A CASE STUDY FOR DEVELOPING SPECIFICATION LIMITS FOR HOT-MIX ASPHALT AND THE IMPACT ON PAY FACTORS

A Thesis

by

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ABSTRACT

Specification limits utilized in percent within limits (PWL) specifications are developed by highway agencies, and used to determine the percent of hot-mix asphalt "Lot" within specified limits, and used later to make payments to contractors. Development of specification limits must be based on the typical variability of test results used in PWL specifications. Using overly wide or tight specification limits to evaluate the new pavement could cause risk for highway agencies or contractors, respectively. This study explains how to develop new specification limits and evaluate the current ones by using different data sets from projects conducted by the Oregon Department of Transportation (ODOT).

All the calculations and analysis performed in this study are based on data collected from 15 different projects and contractors. Typical standard deviations (within-process variability) and "target miss" variability (how the mean values of test results are variable around the target values) have been determined for aggregate gradation, asphalt content, and in-place density which are considered as pay-elements in ODOT standard specifications. New specification limits have been developed based on typical variability. Then current specification limits adopted by ODOT were evaluated and compared to the proposed new specification limits. Three projects have been utilized to investigate the impact of using the proposed new specification limits on final payment. Using the developed new limits will lead to a decrease in the final costs of the projects. Also, ODOT will see an improvement in contractors' performance as these new limits will encourage the contractors to use high-quality materials with a low variability. It is recommended that DOTs consider regular evaluation of their specification limits by using new records and modify the specifications when needed.

DEDICATION

To my almighty God, thank you for the guidance, strength, power of mind, protection and skills and for giving me a healthy life. All of these, I offer to you.

To my mother, father, and wife who have been my source of inspiration and gave me strength when I thought of giving up, who continually provide their moral, spiritual, emotional, and financial support.

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1. INTRODUCTION

Evaluating materials is one of the main tasks in pavement construction projects. Based on this evaluation, the contractors are paid, and highway agencies either accept or reject the product. Percent within Limit (PWL) specifications is one of the most used methods by highway agencies to evaluate construction materials, and is recommended by the Federal Highway Administration (FHWA). Highway agencies must develop specification limits according to variations in test results and the variability of construction processes. The variations occur in response to difficult-to-control factors such as the nature of the materials used, certain construction and testing techniques, and technical errors. Therefore, contractors often cannot achieve, for example, the exact target value (TV) of asphalt content (AC) or density all the time. Thus, highway agencies must set specification limits for TVs and accept all materials that fall within these limits. To understand how wide these limits should be and their effects on payment are the primary goals of this study. Since specification limits directly impact the project cost, they need to be created according to statistical analysis and based on the actual variability of each property considered as the pay-element in the State.

Highway agencies evaluating hot mix asphalt (HMA) based on the construction Quality Control (QC) and Quality Acceptance (QA) tests, and then calculate the pay factors (PFs) for specific list of pay elements. These elements represent the properties of HMA mixture such as aggregate gradation, AC, air voids (AV), voids in mineral aggregate (VMA), density, smoothness, etc. Controlling these properties can assist in achieving a high-quality mixture with adequate performance in service. Each of these pay elements has a particular weight identified by the highway agency's standard specifications according to its importance, which is used to determine the payment for each "Lot" of HMA mixture (Newcomb et al. 2017). Definitions of "Lot" size vary from state to state. For instance, the Oregon Department of Transportation (ODOT) "Lot" size means the amount of material produced under a single job mix formula (JMF) and could be for the entire project. Other highway agencies consider a "Lot" to be the amount of daily production of HMA mixture, while others specify a tonnage of HMA mixture (Newcomb et al. 2017). Typically, highway agencies use a lot-by-lot acceptance approach to pay contractors according to the PWL specifications.

For payment purposes, PWL specifications are applied by many highway agencies within the United States. The agencies run a statistical analysis to find the PWL of each "Lot." PWL is defined as "the percentage of the "Lot" falling above a lower specification limit and below the upper specification limit," or the percent defective (PD), defined as "the percentage of a "Lot" falling outside specification limits" (Muench et al. 2001). Based on PWL specifications, the agency may accept a part of or the entire "Lot" quantity, and the contractor may receive a bonus or penalty based on the test results of pay-elements such as aggregate gradation, AC, density, etc. Some highway agencies use state acceptance QA test results, while others use contractor's QC data, after validation, to determine the PWL. Finding the PWL value of each "Lot" and identifying the weight of each pay-element are the two major steps required to calculate the final payment.

PWL specifications employ the inherent assumption that test results of construction materials follow a normal distribution (Munech et al. 2001). This assumption allows highway agencies to develop specifications limits by setting the upper specification limits (USL) and lower specification limits (LSL) based on the TV and typical variability of each pay-element

(AASHTO, 2016). These limits are often established by using the specification value as the TV and determining the threshold limits based on the achievable variability. The variability that exists within a highway agency's project portfolio helps in initially determining the achievable variability (i.e., the threshold limits). When enough tests results are available, and the typical variability is well known, a PWL can be constructed using 90% acceptable quality level (AQL), for instance, where the contractor receives full payment when 90% of the project test results fall within this range (i.e., the standard deviation of the identified TV is ±1.645) (AASHTO 2016, California Department of Transportation 2015, Willenbrock 1976, Seo 2010). Typical variability is often determined based on historical data or industry capabilities. Bias must be identified and understood when determining variability in the construction process. Ensuring the use of the same test procedure performed by qualified technicians helps to eliminate any influence of potential bias during the testing process. The typical variability for each pay-element (e.g., aggregate gradation) sets the specification limits and can be used to monitor the production and construction processes.

Wide specification limits, that do not require close monitoring during the production or construction processes to achieve the results within limits, lead to having a majority of results within the PWL. Having all results within the PWL specifications maximizes payment to the contractor, and allows for HMA mixture to be easily accepted, but potentially leading to inferior performance. Narrow specification limits decrease the number of test results within the PWL, and therefore decreases the amount paid to the contractor, but the narrower limits may have a positive effect on performance. Reasonably tighter tolerances can help highway agencies push contractors to deliver mixtures with better performance. Specification limits development should be fair to both highway agencies and contractors. Limits that do not account for test method variability and typical material variability are too tight. For instance, Figure 1 shows ten density test results that represent one "Lot." The TV is 94%, represented by the dashed line. When using the correct specification limits (developed based on actual current variability within test results), with a TV of ±2, and represented by "B" limits, 80% of the data fall within these limits. When using the wide limits (developed based on variability higher than actual) represented by "C" limits with a TV of ±4, 100% of the data fall within these limits. Using these wide limits means maximizing payment to the contractor. Conversely, when using the tighter limits (developed based on variability less than actual) represented by "A" limits with a TV of ±1, only 30% of the data fall within limits, meaning that 70% of the materials were not acceptable. In this case, the contractor would be penalized.

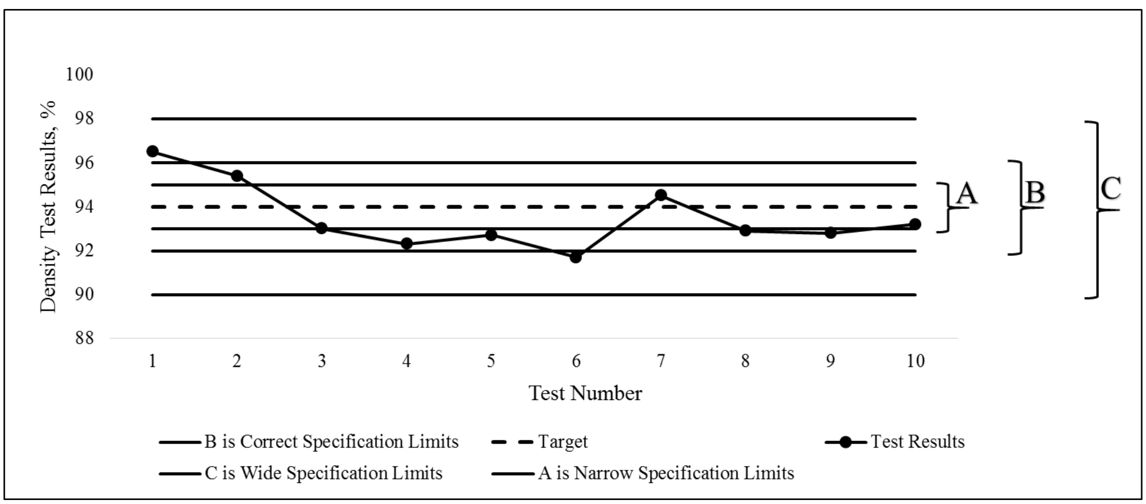

Figure 1 Test Results within Wide, Narrow, and Correct Specification Limits

Highway agencies and contractors have been investigating QA and QC specifications during recent years to improve the quality of HMA pavements. Due to this development, specification limits of pay-elements have been changed to make pay factors fair to both contractors and agencies. These changes occur in specification limits due to variability in materials, sampling techniques, testing methods, and construction methods (Muench et al. 2001). FHWA recommended that monitoring HMA performance is essential to determine how much the current variability values change when compared to the initial values utilized to develop the specification limits (Burati Jr, 2006). The objective of this study is to provide a comprehensive review and recommendations to ODOT for developing their specification limits in PWL specifications to calculate payments. ODOT data and contractor's data from a number of projects will be employed as a case study to develop new specification limits. For this purpose, the proposed new specification limits will be utilized in PWL specifications to show the impact on payment of each pay-element. This study will encourage highway agencies who have not evaluated their current specification limits to do so. The proposed new limits are calculated using the test results collected through contractors and used by ODOT to calculate the PWL.

2. BACKGROUND

PWL is statistical method developed by the Department of Defense in 1958 to measure the quality of HMA pavement (Schlierkamp, 2011). FHWA encouraged highway agencies to use PWL specifications as an approved method for evaluating the quality and to calculate payments (Breakah et al. 2007). In the early 1970s, the New Jersey Department of Transportation was the first highway agency to adopt PWL specifications for its acceptance plan of HMA pavement (Schlierkamp 2011, Breakah et al. 2007). In 2005, and according to a report published by the National Cooperative Highway Research Program (NCHRP), 27 out of 45 state agencies have adopted PWL specifications in their QA plans (Schlierkamp 2011, Breakah et al. 2007). This section will define PWL specification, and present the steps of determining PWL and pay factors.

2.1 Defining Percent within Limits

The term PWL has been used to refer to the quality of a HMA pavement "Lot". The relationship between PWL and PD can be defined with a simple equation (PWL=100-PD). PWL specifications uses a "Lot" mean value ($\overline{x}$) and the standard deviation (STDEV) value to estimate the quality of the "Lot" within the specification limits. This method is similar in concept to the calculation of area under the normal distribution curve, assuming that the data set follows a normal distribution. Contractors may be penalized or rewarded according to the PWL specifications. All this depends on their performance and whether their test results were within specification limits or not.

Some terms are needed in the standard specification to apply PWL specification clearly and adjust the payment. The following are the definitions of these key elements (Newcomb et al. 2017, Burati et al. 2003, Oregon Department of Transportation 2018, Missouri Department of Transportation 2016, Schmitt et al. 1998)

1. **Lot**: The amount of HMA material that is to be judged acceptable or not according to tests results. "Lot" size can be developed based on quantity, area, or time. Some highway agencies consider the "Lot" size as the amount of daily production. Others identify the "Lot" size as a specific tonnage of HMA mixture or the amount of material produced using a consistent process (i.e., JMF).
2. **Sublot**: An equal quantity of HMA mixture subdivided from a "Lot". Typically, the range is from 500 tons to 2,000 tons.
3. **Pay-elements**: Specific properties of HMA mixture selected by a highway agency such as AV, aggregate gradation, AC, density, smoothness, VMA, etc. Selection of these properties must be implemented by highway agency engineers according to their judgment of how important these properties are to performance. For instance, selecting AC as a pay-element is a common choice among highway agencies due to its impact on cracking and rutting resistance. Increasing AC percentage lead to high cracking resistance and low rutting resistance. Therefore, balance is required and the payment to contractors must be based on test results of this kind of properties. Each property has a weight factor according to its performance. Pay-elements and their weights are varied among states. For example, in Oregon, density is one of the pay-elements and weighs 44% of the total payment, while it is 25% in Missouri.

4. **Specification limits**: Tolerance limits is the variability of results around the TV of each property considered as a pay-element or utilized to accept or reject the construction materials. An agency can develop specification limits as USL and LSL and according to the typical variability of tests results for each property. Specification limits are used in PWL specifications to determine the Upper Quality Index (Q_U) and the Lower Quality Index (Q_L). This process is presented subsequently to determine the PWL.

Figure 2 displays the general concept of PWL specifications, which represents the area under the normal distribution curve and between USL and LSL. For each "Lot" the more test results that fall within these limits, the more acceptable the materials and variability in the results. Test results outside the specification limits mean that unacceptable materials fall in the PD area. These materials have a variability higher than the allowable. A 90% PWL is a common choice to define the AQL (Burati et al. 2003). That means when only 10% of materials test results are located in the PD area, then the contractor can receive the full payment. When more than 10% of materials test results are located in the PD area, the contractor will be penalized. Conversely, when less than 10% of materials test results are located in the PD area, the contractor may receive a bonus. In both cases, a highway agency must adjust the payment according to the results for the "Lot." Therefore, specification limits can affect the results and decision, and that will create risk on both sides (i.e., contractor or highway agency) when incorrect specification limits are applied. At the same time, this method can encourage contractors to produce mixtures within the required specifications and have the test results with acceptable variation and close to the desired TVs.

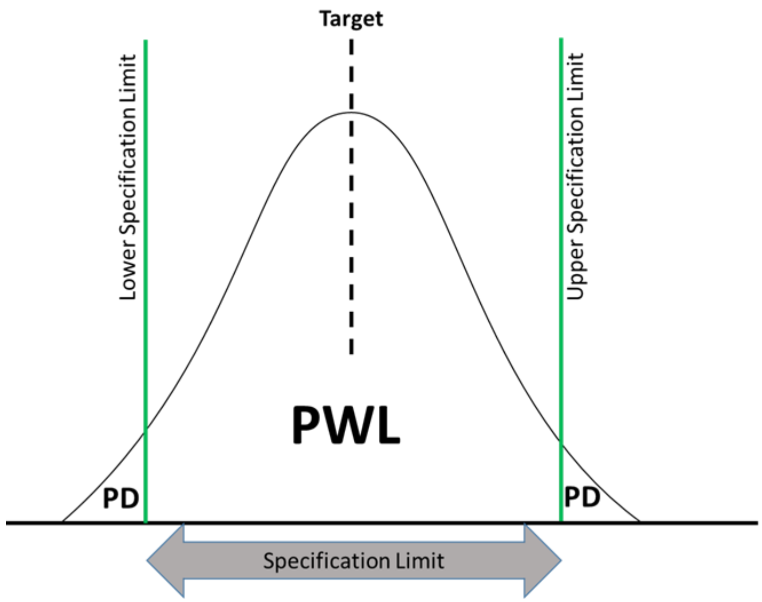

Figure 2 Illustration of PWL Concept

In conclusion, PWL is a powerful tool to estimate the “Lot” quality. Small number of random samples are tested to represent the entire “Lot”. Some factors affect the PWL directly, such as mean value of tests results, STDEV, and USL and LSL. Incorrect usage of one of these parameters gives inaccurate results for the “Lot” quality.

2.2 Steps to Determine PWL

Highway agencies that have started to evaluate the payment and pay contractors according to the PWL specifications should collect samples and test them randomly. Each agency has a specific strategy to choose QC and QA sample locations. Both of them must follow the same method in their sampling and testing procedures to have approximately the same

STDEV. As a part of PWL specifications and acceptance plan requirements, highway agencies should decide to employ tests results of QC, QA, or both for acceptance and payment purposes. In some cases, the third party may do the sampling and testing. In ODOT specifications, QC tests are performed at the highest frequency, while QA tests are conducted at 10% of QC testing (Oregon Department of Transportation, 2018). Therefore, QC test results are utilized for acceptance and payment purposes after verification. For verification, the t-test and the F-test are two statistical analysis tests applied for verification. The F-test is used to measure the degree of agreement between the variabilities of QC and QA data sets, while the t-test is employed to test the agreement in the means of two data sets (Burati et al. 2003). Passing these tests is considered as an approval to use QC tests for PWL specification. The results of F-test and t-test for the projects presented in this study and related definitions are summarized in Appendix A.

Determination of PWL is the next step after selecting the data set for acceptance and payment purposes. PWL is a function of test results mean, TV, STDEV, and specification limits of pay elements. The following steps make up the PWL calculation process applied by ODOT and other states (Oregon Department of Transportation, 2018).

Step 1: determine the Mean ($\bar{x}$) value of test results for "Lot" from equation 1:

$$\bar{x} = \frac{\sum x}{n} \tag{1}$$

where,

$\sum x$ = summation of sample test values; and

n = total number of tests.

Step 2: determine the STDEV of "Lot" using equation 2:

$$STDEV = \sqrt{\frac{\sum x^2 - n\overline{x}^2}{n-1}} \qquad (2)$$

Where,

ΣX^2 = summation of the squares of each test result; and

$\overline{x}^2$ = square of the mean value of lot.

