8298	6708	5384	2917
		N8	12414	12050	10489	9044	7282	6062	4948	2908
		N9	10972	10586	9213	7900	6255	5115	4084	2221
21	L&L	A	3704	3405	2537	1851	1182	829	585	265
		N	5661	5286	4059	2968	1847	1239	826	347
	F&L	A1	3865	3535	2642	1945	1274	921	676	348
		A2	3918	3571	2703	2039	1421	1116	907	629
		A3	4278	3915	2949	2201	1499	1149	908	592
		A4	5113	4734	3685	2828	1975	1513	1185	730
		N1	3608	3370	2628	2008	1361	999	728	344
		N2	2131	1947	1432	1035	652	459	325	155
		N3	4394	4177	3401	2727	1981	1535	1178	601
		N4	4323	4045	3218	2517	1768	1331	993	487
		N5	4328	4085	3296	2625	1889	1453	1104	556
		N6	4107	3869	3093	2434	1722	1308	982	478
		N7	3352	3080	2284	1664	1066	752	533	248
		N8	4021	3748	2883	2173	1451	1052	760	356
		N9	3018	2776	2061	1501	958	678	483	230

Temp (ºC)	Scenario	ID	Dynamic Modulus (MPa)							
			25 Hz	20 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.1 Hz
37	L&L	A	765	679	472	327	200	146	110	62
		N	1006	848	542	349	204	150	115	77
	F&L	A1	929	816	592	433	292	228	185	125
		A2	1223	1109	852	675	516	449	399	324
		A3	1112	1008	767	599	449	386	339	270
		A4	1367	1237	939	729	539	456	395	305
		N1	897	799	578	414	268	197	148	82
		N2	499	435	308	217	137	104	82	53
		N3	1273	1167	869	637	413	303	224	118
		N4	1335	1211	879	629	397	286	210	114
		N5	1174	1072	792	576	370	270	200	107
		N6	1104	1004	733	528	333	242	178	95
		N7	618	528	369	258	161	123	97	62
		N8	834	740	530	375	237	176	136	84
		N9	631	547	388	275	174	134	106	69
54	L&L	A	195	172	126	92	61	51	43	31
		N	192	159	108	77	52	46	41	32
	F&L	A1	222	196	144	106	71	59	50	37
		A2	475	429	357	305	252	235	220	194
		A3	419	382	312	261	208	192	177	153
		A4	498	448	367	310	251	232	214	186
		N1	301	285	211	153	98	76	63	42
		N2	185	168	126	95	64	54	54	44
		N3	353	319	232	167	109	88	72	49
		N4	354	349	269	202	136	106	88	60
		N5	308	270	193	138	92	74	62	43
		N6	327	302	224	164	109	86	70	47
		N7	284	245	180	135	94	83	73	58
		N8	275	242	176	132	91	77	66	50
		N9	197	171	124	92	65	56	49	39

Appendix C Summary of Flow Test Results

Scenario	ID	Max. strain at the end of tests (με)	
		Flow time test	Flow number test
L&L	A	20169	49469
	N	22990	50037
F&L	A1	7084	11798
	A2	6217	8493
	A3	7591	10797
	A4	5738	6736
	N1	19473	32912
	N2	11262	28947
	N3	25631	28835
	N4	52282	50017
	N5	38291	26859
	N6	30539	27513
	N7	26680	15225
	N8	24743	20183
	N9	50151	20974