Step 3: determine the upper-quality index (Q_U) from equation 3:

$$Q_U = \frac{USL - \overline{x}}{STDEV} \qquad (3)$$

where *USL* is the upper specification limit (TV+ specification limit).

Step 4: determine the lower quality index (Q_L) from the following equation:

$$Q_L = \frac{\overline{x} - LSL}{STDEV} \qquad (4)$$

where *LSL* is the lower specification limit (TV – specification limit).

Step 5: determine Percent within Upper limit (P_U) and Percent within the Lower limit (P_L) from quality level analysis table (Table 1 and Table 2). P_U and P_L are a function of Q_U, Q_L, and the number of tests (n). Increasing Q_U or Q_L will increase P_U or P_L and vice versa.

Table 1 Quality Level Analysis by the STDEV Method (n=3 to 11)

P_U or P_L for positive values of Q_U or Q_L	Q_U or Q_L							
	n=3	**n=4**	**n=5**	**n=6**	**n=7**	**n=8**	**n=9**	**n=10 to 11**
100	1.16	1.50	1.79	2.03	2.23	2.39	2.53	2.65
99	-	1.47	1.67	1.80	1.89	1.95	2.00	2.04
98	1.15	1.44	1.60	1.70	1.76	1.81	1.84	1.86
97	-	1.41	1.54	1.62	1.67	1.70	1.72	1.74
96	1.14	1.38	1.49	1.55	1.59	1.61	1.63	1.65
95	-	1.35	1.44	1.49	1.52	1.54	1.55	1.56
94	1.13	1.32	1.39	1.43	1.46	1.47	1.48	1.49
93	-	1.29	1.35	1.38	1.40	1.41	1.42	1.43
92	1.12	1.26	1.31	1.33	1.35	1.36	1.36	1.37
91	1.11	1.23	1.27	1.29	1.30	1.30	1.31	1.31
90	1.10	1.20	1.23	1.24	1.25	1.25	1.26	1.26
89	1.09	1.17	1.19	1.20	1.20	1.21	1.21	1.21
88	1.07	1.14	1.15	1.16	1.16	1.16	1.16	1.17
87	1.06	1.11	1.12	1.12	1.12	1.12	1.12	1.12
86	1.04	1.08	1.08	1.08	1.08	1.08	1.08	1.08
85	1.03	1.05	1.05	1.04	1.04	1.04	1.04	1.04
84	1.01	1.02	1.01	1.01	1.00	1.00	1.00	1.00
83	1.00	0.99	0.98	0.97	0.97	0.96	0.96	0.96
82	0.97	0.96	0.95	0.94	0.93	0.93	0.93	0.92
81	0.96	0.93	0.91	0.90	0.90	0.89	0.89	0.89
80	0.93	0.90	0.88	0.87	0.86	0.86	0.86	0.85
79	0.91	0.87	0.85	0.84	0.83	0.82	0.82	0.82
78	0.89	0.84	0.82	0.80	0.80	0.79	0.79	0.79
77	0.87	0.81	0.78	0.77	0.76	0.76	0.76	0.75
76	0.84	0.78	0.75	0.74	0.73	0.73	0.72	0.72
75	0.82	0.75	0.72	0.71	0.70	0.70	0.69	0.69
74	0.79	0.72	0.69	0.68	0.67	0.66	0.66	0.66
73	0.76	0.69	0.66	0.65	0.64	0.63	0.63	0.62
72	0.74	0.66	0.63	0.62	0.61	0.60	0.60	0.59
71	0.71	0.63	0.60	0.59	0.58	0.57	0.57	0.57
70	0.68	0.60	0.57	0.56	0.55	0.55	0.54	0.54
69	0.65	0.57	0.54	0.53	0.52	0.52	0.51	0.51
68	0.62	0.54	0.51	0.50	0.49	0.49	0.48	0.48
67	0.59	0.51	0.47	0.47	0.46	0.46	0.46	0.45
66	0.56	0.48	0.45	0.44	0.44	0.43	0.43	0.43

Table 1 Continued

P_U or P_L for positive values of Q_U or Q_L	Q_U or Q_L							
	n=3	**n=4**	**n=5**	**n=6**	**n=7**	**n=8**	**n=9**	**n=10 to 11**
65	0.52	0.45	0.43	0.41	0.41	0.40	0.40	0.40
64	0.49	0.42	0.40	0.39	0.38	0.38	0.37	0.37
63	0.46	0.39	0.37	0.36	0.35	0.35	0.35	0.34
62	0.43	0.36	0.34	0.33	0.32	0.32	0.32	0.32
61	0.39	0.33	0.31	0.30	0.30	0.29	0.29	0.29
60	0.36	0.30	0.28	0.27	0.27	0.27	0.26	0.26
59	0.32	0.27	0.25	0.25	0.25	0.24	0.24	0.24
58	0.29	0.24	0.23	0.22	0.21	0.21	0.21	0.21
57	0.25	0.21	0.20	0.19	0.19	0.19	0.18	0.18
56	0.22	0.18	0.17	0.16	0.16	0.16	0.16	0.16
55	0.18	0.15	0.14	0.14	0.13	0.13	0.13	0.13
54	0.14	0.12	0.11	0.11	0.11	0.11	0.10	0.10
53	0.11	0.09	0.08	0.08	0.08	0.08	0.08	0.08
52	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.05
51	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: For negative values of Q_U or Q_L, P_U or P_L is equal to 100 minus the table value for P_U or P_L. if the value of Q_U or Q_L does not correspond exactly to a figure in the table, use the next higher figure.

Table 2 Quality Level Analysis by the STDEV Method (n=12 to ∞)

P_U or P_L for positive values of Q_U or Q_L	Q_U or Q_L						
	n=12 to 14	**n=15 to 18**	**n=19 to 25**	**n=26 to 37**	**n=38 to 69**	**n=70 to 200**	**n=201 to ∞**
100	2.83	3.03	3.20	3.38	3.54	3.70	3.83
99	2.09	2.14	2.18	2.22	2.26	2.29	2.31
98	1.91	1.93	1.96	1.99	2.01	2.03	2.05
97	1.77	1.79	1.81	1.83	1.85	1.86	1.87
96	1.67	1.68	1.70	1.71	1.73	1.74	1.75
95	1.58	1.59	1.61	1.62	1.63	1.63	1.64
94	1.50	1.51	1.52	1.53	1.54	1.55	1.55
93	1.44	1.44	1.45	1.46	1.46	1.47	1.47
92	1.37	1.38	1.39	1.39	1.40	1.40	1.40
91	1.32	1.32	1.33	1.33	1.33	1.34	1.34
90	1.26	1.27	1.27	1.27	1.28	1.28	1.28
89	1.21	1.22	1.22	1.22	1.22	1.22	1.23
88	1.17	1.17	1.17	1.17	1.17	1.17	1.17
87	1.12	1.12	1.12	1.12	1.12	1.13	1.13
86	1.08	1.08	1.08	1.08	1.08	1.08	1.08
85	1.04	1.04	1.04	1.04	1.04	1.04	1.04
84	1.00	1.00	1.00	1.00	0.99	0.99	0.99
83	0.96	0.96	0.96	0.96	0.95	0.95	0.95
82	0.92	0.92	0.92	0.92	0.92	0.92	0.92
81	0.88	0.88	0.88	0.88	0.88	0.88	0.88
80	0.85	0.85	0.85	0.84	0.84	0.84	0.84
79	0.81	0.81	0.81	0.81	0.81	0.81	0.81
78	0.78	0.78	0.78	0.78	0.77	0.77	0.77
77	0.75	0.75	0.75	0.74	0.74	0.74	0.74
76	0.71	0.71	0.71	0.71	0.71	0.71	0.71
75	0.68	0.68	0.68	0.68	0.68	0.68	0.67
74	0.65	0.65	0.65	0.65	0.65	0.65	0.64
73	0.62	0.62	0.62	0.62	0.62	0.61	0.61
72	0.59	0.59	0.59	0.59	0.59	0.58	0.58
71	0.56	0.56	0.56	0.56	0.56	0.55	0.55
70	0.53	0.53	0.53	0.53	0.53	0.53	0.52
69	0.50	0.50	0.50	0.50	0.50	0.50	0.50
68	0.48	0.48	0.47	0.47	0.47	0.47	0.47
67	0.45	0.45	0.45	0.44	0.44	0.44	0.44

Table 2 Continued

P_U or P_L for positive values of Q_U or Q_L	Q_U or Q_L						
	n=12 to 14	**n=15 to 18**	**n=19 to 25**	**n=26 to 37**	**n=38 to 69**	**n=70 to 200**	**n=201 to ∞**
66	0.42	0.42	0.42	0.42	0.41	0.41	0.41
65	0.39	0.39	0.39	0.39	0.39	0.39	0.39
64	0.37	0.37	0.36	0.36	0.36	0.36	0.36
63	0.34	0.34	0.34	0.34	0.33	0.33	0.33
62	0.31	0.31	0.31	0.31	0.31	0.31	0.31
61	0.29	0.29	0.28	0.28	0.28	0.28	0.28
60	0.26	0.26	0.26	0.26	0.26	0.25	0.25
59	0.23	0.23	0.23	0.23	0.23	0.23	0.23
58	0.21	0.21	0.20	0.20	0.20	0.20	0.20
57	0.18	0.18	0.18	0.18	0.18	0.18	0.18
56	0.15	0.15	0.15	0.15	0.15	0.15	0.15
55	0.13	0.13	0.13	0.13	0.13	0.13	0.13
54	0.10	0.10	0.10	0.10	0.10	0.10	0.10
53	0.08	0.08	0.08	0.08	0.08	0.08	0.08
52	0.05	0.05	0.05	0.05	0.05	0.05	0.05
51	0.03	0.03	0.03	0.03	0.03	0.03	0.02
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Note: For negative values of Q_U or Q_L, P_U or P_L is equal to 100 minus the table value for P_U or P_L. if the value of Q_U or Q_L does not correspond exactly to a figure in the table, use the next higher figure.							

Step 6: determine the total percent within specification limit (PT) from equation 5

$$PT = (P_U + P_L) - 100 \tag{5}$$

Step 7: use PT from step 6 to determine the pay factor (PF) of each pay-element from Table 3 and Table 4. The PF is a function of PT and sample size.

Table 3 Determine Pay Factor for Sample Size 3 to 11

Pay Factor	PT							
	n=3	**n=4**	**n=5**	**n=6**	**n=7**	**n=8**	**n=9**	**n=10 to 11**
1.05	100	100	100	100	100	100	100	100
1.04	90	91	92	93	93	93	94	94
1.03	80	85	87	88	89	90	91	91
1.02	75	80	83	85	86	87	88	88
1.01	71	77	80	82	84	85	85	86
1.00	68	74	78	80	81	82	83	84
0.99	66	72	75	77	79	80	81	82
0.98	64	70	73	75	77	78	79	80
0.97	62	68	71	74	75	77	78	78
0.96	60	66	69	72	73	75	76	77
0.95	59	64	68	70	72	73	74	75
0.94	57	63	66	68	70	72	73	74
0.93	56	61	65	67	69	70	71	72
0.92	55	60	63	65	67	69	70	71
0.91	53	58	62	64	66	67	68	69
0.90	52	57	60	63	64	66	67	68
0.89	51	55	59	61	63	64	66	67
0.88	50	54	57	60	62	63	64	65
0.87	48	53	56	58	60	62	63	64
0.86	47	51	55	57	59	60	62	63
0.85	46	50	53	56	58	59	60	61
0.84	45	49	52	55	56	58	59	60
0.83	44	48	51	53	55	57	58	59
0.82	42	46	50	52	54	55	57	58
0.81	41	45	48	51	63	54	56	57
0.80	40	44	47	50	52	53	54	55
0.79	38	43	46	48	50	52	53	54
0.78	37	41	45	47	49	51	52	53
0.77	36	40	43	46	48	50	51	52
0.76	34	39	42	45	47	48	50	51
0.75	33	38	41	44	46	47	49	50
Reject	Quality levels less than those specified for a 0.75							
Note: if the TP does not correspond exactly to a figure in the table, use the next lower value.								

Table 4 Determine Pay Factor for Sample Size 12 to ∞

Pay Factor	PT						
	n=12 to 14	**n=15 to 18**	**n=19 to 25**	**n=26 to 37**	**n=38 to 69**	**n=70 to 200**	**n=201 to ∞**
1.05	100	100	100	100	100	100	100
1.04	95	95	96	96	97	97	99
1.03	92	93	93	94	95	95	97
1.02	89	90	91	92	93	94	95
1.01	87	88	89	90	91	93	94
1.00	85	86	87	89	90	91	93
0.99	83	85	86	87	88	90	92
0.98	81	83	84	85	87	88	90
0.97	80	81	83	84	85	87	89
0.96	78	80	81	83	84	86	88
0.95	77	78	80	81	83	85	87
0.94	75	77	78	80	81	83	86
0.93	74	75	77	78	80	82	84
0.92	72	74	75	77	79	81	83
0.91	71	73	74	76	78	80	82
0.90	70	71	73	75	76	79	81
0.89	68	70	72	73	75	77	80
0.88	67	69	70	72	74	76	79
0.87	66	67	69	71	73	75	78
0.86	64	66	68	70	72	74	77
0.85	63	65	67	69	71	73	76
0.84	62	64	65	67	69	72	75
0.83	61	63	64	66	68	71	74
0.82	60	61	63	65	67	70	72
0.81	58	60	62	64	66	69	71
0.80	57	59	61	63	65	67	70
0.79	56	58	60	62	64	66	69
0.78	55	57	59	61	63	65	68
0.77	52	56	57	60	62	64	67
0.76	51	55	56	58	61	63	66
0.75	51	53	55	57	59	62	65
Reject	Quality levels less than those specified for a 0.75						

Step 8: use PF from step 7 and weighting factor to determine the weighted pay factor (WPF) for each pay-element from the following equation

$$WPF = (PF) \times (f_i) \quad (6)$$

where (f_i) is a weighting factor of pay-element

Step 9: determine the Composite Pay Factor (CPF) for each "Lot" for all pay-elements from equation 7

$$CPF = \frac{\sum WPF}{\sum f_i} \quad (7)$$

where,

ΣWPF is the sum of weighted pay-elements

Σf_i is the sum of weighting factors

Figure 3 is a flow chart summarizing the previous steps and showing where highway agencies need to utilize the specification limits to determine the PWL and PFs for each "Lot".

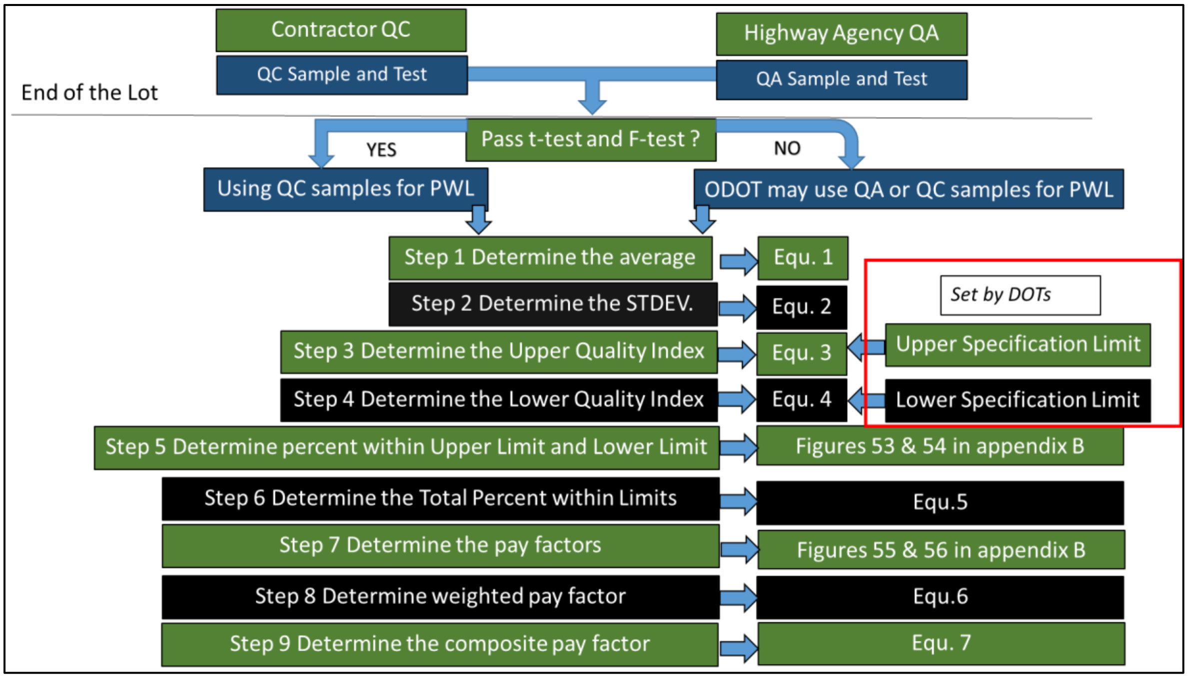

Figure 3 Adopted Procedure Summarized in a Flow Chart to Determine PWL in This Study

3. SPECIFICATION LIMITS

Specification limits utilized in PWL specifications play a significant role in accepting or rejecting the HMA pavement, calculating PWL, and paying contractors. Highway agencies have developed these limits since contractors cannot achieve the exact TVs from the JMF during production. Typically, highway agencies accept materials that fall within these limits and reward contractors who achieve more than the AQL (90% is most cases) within specification limits. Accordingly, specification limits must be developed correctly taking into account all sources of variability (within-process variability and “target miss” variability). In addition, highway agencies should take into account the number of contractors that can achieve these limits and ensure the quality of HMA pavement at the same time.

HMA pavement consists of aggregates, AC, and additives, all of which are required to meet the desired specifications for the individual components and final mixture. The complexity of HMA pavement requires laboratory and field testing of the materials, statistical analyses, and verification to reach the desired goal of a well-constructed and long-lasting pavement. Differences among the highway agencies’ specification limits arise due to typical variability used to develop the specification limits. Additionally, the time that has passed since these limits were and how highway agencies calculate the specification limits are other important factor. Table 5 shows two characteristics that are utilized as pay-elements and their specification limits in different states (Newcomb et al. 2017, California Department of Transportation 2015, Oregon Department of Transportation 2018, Missouri Department of Transportation 2016, Boesen 2013, Sholar et al, 2001).

Table 5 Specification Limits for AC and Density in some States

State	**AC**	**Density**
Oregon	TV ±0.50%	TV +8.00%
Arizona	TV ±0.50%	TV ±3.00%
Colorado	TV±0.30%	TV ±4.00%
California	TV -0.30% to TV +0.50%	TV ±3.00%
Missouri	TV ±0.30%	TV ±2.50%
Florida	TV ±0.40%	TV ±2.00%
Utah	TV ±0.35%	TV –2.00% to TV +3.00%

Some specification limits have been developed and used for a long time without updates. The use of these outdated specification limits may affect the project cost.

This section includes literature review of specification limits and present some highway agencies practices for developing their specification limits. Also, the section will present the problem of ODOT specifications limits.

3.1 Literature Review of Specification Limits

The ODOT HMA pay-elements include 0.75 inch and 0.5 inch sieves, Nos. 4, 8, 30, and 200 sieves, AC, and in-place density (Oregon Department of Transportation, 2018). Each element has a weighting factor representing the importance of that element in the total payment.

Table 6 shows the weighting factors for each pay-element and the current ODOT specification limits (Oregon Department of Transportation, 2018).

Table 6 ODOT Pay Elements, Weighting Factor, and Specification Limits

Pay-Elements	**Weighting Factor**	**Specification Limits**			
Aggregate gradation	28% (asymmetrically distributed)	Mixture Design (as specified by gradation)			
		Percent Passing	3/4"	1/2"	3/8"
		1" sieve	±5%	-	-
		3/4" sieve	90%–100%	±5%	-
		1/2" sieve	±5%	90%-100%	±5%
		No. 4 sieve	±5%	±5%	±5%
		No. 8 sieve	±4%	±4%	±4%
		No. 30 sieve	±4%	±4%	±4%
		No. 200 sieve	±2%	±2%	±2%
Asphalt content (Ignition)	28%		± 0.5%		
In-place density	44%		92 % minimum		

Balance is required to reward contractors who achieve high performance (low variability) and penalize those with low performance (high variability). As mentioned in Table 5, the Colorado AC specification limits are ±0.30%; thus, a back-calculation of the AC variability is

0.182 (i.e., the specification limits determined by multiplying the typical variability by 1.645 when the AQL is 90%; so 0.30 divided by 1.645 should give the variability of AC in Colorado. ODOT uses ±0.50% as specification limits for AC. Dividing 0.50% by 1.645 gives 0.30%, which is consider one of the higher typical variability of AC among highway agencies standards. Developing specification limits based on higher typical variability than actual (within test results) variability could result in the highway agency routinely paying out the maximum amount of bonus which is 1.05. The red dots in Figure 4 represent test results within variability values lower than one used to develop the specification limits presented.

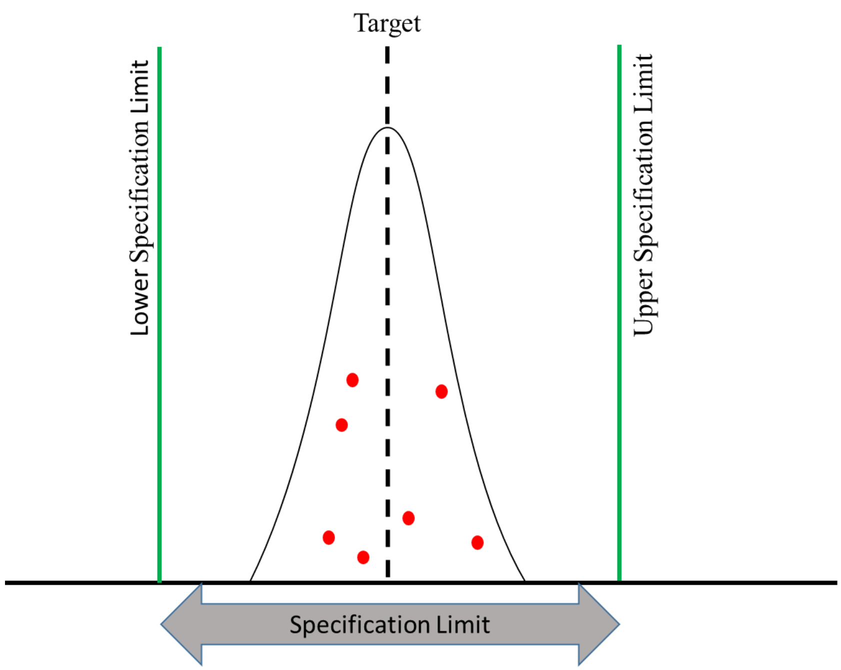

Figure 4 Development Specification Limits Using Higher Variability Value than Actual

The Florida Department of Transportation (FDOT) uses PWL specifications for payment purposes as well. In 2005, FDOT decided to refine its PWL specification limits. This change was the first significant modification impacting the contractor's payments related to paving since 1977 (Sholar et al. 2001). During these changes, FDOT employed contractors QC test results from some previous projects. These results helped FDOT arrive at mean and typical STDEV (within-process variability) values required for the modification. Using the initial results, FDOT engaged other stakeholders for input. After gathering stakeholders' input, FDOT finalized the specification in a way that tightened specification limits while assuaging the concerns of the contractor community. Table 7 shows the previous specification limits and the new specification limits developed by FDOT (Sholar et al. 2001, Florida Department of Transportation 2000).

Table 7 Florida Department of Transportation Hot Mix Asphalt Specification Limits

Pay Element (percent)	**Previous Specification Limits,%**	**New Specification Limits,%**
Passing No.8 sieve	TV ±5.50	TV ±3.10
Passing No. 200 sieve	TV ±2.00	TV ±1.00
AC	TV ±0.55	TV ±0.40
AV	N.A.	TV ±1.20
Density, vibratory mode (percent of Gmm):	N.A.	TV -1.20 to TV +2.00
Density, static mode (percent of Gmm):	N.A.	TV -1.50* to TV +3

* No vibratory mode in the vertical direction will be allowed. Other vibratory modes will be allowed if approved by the Engineer.

One of the significant factors when developing a new standard specification is reevaluating the previous specification limits (Burati Jr, 2006). Assumed variability values to develop the specification limits or applying the same specification limits based upon old data are incorrect, especially for highway agencies who are using these limits in PWL specifications to determine payments. The South Carolina Department of Transportation (SCDOT) decided to evaluate their specification limits which were developed based on assumed values (Burati Jr, 2006). SCDOT utilized the historical data obtained from FHWA to determine the typical variability values and applied them to develop new specification limits for PWL specifications. SCDOT used 39 different projects to determine the typical variability values of test results for AC, AV, VMA, and density. As a result of this study, the new specification limits became tighter than original limits. Table 8 shows the specification limits in both cases (Burati Jr, 2006).

Table 8 Specification Limits in Initial and Revised SCDOT HMA QA Specifications

Acceptance Quality Characteristic	**Original Specification Limits,%**	**New Specification Limits, %**
AC / Surface	TV ±0.41	TV ±0.36
AC / Intermediate	TV ±0.48	TV ±0.43
AV	TV ±1.25	TV ±1.15
VMA	TV ±1.25	TV ±1.15
Density	TV-2 to TV+2	TV-1.2 to TV+3

It is essential to develop reasonable specification limits that minimize the risk to contractors and highway agencies. For instance, a ±0.1% in AC specification limits does not make statistical sense since the variability of materials, testing methods, and sampling techniques are higher than 0.1% (Muench et al. 2001). In this case, the chance of penalizing the contractor is high. Conversely, a ±0.7% in AC specification limits could be too wide and more than the typical variability (Figure 4). This situation will increase the risk for highway agencies and increase the chance of accepting a low quality pavement, and the agency will pay more bonus to contractors.

According to AASHTO R42-06 (2016), when the AQL is 90% PWL, the specification limits can be calculated using a typical STDEV (within-process variability) and multiplying it by 1.645 (±1.645 × STDEV) (AASHTO, 2016). Table 9 represents the typical industry STDEV for HMA composition property recommended by AASHTO and taking into account the test methods only. It should be noted that ODOT used the ignition furnace method to determine AC.

Table 9 Developed Typical STDEVs for HMA Parameters during NCHRP 9-7 (AASHTO, 2016)

HMA Composition Property	Extraction	Nuclear Gauge	Ignition Furnace	Cold Feed
AC	±0.25	±0.18	±0.13	NA
Gradation Passing 4.75mm (No.4) and larger sieve	±3	N.A.	*	±3
Passing 2.36mm (No.8) to 0.150 (100) mm Sieve %	±2	N.A.	*	±2
Passing 0.075mm (No.200) Sieve %	±0.7	N.A.	*	±0.7
Maximum Theoretical Specific Gravity (Gmm)	±0.015			
Gyratory Compacted HMA Property				
AV, %	±1			
VMA, %	±1			
Voids Filled with Asphalt, VFA, %	±5			
Bulk Specific Gravity (G_{mb})	±0.022			
Roadway Core Density (%G_{mm})	±1.4			

Note:
a: Agency-specific standard deviations may be developed in lieu of the industry deviation
*: NCHRP 9-7 did not develop standard deviations for the gradation of aggregate recovered from the furnace. However, the standard deviation is expected to be the same as for cold feed or solvent – extracted aggregates.

According to AASHTO R42-06 (2016), highway agencies should determine their STDEV values by considering the recommendations offered by the NCHRP study 9-7 and summarized in Table 9. When a highway agency has reliable historical records, using an agency-specific STDEV multiplied by 1.645 is acceptable, but the product should not be substantially larger than STDEV values in Table 9 according to AASHTO recommendations (AASHTO, 2016). This concept is presented in Figure 5.

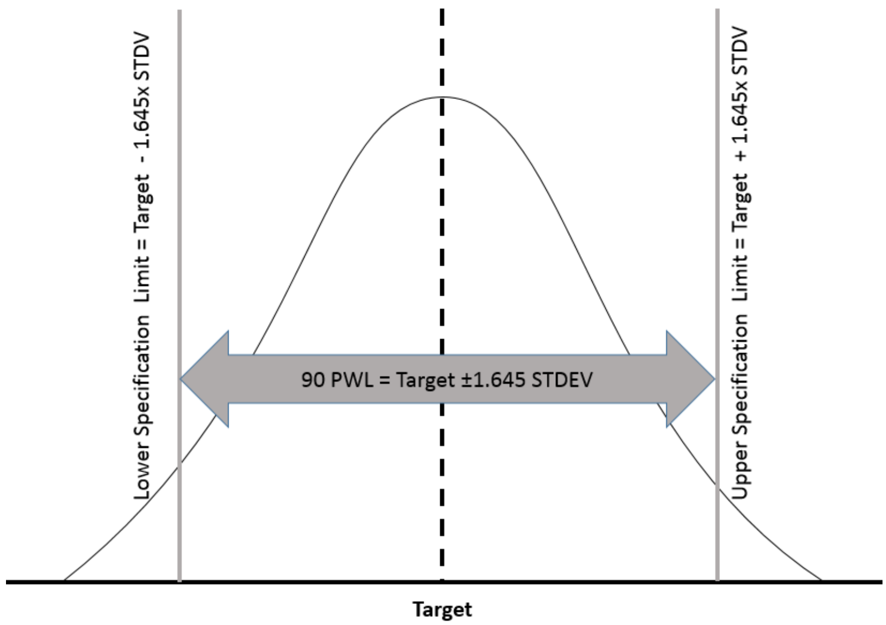

Figure 5 Specification Limits According to PWL Requirements

The STDEV (within-process variability) of AC test results in the FDOT study was 0.21%, while AASHTO suggests using 0.13%, but the development of specification limits using state historical records is acceptable and more representative of local conditions than those suggested by AASHTO. The specification limits for AC recommended by AASHTO are approximately ±0.21% which are different from the limits in many states, as shown in Table 10 (Oregon Department of Transportation 2018, California Department of Transportation 2015, Arizona Department of Transportation 2009, Colorado Department of Transportation 2016, Sholar et al. 2016).

Table 10 Asphalt Specification Limits Adopted in Different States

State	**AC Specification Limits,%**
Colorado	TV ±0.30
Florida	TV ±0.40
California	TV ±0.45
Oregon	TV ±0.50
Arizona	TV ±0.50
South Carolina (Surface layer)	TV ±0.36
South Carolina (Intermediate layer)	TV ±0.43

3.2 Problem Statement

The ODOT utilizes PWL specifications to evaluate new payments and calculate the payment that a contractor receives. The final payment that a contractor receives depends on the test results of three pay-elements including aggregate gradation, AC, and in-place density. Each property has a TV set in the JMF and a contractor tries to achieve this value. Therefore, specification limits must be developed correctly and represent the typical variability of tests for each property. Table 6 shows the current specification limits and the weighting factors utilized by ODOT for PWL specification

These specification limits were adopted by ODOT to calculate the PWL. According to recent QC and QA test results in Oregon and practices in other states, the current specification limits are wide enough to allow all test results to fall within them. This fact is a risk to ODOT and maximize the payment that a contractor will receive. ODOT will not be able to identify the variations among contractors' performance with current specification limits, and that will not encourage contractors to achieve high quality or reduce the variability of test results. Additionally, QC data will be always use to calculate the PWL and PFs.

4. DEVELOPING NEW SPECIFICATION LIMITS FOR ODOT

The most important question that must be answered in developing new specification limits is: "what variability will be used for the typical variability on which to base the specification limits?" (Burati et al. 2003). First, highway agencies need to determine variability within "Lot" from previous projects constructed by a number of contractors within the state (Burati Jr, 2006). For states that use lot-by-lot acceptance in PWL specification with a specific "Lot" size, determining the variability must be based on the same concept: lot-by-lot. Determining the variability from all tests results (combined) of the project is inaccurate due to fluctuations in construction and the large number of samples. Project test results may come from a number of "Lots", and each "Lot" may have a different means. In this case, the STDEV of all tests results (combined) will be not similar to the ones calculated from each "Lot" (individually). Therefore, variability within "Lot" calculated from combined tests results may not represent the actual variability that a highway agency needs to develop specification limits (Burati Jr, 2006). In this study, the variability was calculated based on lot-by-lot concept. Figure 6 shows the number of lots from the same hypothetical project with similar STDEV but different means.

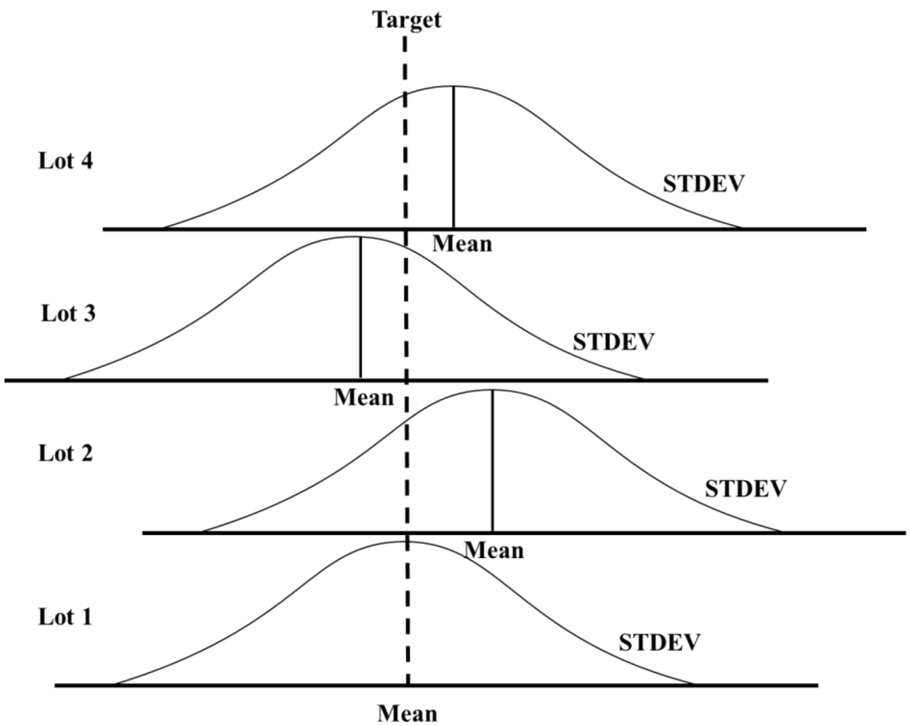

Figure 6 Number of "Lots" From Same Project with Similar STDEVs and Different Means

Data from previous projects can be used to calculate the individual STDEV within each "Lot". The agency must make a decision and select the typical process STDEV value (within-process variability) to be used to establish specification limits (Burati et al. 2003). It is probably not appropriate to select the smallest nor largest STDEV and use it as a typical value to establish specification limits (Burati et al. 2003). The highway agency might sort the STDEV values from smallest to largest and detect the gap between the values and find how many contractors can perform with low or high variability and then decide (Burati et al. 2003). Furthermore, the agency might select the median value that is most reasonable for the contractors and the agency, which is what was utilized in this study. In general, “there is no single “correct” way to decide on the typical value for process variability.” (Burati et al. 2003).