Appendix D Summary of IDT Creep Test Results

Scenario	ID	Creep Stiffness (GPa)					
		50s loading			500s loading		
		-10 ºC	-20 ºC	-30 ºC	-10 ºC	-20 ºC	-30 ºC
L&L		6.16	17.54	20.00	2.81	10.15	14.08
		9.82	21.20	27.46	7.03	16.43	23.83
F&L	A1	6.89	14.76	21.43	3.57	8.03	17.21
	A2	8.68	15.14	25.99	4.18	8.30	19.97
	A3	8.83	14.28	23.42	4.33	8.45	19.33
	A4	8.70	20.21	25.01	4.84	13.81	19.56
	N1	6.23	20.33	15.98	2.96	12.75	11.81
	N2	10.31	15.65	23.39	4.96	10.10	19.29
	N3	6.64	16.68	19.11	2.97	10.20	15.86
	N4	4.75	17.66	23.13	1.88	11.13	19.22
	N5	6.72	16.95	18.96	3.51	10.95	15.30
	N6	8.23	16.68	20.13	3.49	9.47	15.03
	N7	5.60	10.61	29.19	2.18	5.47	20.93
	N8	5.20	12.67	21.63	2.17	7.34	17.27
	N9	6.69	12.77	15.94	2.87	7.66	12.20
F&F	A1	5.97	14.62	22.57	2.47	8.65	17.17
	A2	4.42	16.95	20.94	1.84	10.59	17.16
	A3	5.19	13.64	18.35	2.11	8.51	14.88
	A4	6.98	12.75	24.83	3.04	7.68	18.89
	N1	5.69	13.75	20.34	2.32	8.11	14.54
	N2	5.35	14.83	21.98	2.17	8.12	15.27
	N3	4.66	13.81	16.56	1.97	8.43	12.77
	N4	4.78	14.69	13.63	1.89	9.20	10.06
	N5	4.61	13.93	21.31	1.85	7.53	15.79
	N6	3.82	11.97	11.48	1.48	6.39	5.84
	N7	5.61	11.95	15.85	2.34	5.77	7.89
	N8	5.85	13.46	17.06	2.42	6.81	11.73
	N9	5.72	12.58	18.82	2.36	5.94	13.88
Core	A1	5.17	10.19	25.04	1.87	4.82	16.32
	A2	6.81	13.28	22.34	2.49	6.51	16.56
	A3	5.10	11.68	14.12	2.05	6.23	12.08
	A4	3.99	12.30	13.14	1.50	6.75	9.80
	N1	5.28	10.66	17.48	1.89	5.69	13.75
	N2	2.87	9.93	18.21	1.02	5.03	13.78
	N3	2.40	13.80	21.67	0.89	6.05	16.92
	N4	4.01	11.29	15.29	1.43	5.93	12.32
	N5	3.91	10.09	12.51	1.48	5.30	10.62
	N6	3.33	11.70	11.80	1.17	5.91	9.88
	N7	2.68	7.43	14.38	0.90	3.55	11.90
	N8	4.69	12.65	15.14	1.67	6.40	11.84
	N9	3.07	9.05	13.23	1.08	4.86	9.70

Appendix E Summary of Flow Test Results

ID	-10ºC		-20ºC		-30ºC	
	Scenario	IDT Strength (MPa)	Scenario	IDT Strength (MPa)	Scenario	IDT Strength (MPa)
AIA	L&L	6.8	L&L	6.9	L&L	7.1
N	L&L	3.8	L&L	4.7	L&L	5.1
A1	F&F	5.7	F&L	7.5	F&F	6.7
A2	F&F	5.9	F&L	7.5	F&F	7.9
A3	F&F	5.7	F&L	7.0	F&F	6.7
A4	F&F	6.1	F&L	6.4	F&F	8.2
N1	F&F	4.0	F&L	5.3	F&F	5.5
N2	F&F	4.5	F&L	4.7	F&F	5.4
N3	F&F	3.6	F&L	5.6	F&F	5.1
N4	F&F	4.1	F&L	5.2	F&F	5.1
N5	F&F	4.0	F&L	5.0	F&F	5.1
N6	F&F	4.1	F&L	4.6	F&F	5.6
N7	F&F	3.9	F&L	5.7	F&F	4.9
N8	F&F	4.7	F&L	4.5	F&F	5.6
N9	F&F	3.8	F&L	5.1	F&F	5.4
A1	F&L	4.9	Core	5.1	F&L	8.0
A2	F&L	5.4	Core	6.6	F&L	7.5
A3	F&L	5.5	Core	5.5	F&L	7.3
A4	F&L	5.7	Core	5.5	F&L	6.5
N1	F&L	4.7	Core	4.5	F&L	6.2
N2	F&L	4.1	Core	3.4	F&L	5.5
N3	F&L	4.8	Core	4.3	F&L	5.9
N4	F&L	4.1	Core	3.7	F&L	6.1
N5	F&L	4.3	Core	3.8	F&L	6.1
N6	F&L	4.1	Core	4.4	F&L	5.2
N7	F&L	4.4	Core	4.0	F&L	4.9
N8	F&L	4.0	Core	4.0	F&L	4.0
N9	F&L	4.3	Core	3.0	F&L	5.5