Highway agencies might take into account another source of variability when establishing two-sided (upper and lower) specification limits. The inability of contractors to produce a HMA mixture “Lot” with a mean value similar to the TV might be considered as another source of variability (“target miss” variability) (Burati et al. 2003). The agency may take into account this variability when developing new specification limits. In this case, the summation of the two variabilities values is recommended to establish specification limits (Burati et al. 2003). However, if the agency believes that contractors can produce a “Lot” with a mean value similar to the TV, only within-process variability (STDEV) values will be enough to develop the specification limits by multiplying the selected STDEV value by 1.645. In this case, 90 PWL is the AQL. Figure 7 shows the two types of variations: the solid-line curve at the bottom represents within-process variability, and the solid-line curve at the top represents the “target miss” variability. Dashed-line curves represent both process and “target miss” variabilities which gives wider specification limits when used.

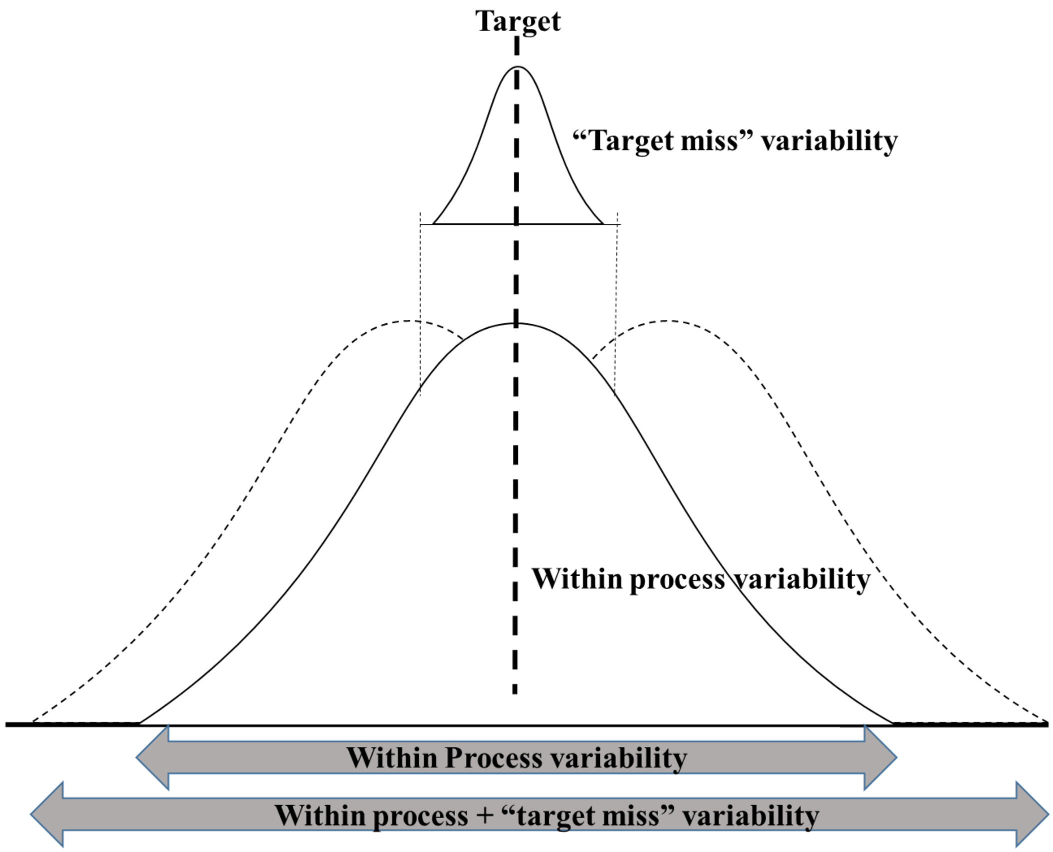

Figure 7 Types of Variabilities

Table 11 presents an example of typical variability (within-process variability and "target miss" variability) calculation using the AC QC test results from ODOT projects.

Table 11 ODOT AC STDEV and "Target miss" Values

Lot #	Measured mean AC,%	STDEV of measured AC	TV,%	Target Miss (Target – Mean),%
1	5.655	0.165	5.600	0.056
2	5.770	0.142	5.800	0.029
3	5.284	0.114	5.300	0.015
4	5.382	0.130	5.200	-0.183
5	5.678	0.208	5.800	0.121
6	5.362	0.140	5.800	0.438
7	5.706	0.235	5.800	0.094
8	5.628	0.144	5.500	0.129
9	5.472	0.285	5.400	0.073
10	5.821	0.115	5.700	0.122

The median value of the STDEV values (of measured AC) is 0.143 which represents (within-process variability). Its variance (V1) equals 0.021 (i.e. variance value equal to STDEV square), which represents the process variance. The STDEV of "Target miss" values is 0.152, and the variance is 0.023 which represents the target miss variance (V2). Therefore, combined variability (typical variability) that needs to be used to develop specification limits can be calculated from the square root of the summation of the two variances (V1 and V2) as shown in equation 8.

$$Typical_{\text{variability}} = \sqrt{V1 + V2}$$

$$Typical_{\text{variability}} = \sqrt{0.021 + 0.023} \quad (8)$$

$$Typical_{\text{variability}} = 0.209$$

Where,

V1= process variance

V2= target miss variance

In this study, the two types of variabilities have been considered assuming a constant process throughout the ODOT projects. Typically, ODOT “Lot” size may be consistent for the entire project but is essentially broken down by mixture type and JMF. The big “Lot” size gives a good opportunity for contractors to center the process and have a mean value within each "Lot" close to TV. Previous projects performed by ODOT were analyzed to determine the typical variability from equation (8) for the following pay-elements: 0.75 inch sieve, 0.50 inch sieve, No. 4 sieve, No. 8 sieve, No. 30 sieve, No. 200 sieve, AC, and in-place density. ODOT uses a one-sided specification for in-place density, requiring a 92% minimum (Newcomb et al. 2017, Oregon Department of Transportation 2018). The STDEV for density were calculated twice. First, the mean value of five density readings from each sublot was used. This method is employed by ODOT to obtain a single value representing the density of a sublot. Particularly, each of five density test results were averaged into a single value to represent the sublot density. The first one is entitled “density 1” in Table 12. Second, individual density test results were utilized to determine the STDEV. The second one is entitled “density 2” in Table 12. For density, only STDEV values (within-process variability) were used to establish specification limits since ODOT has no double specification limits (TV, USL, and LSL) in their specification for density.

Two types of specification limits developed are shown in Table 12. The first one was developed based on the typical variability calculated from equation (8). More flexible and achievable limits were also determined by rounding these limits up as shown in Table 12 as “proposed new specification limits”. The second type of specification limits are developed based on V1 only, assuming that V2 is zero (i.e. contractors are able to produce a HMA mixture "Lot" with mean value similar to the TV). This method was used by FDOT to develop their specification limits (using only V1). Specification limits have developed based on V1 only will not be used in calculation of pay factors in this study, and developed just to compare them with the first one (refer to specification limits developed based on typical variability) . The proposed new specification limits have been utilized to calculate the PWL and PFs for three projects referred to as project 1, 2 and 3. These projects have been performed by three different contractors in 2014, and were adopted as case studies to compare the impact of the proposed new specification limits on payment. Table 12 shows all ODOT pay-elements and calculation of typical variabilities, two types of specification limits, and ODOT current specification limits.

Table 12 Calculated, Proposed, and Current Specification Limits

	ODOT Pay - Elements								
	0.75 Inch Sieve	**0.5 Inch Sieve**	**No.4 Sieve**	**No.8 Sieve**	**No.30 Sieve**	**No.200 Sieve**	**AC%**	**Density 1***	**Density 2****
No. of Projects/Lots	6/11	6/11	6/10	6/10	6/10	6/11	6/10	13/25	13/25
Weighting Factors, %	1	1	5	5	3	12	28	44	
No. of QC Tests	320	320	300	300	300	320	300	349	3445
STDEV (Median)	0.000	1.156	1.883	1.460	1.123	0.504	0.154	0.549	1.180
Process Variance (V1)	0.000	1.336	2.909	2.131	1.262	0.437	0.021	0.301	1.392
"Target miss" Variance (V2)	0.043	2.461	3.254	1.015	1.340	0.122	0.023	N.A.	N.A.
Typical Variability	0.207	1.949	2.483	1.774	1.613	0.748	0.210	0.549	1.18
Specification Limits Based on Typical Variability	± 0.341	± 3.205	± 3.982	± 2.917	± 2.654	± 1.231	±0.345	± 0.903	± 1.941
Specification Limits Based on V1 only(± 1.645× STDEV)	±0.000	±1.901	±3.097	±2.401	±1.847	±0.829	±0.253	±0.903	± 1.941
Proposed New Specification Limits	±1.000	±3.500	±4.000	±3.000	±3.000	±1.500	±0.350	±1.000	±2.000
Current ODOT Specification Limits	±5.000	±5.000	±5.000	±4.000	±4.000	±2.000	±0.500	+8.000	+8.000

*: Mean of five or ten individual density tests

**: Individual density test

4.1 Case Study of the Impact of New Specification Limits on Payments

This section will include three projects performed by ODOT in 2014 and 2015 to used as a case study to evaluate the current ODOT specification limits and the proposed new specification limits.

4.1.1 Project 1

Project 1 is the largest project evaluated in this study. The project has one "Lot", 114 sublots, 114 QC tests, and 17 QA tests. Figure 8 through Figure 16 show the TV, ODOT current specification limits, proposed new specification limits, and QC and QA test results for the project. The solid red lines present the current limits used by ODOT for PWL specifications. The proposed new specification limits are presented by dashed lines, the TV is presented by a green line, QC tests are presented by dots, and QA tests are presented by triangles. Table 13 through Table 21 show all the statistical analysis and required calculations to determine the PWL and PFs for each pay-element. In all projects, QC tests has been employed to determine the PWL and PFs when F-tests and t-tests were passed or failed but the data were within specification limits.

For the 0.75 inch sieve, ODOT TV and USL are similar (100% passing) for the 1/2 inch mixture (referred to as nominal maximum aggregate size). In this case, the STDEV value is zero and PWL calculations cannot be performed. Therefore, contractors will receive a maximum PF (1.05) since all tests were within required limits (Figure 8).

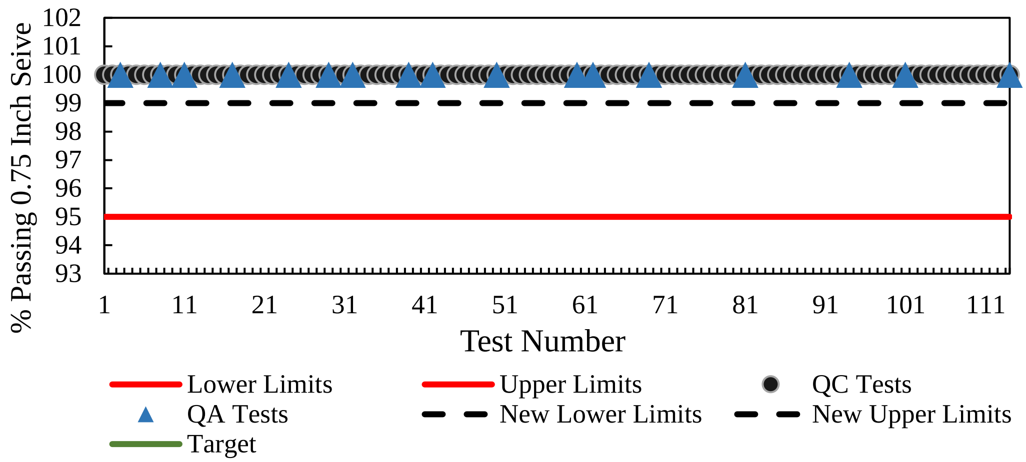

Figure 8 Project 1: QC and QA Tests of Aggregate Passing 0.75 Inch Sieve

Table 13 Project 1: Statistical Analysis and PFs Calculations for 0.75 Inch Sieve

Project No.1 Lot No.1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
0.75 Inch Sieve	100	0	100	0	1	-	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	1%	1%
Mean	100	100
STDEV	100	100
Specification Limits	±5.00	± 1.00
TV	100	100
USL	100	100
LSL	95	99
Q_U	-	-
Q_L	-	-
P_U	100	100
P_L	100	100
PT	100	100
Pay Factor	1.05	1.05

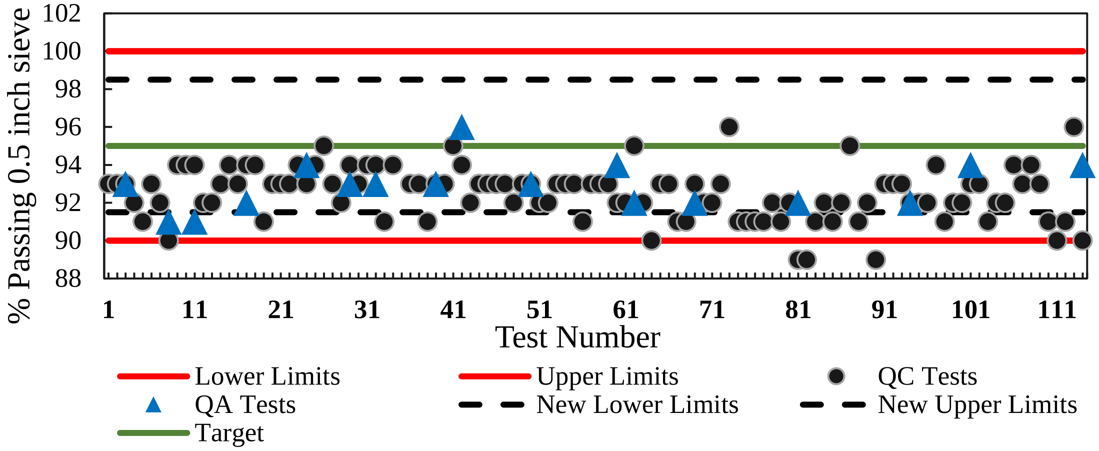

Figure 9 Project 1: QC and QA Tests of Aggregate Passing 0.50 Inch Sieve

Table 14 Project 1: Statistical Analysis and PFs Calculations for 0.50 Inch Sieve

Project Number: 1 Lot No. 1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
0.5 Inch Sieve	92.42	1.48	92.82	1.28	0.53	0.31	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	1%	1%
Mean	92.42	92.42
STDEV	1.48	1.48
Specification Limits	±5.00	±3.50
TV	95	95
USL	100	98.50
LSL	90	91.50
Q_U	5.12	4.10
Q_L	1.63	0.62
P_U	100	100
P_L	95	74
PT	95	74
Pay Factor	1.03	0.86

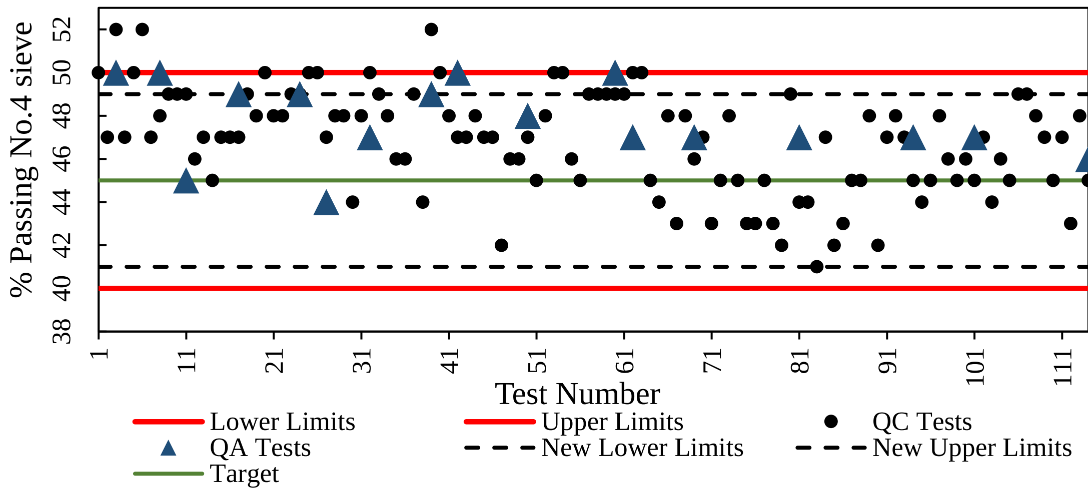

Figure 10 Project 1: QC and QA Tests of Aggregate Passing No.4 Sieve

Table 15 Project 1: Statistical Analysis and PFs Calculations for No.4 Sieve

Project No.1 Lot No.1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay -element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 4 Sieve	46.84	2.37	47.76	1.82	0.22	0.12	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	5%	5%
Mean	46.84	46.84
STDEV	2.38	2.38
Specification Limits	±5.00	±4.00
TV	45.00	45.00
USL	50	49
LSL	40	41
Q_U	1.33	0.91
Q_L	2.88	2.46
P_U	90	82
P_L	100	100
PT	90	82
Pay Factor	0.99	0.93

For the No.8 sieve, and according to the F-test, the variances of the QC and QA datasets are equal (F-test is passed) while, the means of these two datasets are significantly different according to the t-test result (t-test is failed). In this case, and according to the ODOT specification, QC data can be used to calculate the PWL since all data fall within ODOT current specification limits. Five out of 114 QC tests fall outside of the new proposed specification limits, and 14 out of 114 fall on upper and lower proposed new limits. The QC dataset was used to determine the PWL since only around 4% of the QC data fall out of the proposed new specification limits.

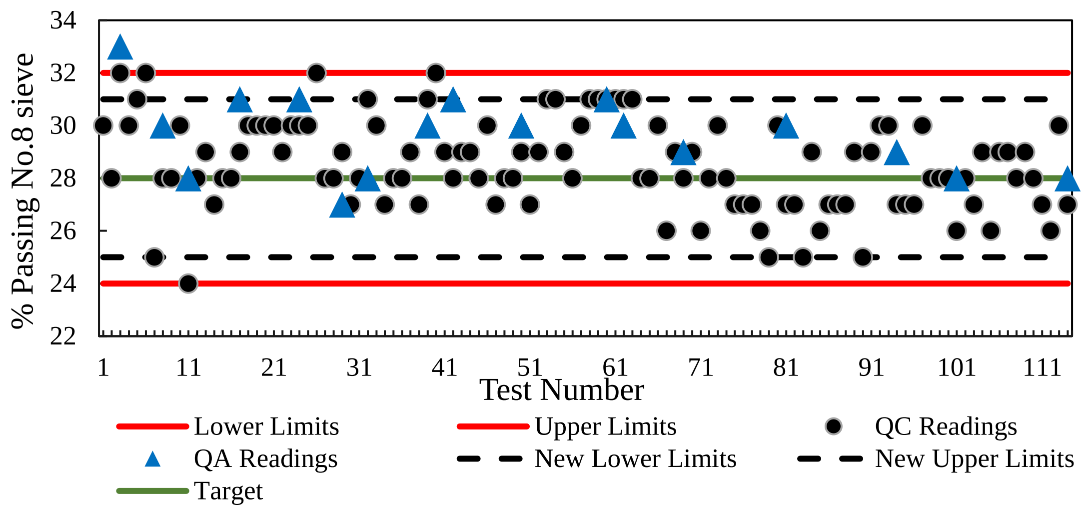

Figure 11 Project 1: QC and QA Tests of Aggregate Passing No.8 Sieve

Table 16 Project 1: Statistical Analysis and PFs Calculations for No.8 Sieve

Project No.1 Lot No. 1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 8 Sieve	28.51	1.71	29.64	1.53	0.64	**0.01**	

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	6%	6%
Mean	28.52	28.52
STDEV	1.72	1.72
Specification Limits	±4.00	±3.00
TV	28.00	28.00
USL	32	31
LSL	24	25
Q_U	2.03	1.45
Q_L	2.63	2.05
P_U	98	93
P_L	100	99
PT	98	92
Pay Factor	1.04	1.00

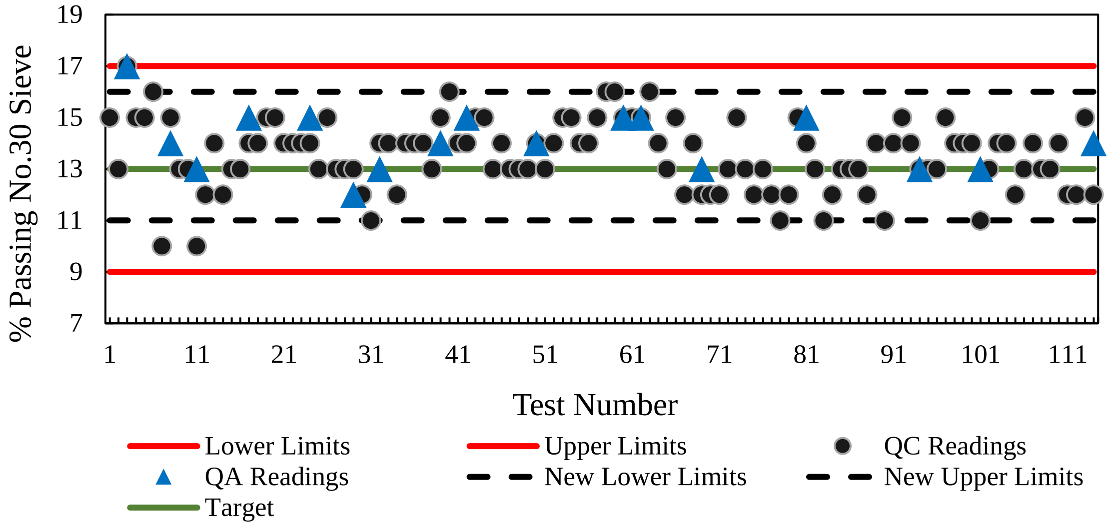

Figure 12 Project 1: QC and QA Tests of Aggregate Passing No.30 Sieve

Table 17 Project 1: Statistical Analysis and PFs Calculations for No.30 Sieve

Project No. 1 Lot No.1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 30 Sieve	13.54	1.33	14.05	1.19	0.63	0.13	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	3%	3%
Mean	13.54	13.54
STDEV	1.34	1.34
Specification Limits	±4.00	±3.00
TV	13.00	13.00
USL	17	16
LSL	9	10
Q_U	2.58	1.84
Q_L	3.40	2.65
P_U	100	97
P_L	100	100
PT	100	97
Pay Factor	1.05	1.04

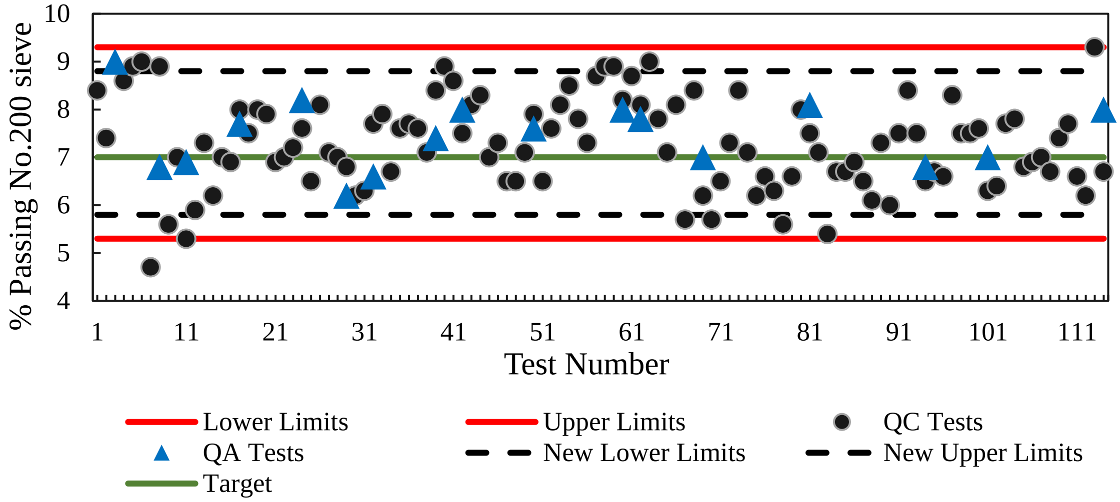

Figure 13 Project 1: QC and QA Tests of Aggregate Passing No.200 Sieve

Table 18 Project 1: Statistical Analysis and PFs Calculations for No.200 Sieve

Project No. 1 Lot No.1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 200 Sieve	7.31	0.97	7.47	0.72	0.17	0.50	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	12%	12%
Mean	7.31	7.31
STDEV	0.97	0.97
Specification Limits	±2.00	±1.50
TV	7.30	7.30
USL	9.3	8.8
LSL	5.3	5.8
Q_U	2.05	1.53
Q_L	2.07	1.55
P_U	99	94
P_L	99	94
PT	98	88
Pay Factor	1.04	0.98

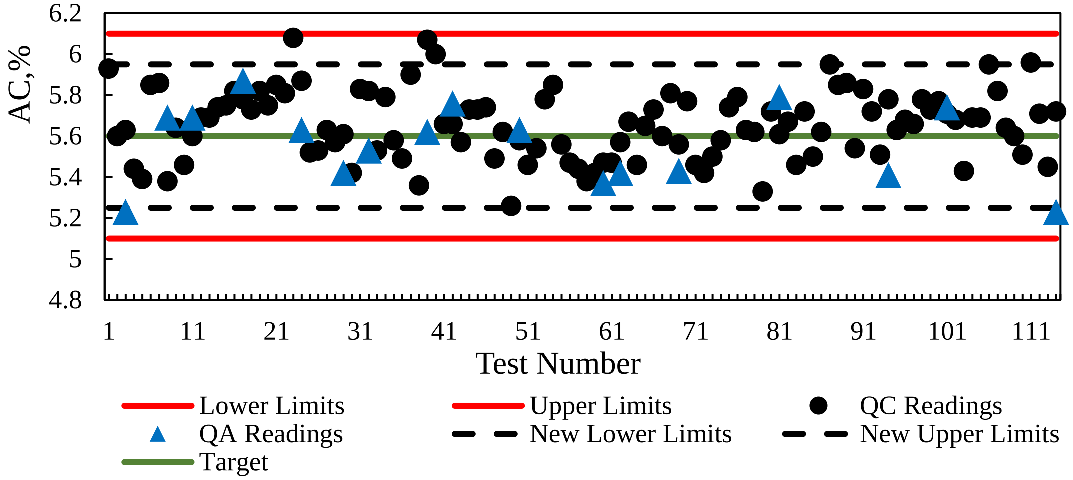

Figure 14 Project 1: QC and QA Tests of AC

Table 19 Project 1: Statistical Analysis and PFs Calculations for AC

Project No. 1 Lot No.1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
%AC	5.65	0.16	5.55	0.19	0.34	**0.02**	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	28%	28%
Mean	5.66	5.66
STDEV	0.17	0.17
Specification Limits	±0.50	±0.35
TV	5.60	5.60
USL	6.1	5.95
LSL	5.1	5.25
Q_U	2.68	1.77
Q_L	3.35	2.44
P_U	100	96
P_L	100	100
PT	100	96
Pay Factor	1.05	1.03

For density 1, ODOT used a one-sided specification limit (minimum 92%). In this study, two-sided specification limits have been established after determining the typical within-process variability and taking into account the requirements of ODOT (minimum 92%). So, the TV was set at 93%, and the specification limits are ±1 from the TV.

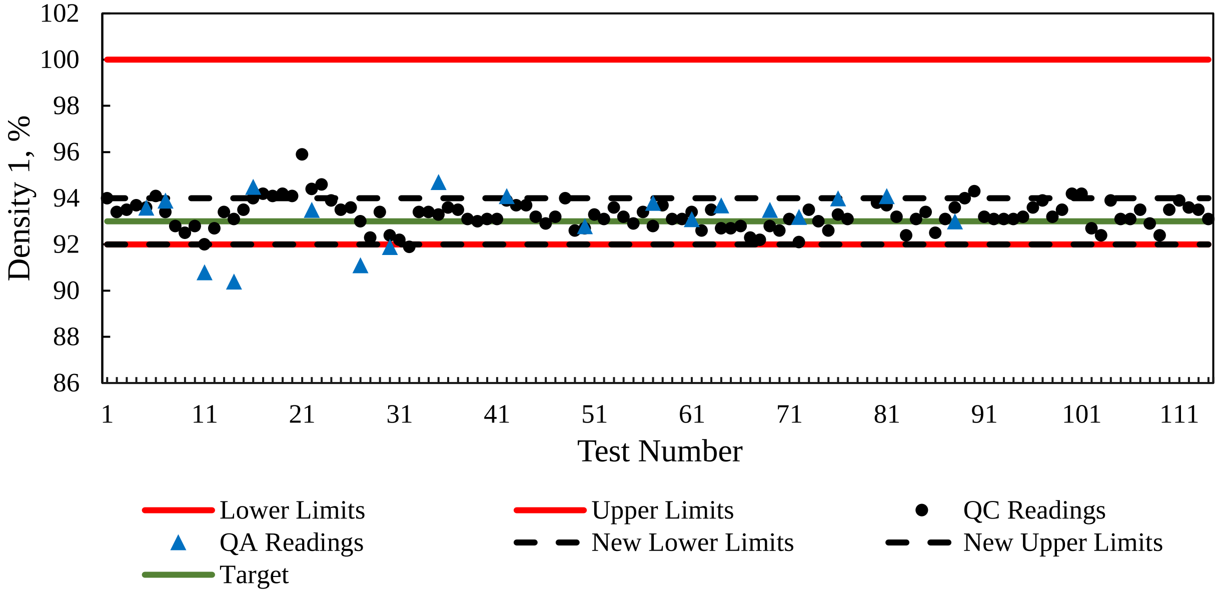

Figure 15 Project 1: QC and QA Tests of Density 1

Table 20 Project 1: Statistical Analysis and PFs Calculations for Density 1

Project No. 1 Lot No.1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
Density 1	93.25	0.56	93.14	1.23	**0.0001**	-	0.68

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	44%	44%
Mean	93.27	93.27
STDEV	0.62	0.62
Specification Limits	+8.00	±1.00
TV	92.00	93.00
USL	100	94
LSL	92	92
Q_U	10.85	1.18
Q_L	2.05	2.05
P_U	100	88
P_L	99	99
PT	99	87
Pay Factor	1.04	0.97

For density 2, the STDEV value (within-process variability) was higher than ones calculated for density 1. As mentioned previously, density 1 represents the mean of five values of density 2. Therefore, the specification limits of density 2 is +2 and the TV is 94% to keep the minimum value at 92% which is ODOT LSL.

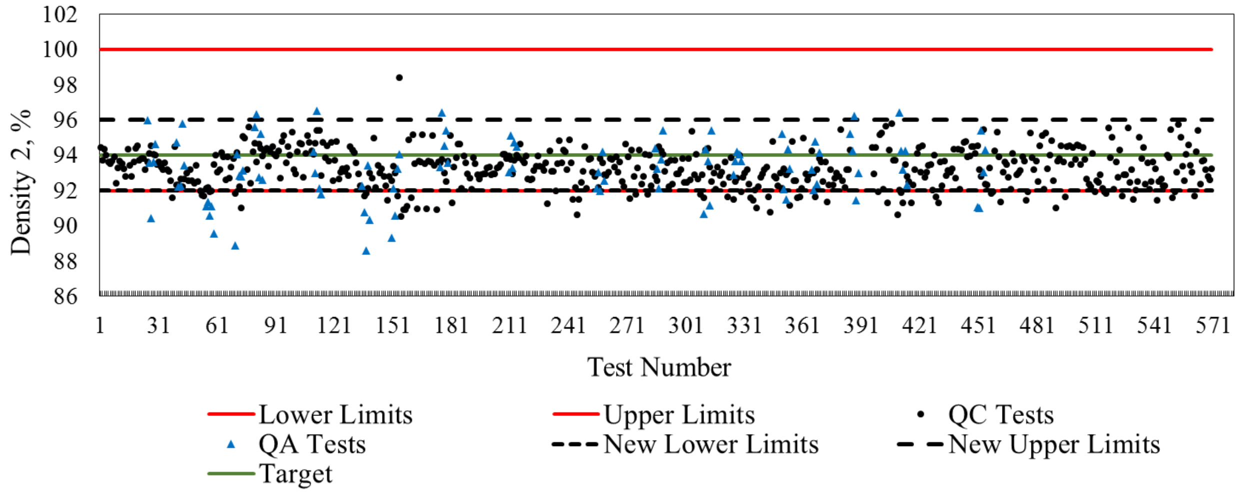

Figure 16 Project 1: QC and QA Tests of Density 2

Table 21 Project 1: Statistical Analysis and PFs Calculations for Density 2

Project No. 1 Lot No.1							
	QC		**QA**		**QC (114) Vs QA (17)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
Density 2	93.25	1.04	93.22	1.76	**0.0001**	-	0.87
PWL and Pay Factor Based on QC Tests							
	Using Current Specification Limits				Using Proposed Specification Limits		
Weight Factor	44%				44%		
Mean	93.27				93.26		
STDEV	0.62				1.07		
Specification Limits	+8.00				+2.00		
TV	92.00				94.00		
USL	100				96		
LSL	92				92		
Q_U	10.85				2.57		
Q_L	2.05				1.18		
P_U	100				100		
P_L	99				88		
PT	99				88		
Pay Factor	1.04				0.98		

4.1.2 Project 2

Project 2 is the second project evaluated in this study which represents the second contractor to determine the PFs using the ODOT current specification limits and the proposed new specification limits. The project has one "Lot", 33 sublots and QC tests, and 7 QA tests. Figure 17 through Figure 25 show the current specification limits presented by solid red lines, proposed new specification limits presented by dashed lines, TV presented by a green line, QC tests presented by dots and QA tests presented by triangles for all ODOT pay elements.

Table 22 through Table 30 show all the statistical analysis and required calculations to determine the PWL and PFs in Project 2.

For the 0.75 inch sieve, PWL calculations cannot be performed since STDEV is zero, the same as in Project 1.

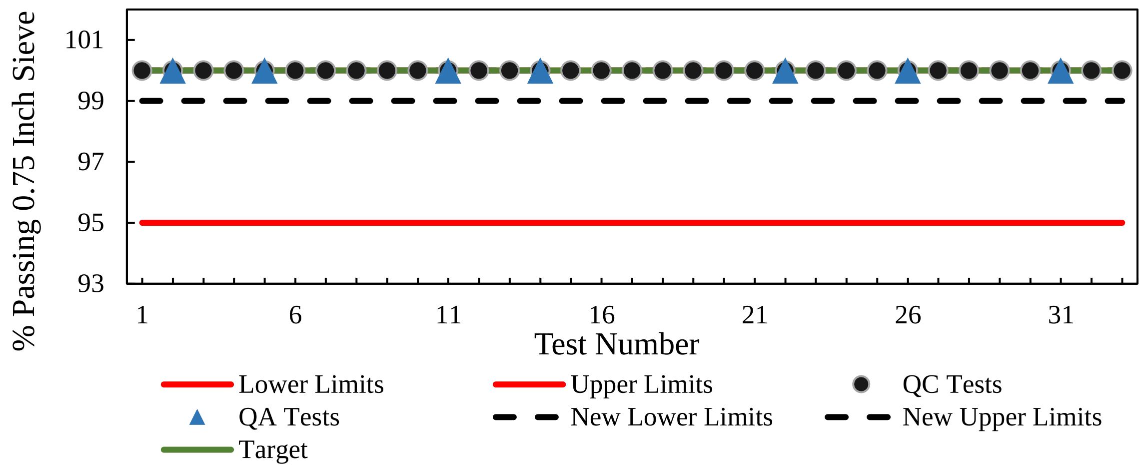

Figure 17 Project 2: QC and QA Tests of Aggregate Passing 0.75 Inch Sieve

Table 22 Project 2: Statistical Analysis and PFs Calculations for 0.75 Inch Sieve

Project No.2 Lot No. 1							
	QC Data		**QA Data**		**QC Data (33) Vs QA Data (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
3/4″	100	0	100	0	1	-	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	1%	1%
Mean	100	100
STDEV	0	0
Specification Limits	±5.00	±1.00
TV	100	100
USL	100	100
LSL	95	99
Q_U	-	-
Q_L	-	-
P_U	-	-
P_L	-	-
PT	100	100
Pay Factor	1.05	1.05

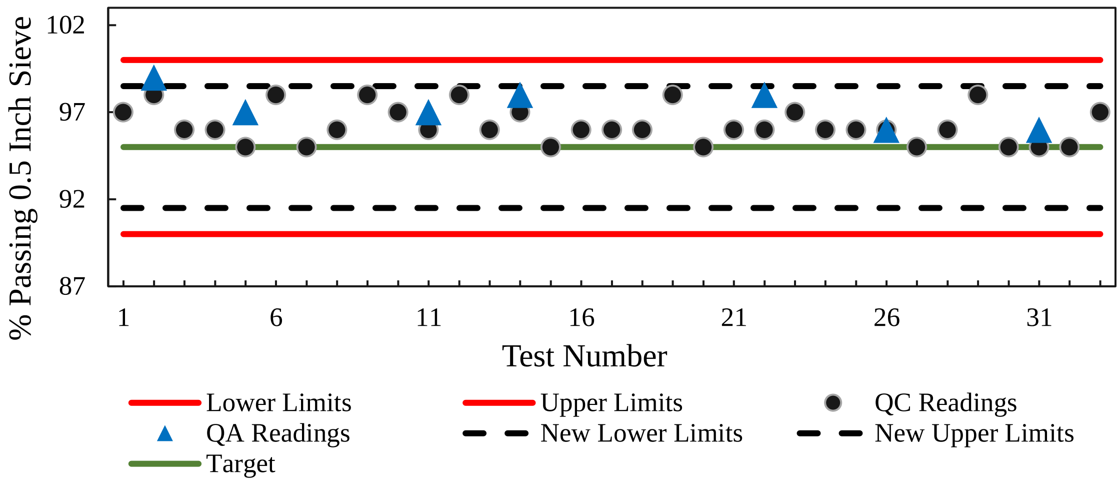

Figure 18 Project 2: QC and QA Tests of Aggregate Passing 0.50 Inch Sieve

Table 23 Project 2: Statistical Analysis and PFs Calculations for 0.50 Inch Sieve

Project No.2 Lot No.1							
	QC		**QA**		**QC (33) Vs QA (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
0.5 Inch	96.27	1.03	97.28	1.11	0.71	**0.02**	-

PWL and PFs Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	1%	1%
Mean	96.27	96.27
STDEV	1.03	1.03
Specification Limits	±5.00	±3.50
TV	95	95
USL	100	98.5
LSL	95	91.5
Q_U	3.62	2.01
Q_L	6.09	4.30
P_U	100	100
P_L	100	99
PT	100	99
Pay Factor	1.05	1.04

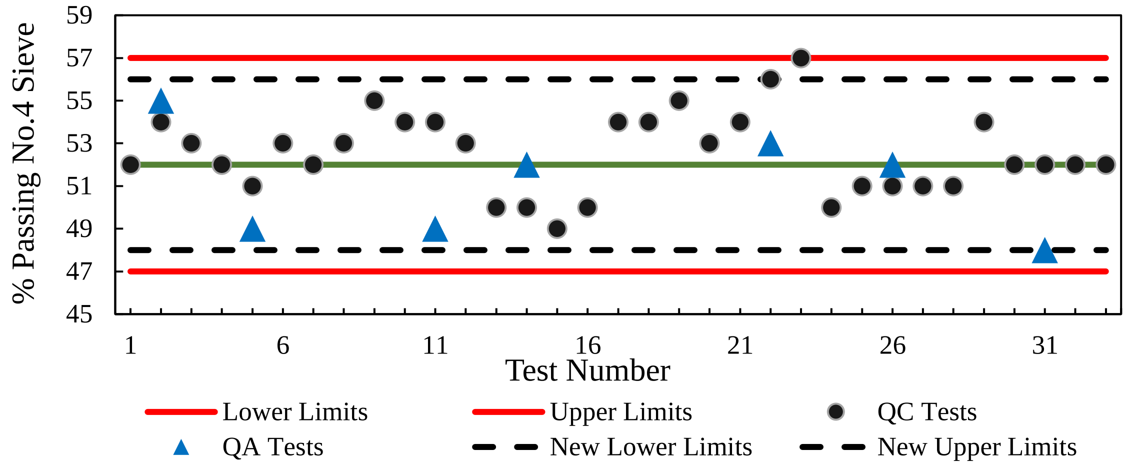

Figure 19 Project 2: QC and QA Tests of Aggregate Passing No.4 Sieve

Table 24 Project 2: Statistical Analysis and PFs Calculations for No.4 Sieve

Project No.2 Lot No.1							
	QC		**QA**		**QC (33) Vs QA (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 4 Sieve	52.54	1.87	51.14	2.54	0.24	0.09	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	5%	5%
Mean	52.54	52.54
STDEV	1.87	1.87
Specification Limits	±5.00	±4.00
TV	53	53
USL	58	38
LSL	48	32
Q_U	2.92	2.94
Q_L	2.43	1.47
P_U	100	100
P_L	100	94
PT	100	94
Pay Factor	1.05	1.04

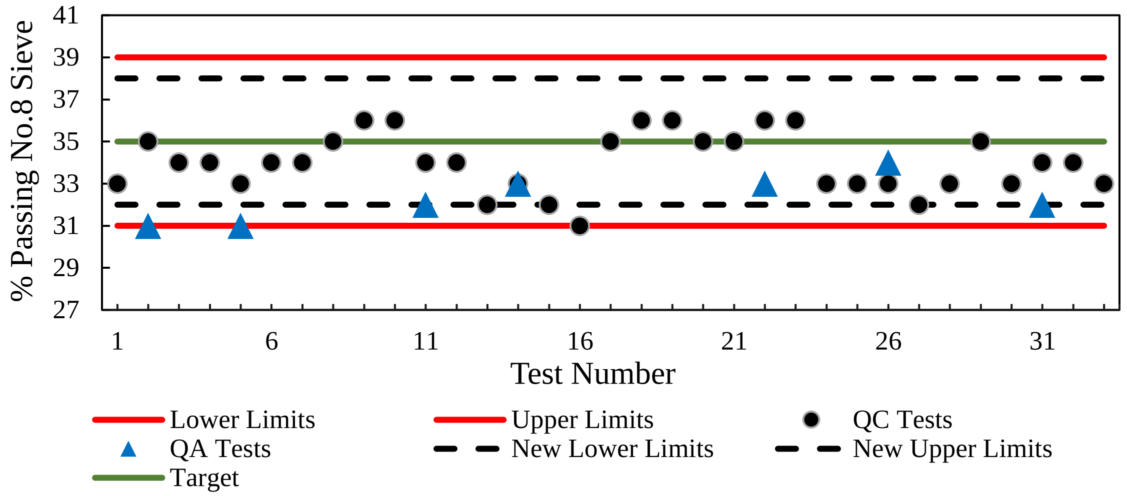

Figure 20 Project 2: QC and QA Tests of Aggregate Passing No.8 Sieve

Table 25 Project 2: Statistical Analysis and PFs Calculations for No.8 Sieve

Project No. 2 Lot No.1							
	QC		**QA**		**QC (33) Vs QA (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 8 Sieve	34	1.36	32.71	1.11	0.63	**0.02**	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	6%	6%
Mean	34	34
STDEV	1.36	1.36
Specification Limits	±4.00	±3.00
TV	35	35
USL	39	38
LSL	31	32
Q_U	3.68	2.94
Q_L	2.21	1.47
P_U	100	100
P_L	99	94
PT	99	94
Pay Factor	1.04	1.03

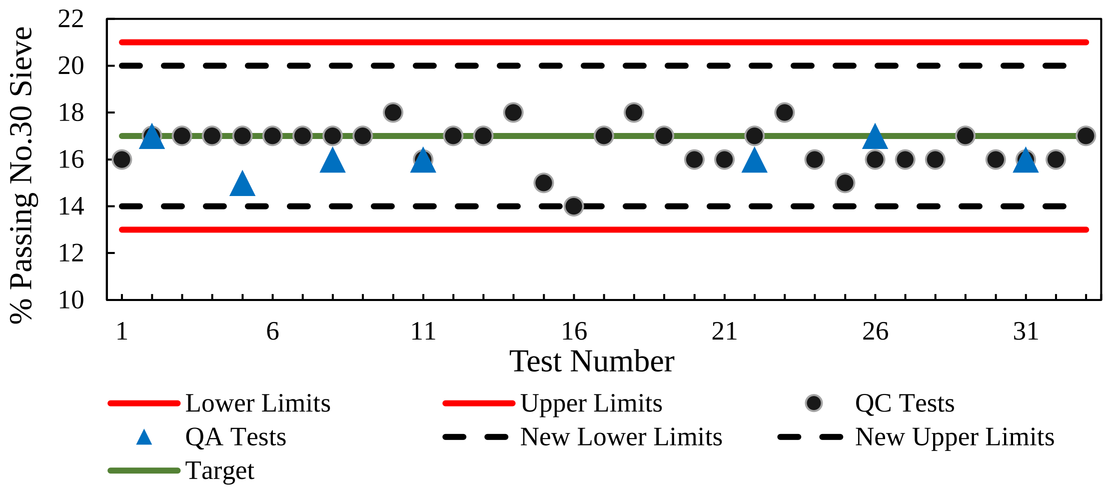

Figure 21 Project 2: QC and QA Tests of Aggregate Passing No.30 Sieve

Table 26 Project 2: Statistical Analysis and PFs Calculations for No.30 Sieve

Project No: 2 Lot No.1							
	QC		**QA**		**QC (33) Vs QA (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 30 Sieve	16.57	0.90	16.14	0.69	0.52	0.24	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	3%	3%
Mean	16.57	16.57
STDEV	0.9	0.9
Specification Limits	±4.00	±3.00
TV	17	17
USL	21	20
LSL	13	14
Q_U	4.92	3.81
Q_L	3.97	2.86
P_U	100	100
P_L	100	100
PT	100	100
Pay Factor	1.05	1.05

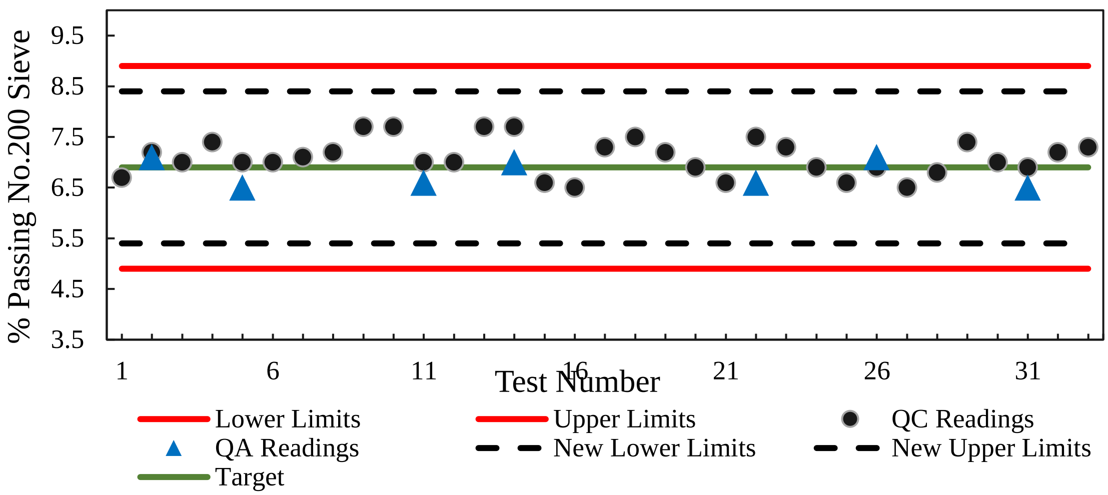

Figure 22 Project 2: QC and QA Tests of Aggregate Passing No.200 Sieve

Table 27 Project 2: Statistical Analysis and PFs Calculations for No.200 Sieve

Project No. 2 Lot No.1							
	QC		**QA**		**QC (33) Vs QA (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 200 Sieve	7.10	0.35	6.77	0.28	0.58	**0.02**	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	12%	12%
Mean	7.10	7.10
STDEV	0.35	0.35
Specification Limits	±2.00	±1.50
TV	6.9	6.9
USL	8.9	8.4
LSL	4.9	5.4
Q_U	5.14	3.71
Q_L	6.29	4.86
P_U	100	100
P_L	100	100
PT	100	100
Pay Factor	1.05	1.05

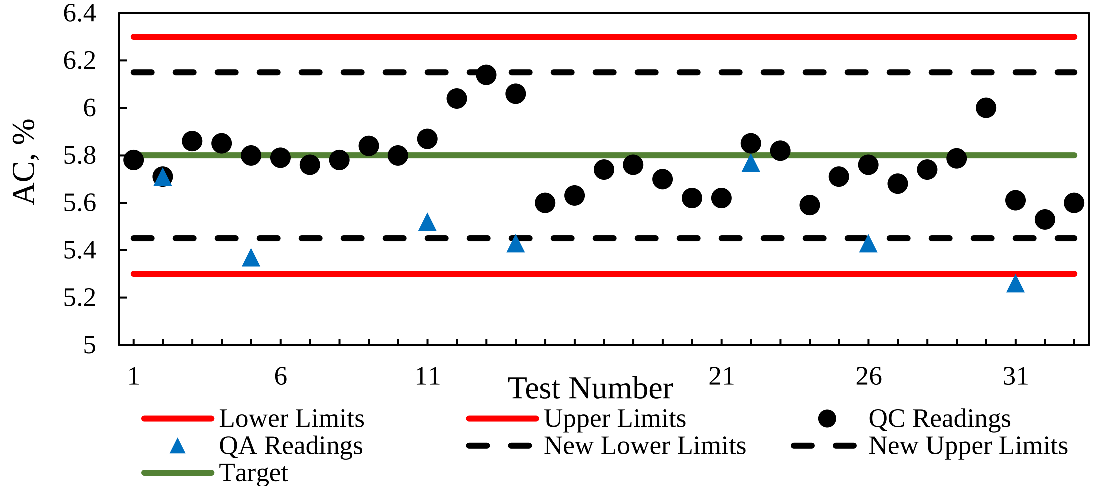

Figure 23 Project 2: QC and QA Tests of AC

Table 28 Project 2: Statistical Analysis and PFs Calculations for AC

Project No.2 Lot No.1							
	QC		**QA**		**QC (33) Vs QA (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
% AC	5.77	0.14	5.49	0.18	0.32	**0.0001**	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	28%	28%
Mean	5.77	5.77
STDEV	0.14	0.14
Specification Limits	±0.50	±0.35
TV	5.8	5.8
USL	6.3	6.15
LSL	5.3	5.45
Q_U	3.79	2.71
Q_L	3.36	2.29
P_U	100	100
P_L	100	100
PT	100	100
Pay Factor	1.05	1.05

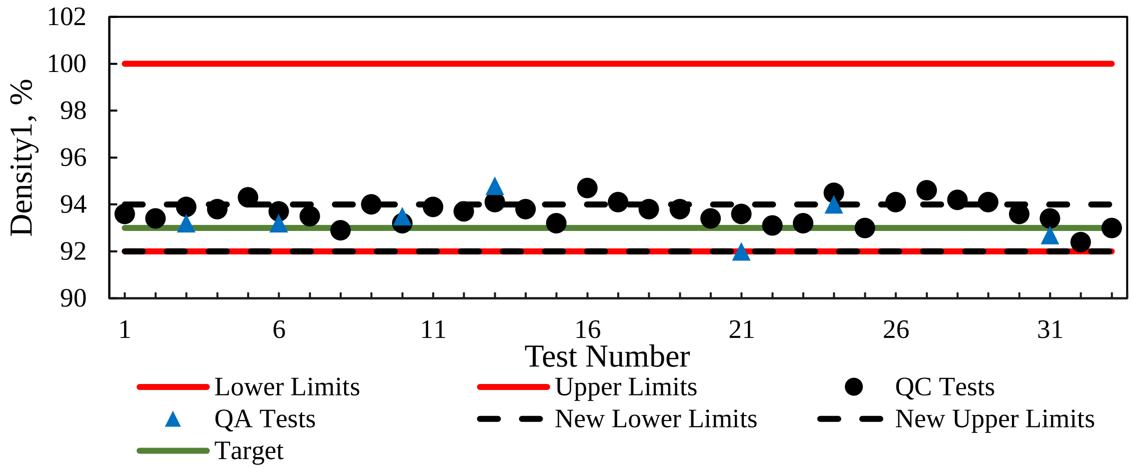

Figure 24 Project 2: QC and QA Tests of Density 1

Table 29 Project 2: Statistical Analysis and PFs Calculations for Density 1

Project No. 2 Lot No.1							
	QC		**QA**		**QC (33) Vs QA (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
Density 1	93.68	0.52	93.34	0.89	0.04	-	0.36

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	44%	44%
Mean	93.68	93.68
STDEV	0.52	0.52
Specification Limits	+8.00	±1.00
TV	92	93
USL	100	94
LSL	92	92
Q_U	12.15	0.62
Q_L	3.23	3.23
P_U	100	73
P_L	100	100
PT	100	73
Pay Factor	1.05	0.89

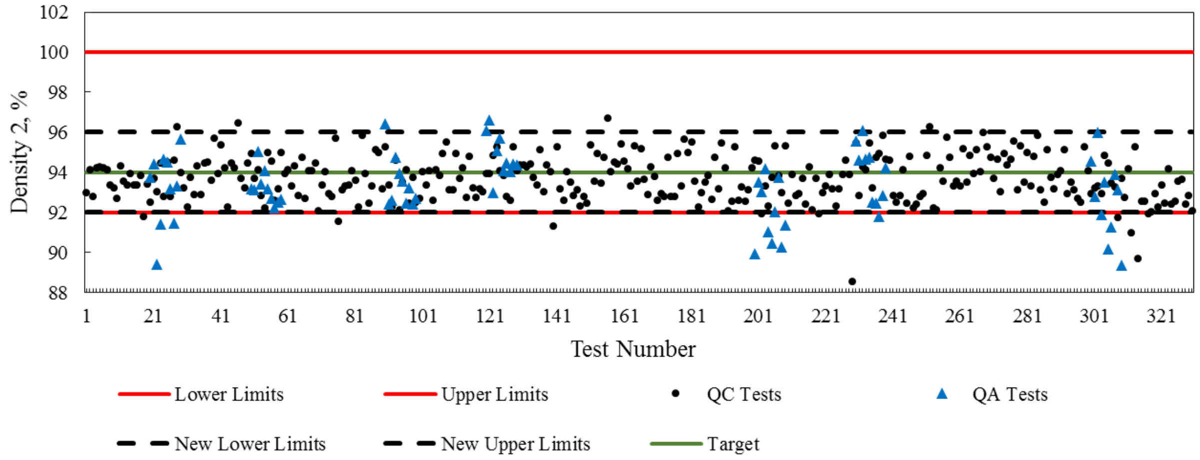

Figure 25 Project 2: QC and QA Tests of Density 2

Table 30 Project 2: Statistical Analysis and PFs Calculations for Density 2

Project No. 2 Lot No.1							
	QC		QA		QC (33) Vs QA (7)		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
Density 2	93.71	1.10	93.31	1.66	**0.0001**	-	0.06

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	44%	44%
Mean	93.68	93.68
STDEV.	1.10	1.10
Specification Limits	+8.00	±2.00
TV	92	94
USL	100	96
LSL	92	92
Q_U	5.72	2.08
Q_L	1.55	1.55
P_U	100	99
P_L	95	95
PT	95	94
Pay Factor	1.03	1.03

4.1.3 Project 3

Project 3 was the third project evaluated in this study with a contractor working on an ODOT project. The PFs were determined by applying the ODOT current HMA specification limits and the proposed new specification limits for comparison. The project had six “Lots”. Only “Lot” number six was evaluated in this study. The “Lot” has 17 sublots and QC tests and 4 QA tests. Figure 26 through Figure 34 show the ODOT current specification limits presented by solid red lines, proposed new specification limits presented by dashed lines, TV presented by a green line, QC tests presented by black dots and QA tests presented by triangles for all pay elements. Table 31 to Table 39 show all the statistical analysis and required calculations to determine the PWL and the PFs.

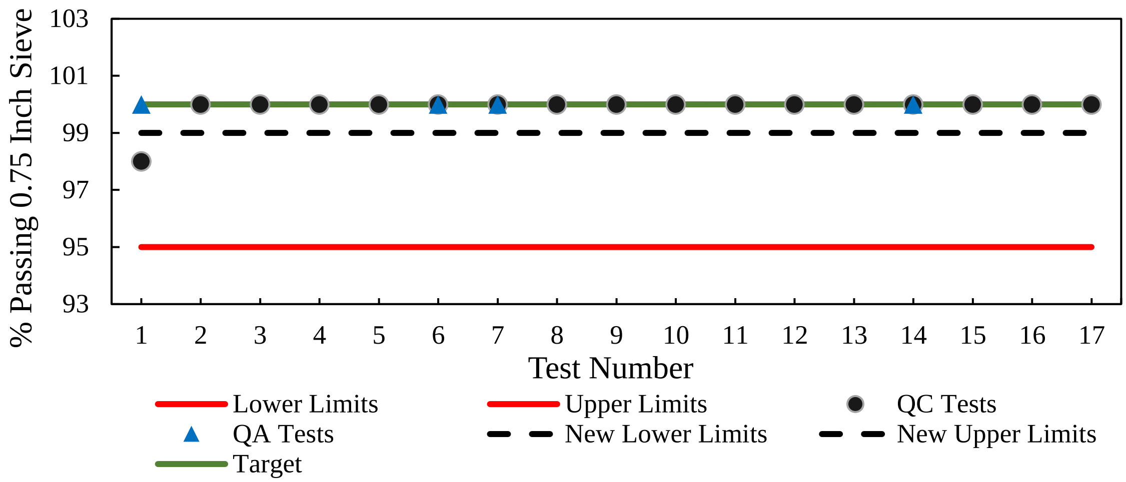

Figure 26 Project 3: QC and QA Tests of Aggregate Passing 0.75 Inch Sieve

Table 31 Project 3: Statistical Analysis and PFs Calculations for 0.75 Inch Sieve

Project No.3	**Lot No.6**						
	QC Data		**QA Data**		**QC Data (17) Vs QA Data (4)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
0.75 Inch Sieve	99.88	0.48	100	0	1	0.63	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	1%	1%
Mean	99.88	99.88
STDEV	0.48	0.48
Specification Limits	±5.00	±1.00
TV	100	100
USL	100	100
LSL	95	99
Q_U	0.25	0.25
Q_L	10.17	1.83
P_U	60	60
P_L	100	98
PT	60	58
Pay Factor	0.81	0.79

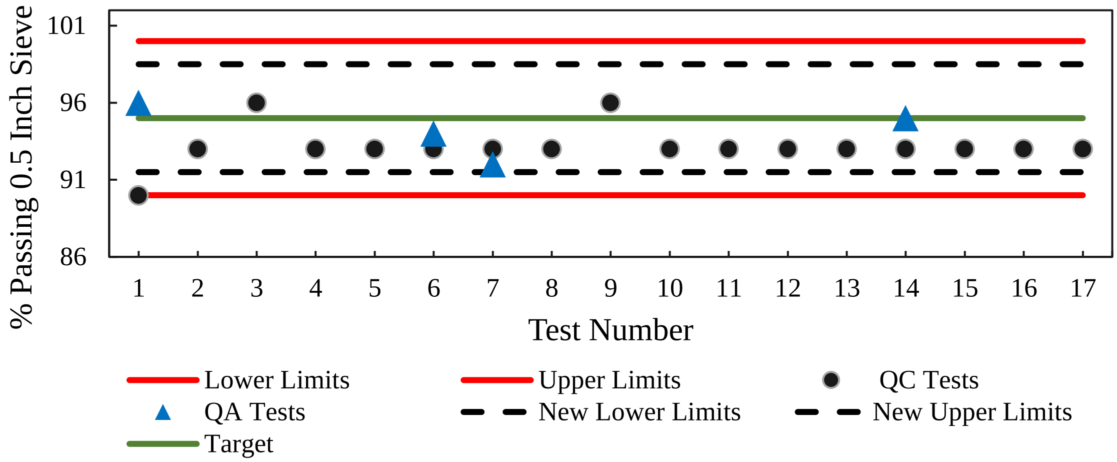

Figure 27 Project 3: QC and QA Tests of Aggregate Passing 0.50 Inch Sieve

Table 32 Project 3: Statistical Analysis and PFs Calculations for 0.50 Inch Sieve

Project No.3 Lot No.6							
	QC		QA		QC (17) Vs QA (4)		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
0.5 Inch Sieve	93.17	1.28	94.25	1.70	0.38	0.17	-

PWL and Pay Factor		
	Using Current Specification Limits and QC tests	Using Proposed Specification Limits And QA tests
Weight Factor	1%	1%
Mean	93.17	94.25
STDEV	1.28	1.70
Specification Limits	±5.00	±3.50
TV	95	95
USL	100	98.5
LSL	90	91.5
Q_U	5.34	4.16
Q_L	2.48	1.30
P_U	100	100
P_L	100	91
PT	100	91
Pay Factor	1.05	1.02

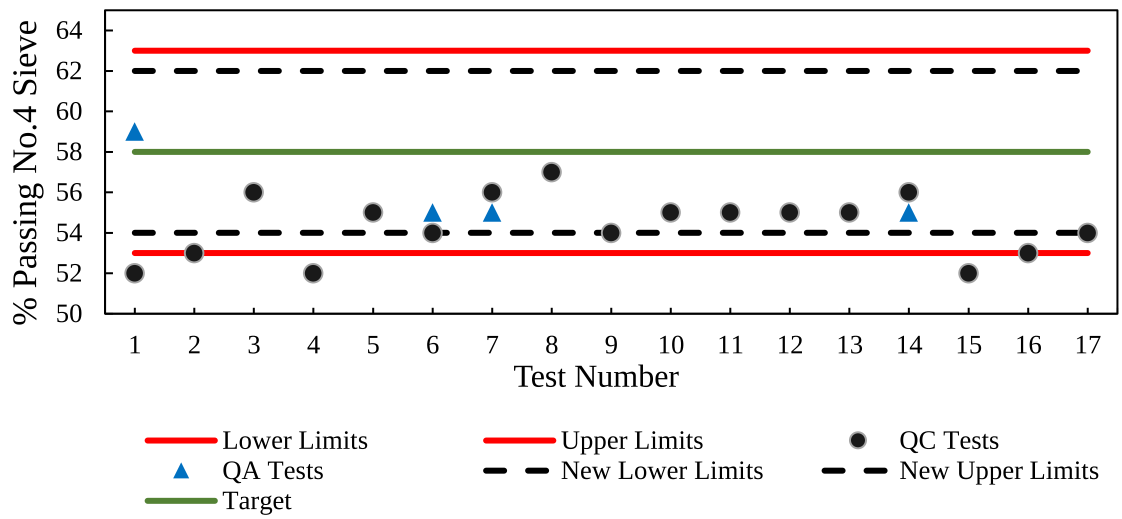

Figure 28 Project 3: QC and QA Tests of Aggregate Passing No.4 Sieve

Table 33 Project 3: Statistical Analysis and PFs Calculations for No.4 Sieve

Project No.3 Lot No.6							
	QC		QA		QC (17) Vs QA (4)		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 4 Sieve	54.35	1.53	56	2	0.41	0.08	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	5%	5%
Mean	54.35	56
STDEV.	1.53	2
Specification Limits	±5.00	±4.00
TV	58	58
USL	63	62
LSL	53	54
Q_U	5.65	5
Q_L	0.88	0.23
P_U	100	100
P_L	81	59
PT	81	59
Pay Factor	0.97	0.80

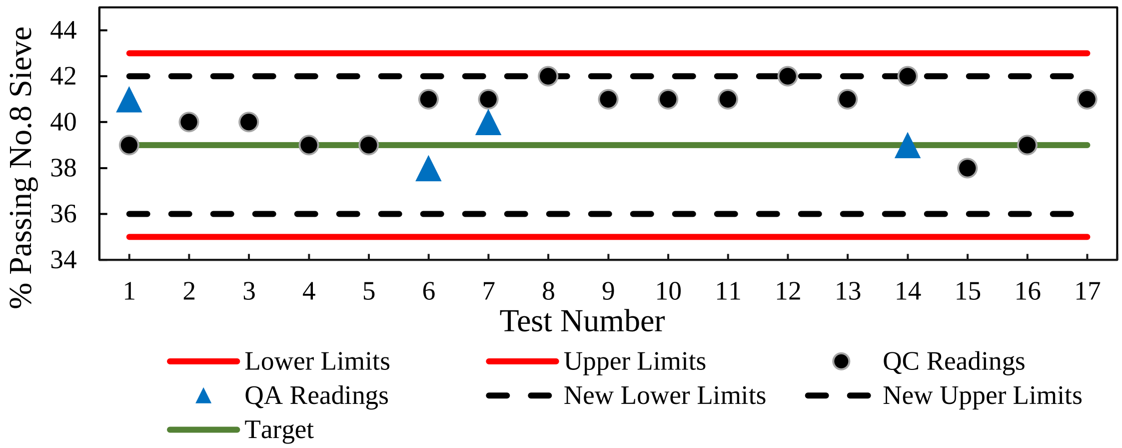

Figure 29 Project 3: QC and QA Tests of Aggregate Passing No.8 Sieve

Table 34 Project 3: Statistical Analysis and PFs Calculations for No.8 Sieve

Project No.3 Lot No.6							
	QC		**QA**		**QC (17) Vs QA (4)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 8 Sieve	40.41	1.22	39.50	1.29	0.75	0.20	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	6%	6%
Mean	40.41	40.41
STDEV.	1.22	1.22
Specification Limits	±4.00	±3.00
TV	39	39
USL	43	42
LSL	35	36
Q_U	2.12	1.30
Q_L	4.43	3.61
P_U	99	91
P_L	100	100
PT	99	91
Pay Factor	1.04	1.02

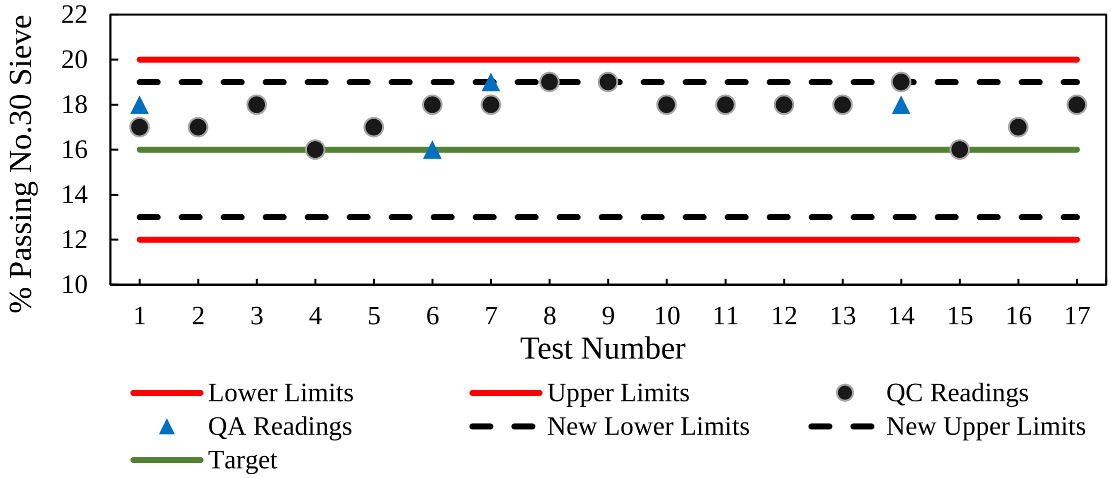

Figure 30 Project 3: QC and QA Tests of Aggregate Passing No.30 Sieve

Table 35 Project 3: Statistical Analysis and PFs Calculations for No.30 Sieve

Project No.3 Lot No.6							
	QC		QA		QC (17) Vs QA (4)		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 30 Sieve	17.70	0.91	17.75	1.25	1	0.63	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	3%	3%
Mean	17.70	17.70
STDEV	0.91	0.91
Specification Limits	±4.00	±3.00
TV	16	16
USL	20	19
LSL	12	13
Q_U	2.53	1.43
Q_L	6.26	5.16
P_U	100	93
P_L	100	100
PT	100	93
Pay Factor	1.05	1.03

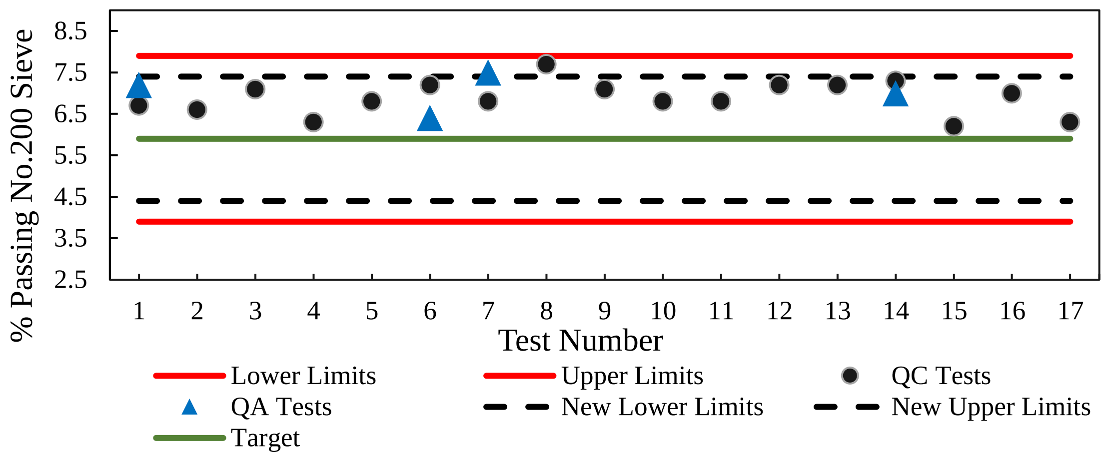

Figure 31 Project 3: QC and QA Tests of Aggregate Passing No.200 Sieve

Table 36 Project 3: Statistical Analysis and PFs Calculations for No.200 Sieve

Project No.3 Lot No.6							
	QC		**QA**		**QC (17) Vs QA (4)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
No. 200 Sieve	6.88	0.39	7.02	0.46	0.58	0.55	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	12%	12%
Mean	6.88	7.02
STDEV	0.39	0.46
Specification Limits	±2.00	±1.50
TV	5.90	5.90
USL	7.9	7.4
LSL	3.9	4.4
Q_U	2.62	1.33
Q_L	7.64	6.36
P_U	100	92
P_L	100	100
PT	100	92
Pay Factor	1.05	1.02

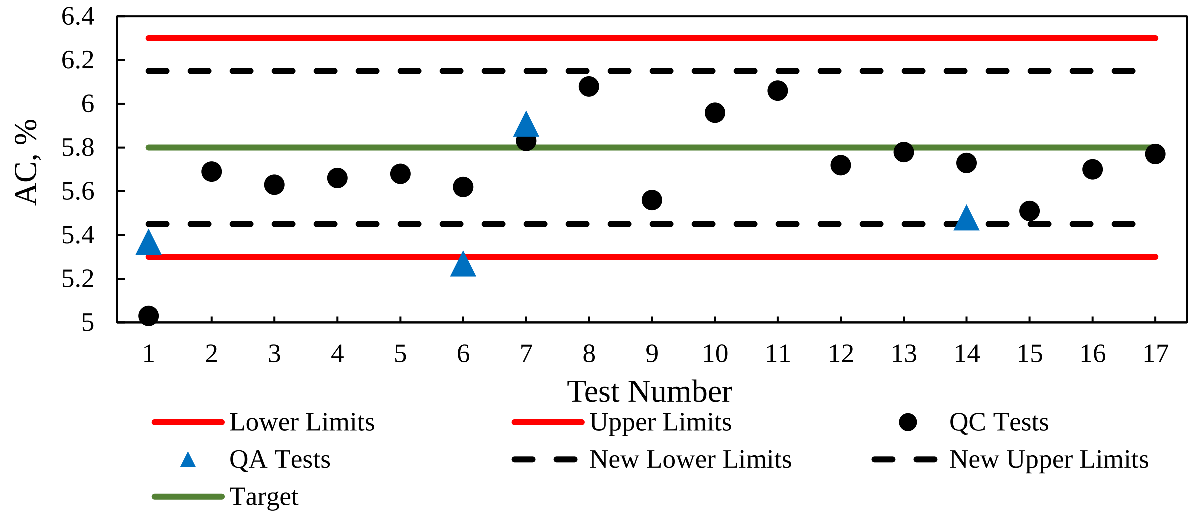

Figure 32 Project 3: QC and QA Tests of AC

Table 37 Project 3: Statistical Analysis and PFs Calculations for AC

Project No. 3 Lot No.6							
	QC		**QA**		**QC (33) Vs QA (7)**		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
% AC	6.70	0.23	5.50	0.28	0.54	0.15	-

PWL and Pay Factor Based on QC Tests		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	28%	28%
Mean	6.70	5.50
STDEV.	0.23	0.28
Specification Limits	±0.50	±0.35
TV	5.80	5.80
USL	6.3	6.15
LSL	5.3	5.45
Q_U	2.61	1.96
Q_L	1.74	1.09
P_U	100	99
P_L	97	87
PT	97	86
Pay Factor	1.04	1

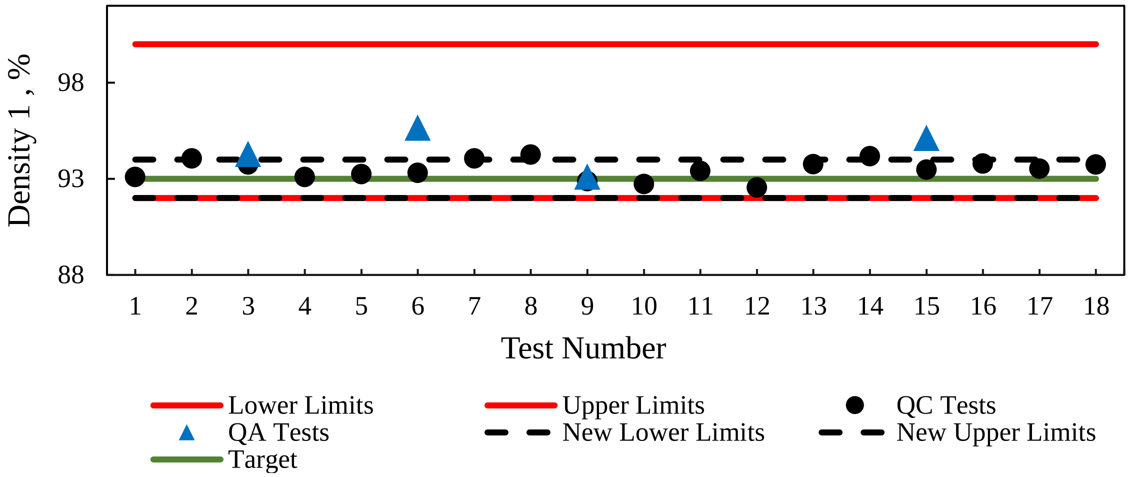

Figure 33 Project 3: QC and QA Tests of Density 1

Table 38 Project 3: Statistical Analysis and PFs Calculations for Density 1

Project No.3 Lot No.3							
	QC		QA		QC (18) Vs QA (4)		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
Density 1	93.50	0.50	94.55	1.11	0.02	-	0.15

PWL and Pay Factor Based on QC Data		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	44%	44%
Mean	93.50	93.50
STDEV.	0.49	0.49
Specification Limits	+8.00	±1.00
TV	92	93
USL	100	94
LSL	92	92
Q_U	13.32	1.03
Q_L	3.07	3.07
P_U	100	85
P_L	100	100
PT	100	85
Pay Factor	1.05	0.99

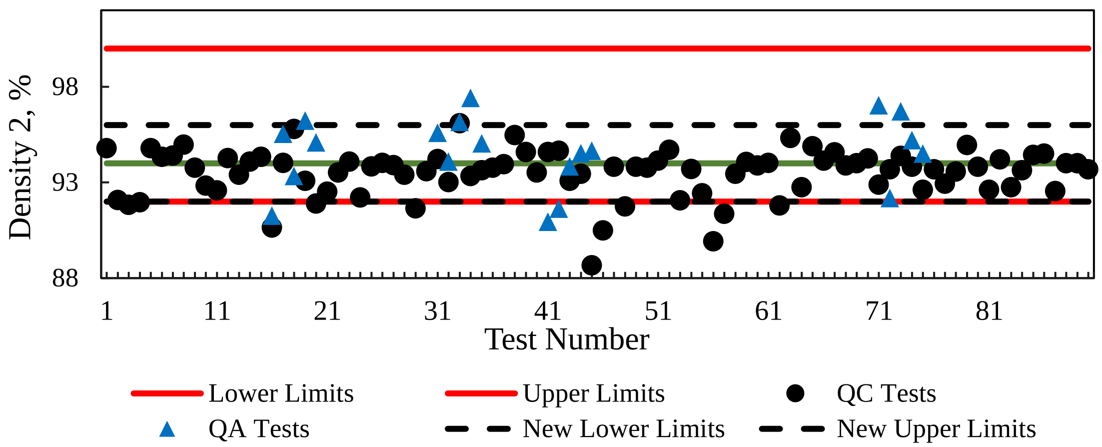

Figure 34 Project 3: QC and QA Tests of Density 2

Table 39 Project 3: Statistical Analysis and PFs Calculations for Density 2

Project No.3 Lot No.6							
	QC		QA		QC (33) Vs QA (7)		
Pay-element	Mean	STDEV	Mean	STDEV	F-test P-value	t-test p-value (equal variances)	t-test p-value (unequal variances)
Density 2	93.49	1.23	94.55	1.88	**0.008**	-	**0.02**

PWL and Pay Factor Based on QC Data		
	Using Current Specification Limits	Using Proposed Specification Limits
Weight Factor	44%	44%
Mean	93.50	93.50
STDEV.	1.23	1.23
Specification Limits	+8.00	±2.00
TV	92	94
USL	100	96
LSL	92	92
Q_U	5.28	2.03
Q_L	1.22	1.22
P_U	100	99
P_L	89	89
PT	89	88
Pay Factor	1.01	1.01

4.2 Discussion

The PWL and PFs calculated through this study were applied on projects 1, 2, and 3 using the proposed new specification limits and Oregon's current specification limits (Table 12). Based on the QC data points from the projects performed in 2014 and 2015 in Oregon, the variability of QC test results were low compared to those utilized to develop the ODOT current specification limits. These low variabilities are based on empirical data that indicate that tighter specification limits could be developed. The calculations of PWL and PFs presented in the statistical analysis tables were based on limits were between the calculated and current limits, referred to here as the proposed new specification limits. The proposed new limits were chosen to reflect the likely result of a negotiation between the managing agency and its contracting community. While the empirical evidence suggests that a tighter limit can be achieved, agencies often implement changes on a gradual basis to allow the contracting community to adapt and adjust to the new requirements.

For project 1, utilizing either of the specification limits will give the maximum pay factor (1.05) for 0.75 inch sieve. This is because the STDEV of 0.75 inch sieve equals zero. For the 0.5 inch sieve, using the new specification limits would lead to the contractor being penalized instead of being paid a bonus. The penalty is considered when 97% of the QC data fall below the TV. In a PWL specification, non-normally distributed data leads to a substantial effect on PFs and creating risks for contractors. For the 0.5 inch sieve, reducing the specification limits from ±5 to ±3.5 results in a pay factor of 0.86. For the Nos. 4 and 8 sieves, the proposed new specification limits would reduce the pay factor from 0.99 to 0.93 and from 1.04 to 1.00, respectively. For the No. 30 sieve, the pay factor would change from 1.05 to 1.04. For the No.

200 sieve, the pay factor would change from 1.04 to 0.98 since the specification limits changed from ±2 to ±1.5.

In Oregon, AC constitutes 28% of the total payment. Using the proposed new specification limits would reduce the pay factor from 1.05 to 1.03. For in-place density, the pay factor would change from 1.04 to 0.97 for Density 1 and 1.03 for Density 2. For all pay elements, contractor's QC data have been used to perform the pay factor calculations. Figure 35 shows how the proposed new specification limits impact the PFs of project 1.

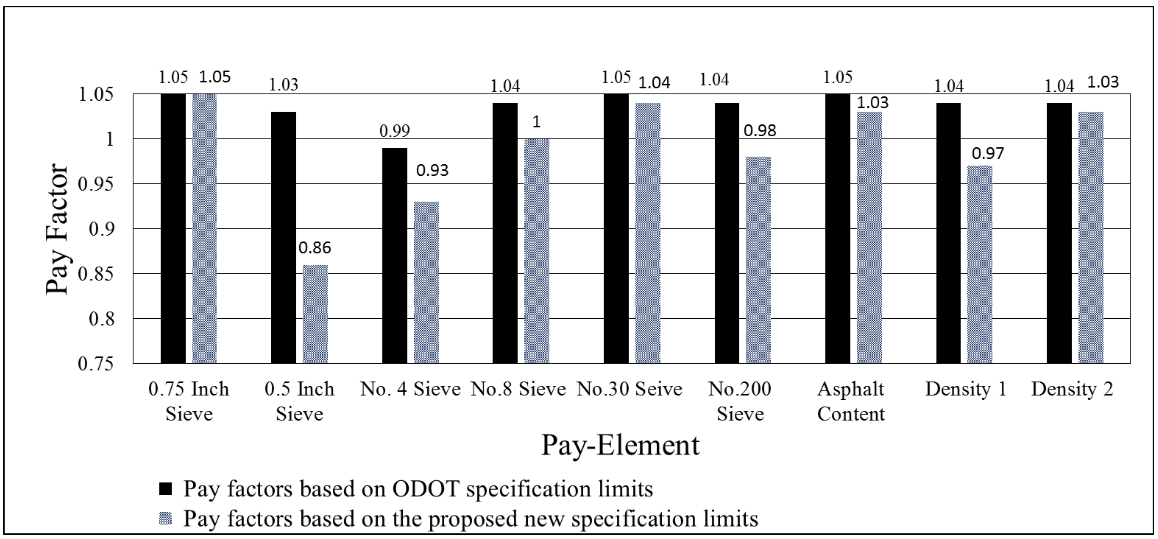

Figure 35 Project 1: PFs after Applying the Current ODOT Limits and Proposed New Specification Limits

For project 2, applying either of the specification limits will give the maximum pay factor (1.05) for the 0.75 inch sieve. PWL calculations cannot be performed on this element because the STDEV of the 0.75 inch sieve equals zero, and all tests fall on the USL. For the 0.5 inch sieve, using the proposed new specification limits will change from 1.05 to 1.04. For the Nos. 4 and 8 sieves, the proposed new specification limits reduced the pay factor from 1.05 to 1.04 and from 1.04 to 1.03, respectively. For Nos. 30 and 200 sieves applying either of the specification limits will lead to the maximum pay factor (i.e., 1.05). For AC, using either of the specification limits gives a pay factor of 1.05. For density 1, applying the new proposed specification limits would reduce the pay factor from 1.05 to 0.89. In this case, the contractor will be penalized instead of receiving a bonus of 5%. For density 2, utilizing either of the specification limits give 3% bonus to a contractor.

In project 2, the change of PFs were not significant when applying the proposed specification limits in PWL specifications. The contractor will still be able to achieve them and receive the maximum bonus (5%). Figure 36 shows how the proposed new specification limits impacts the PFs of project 2.

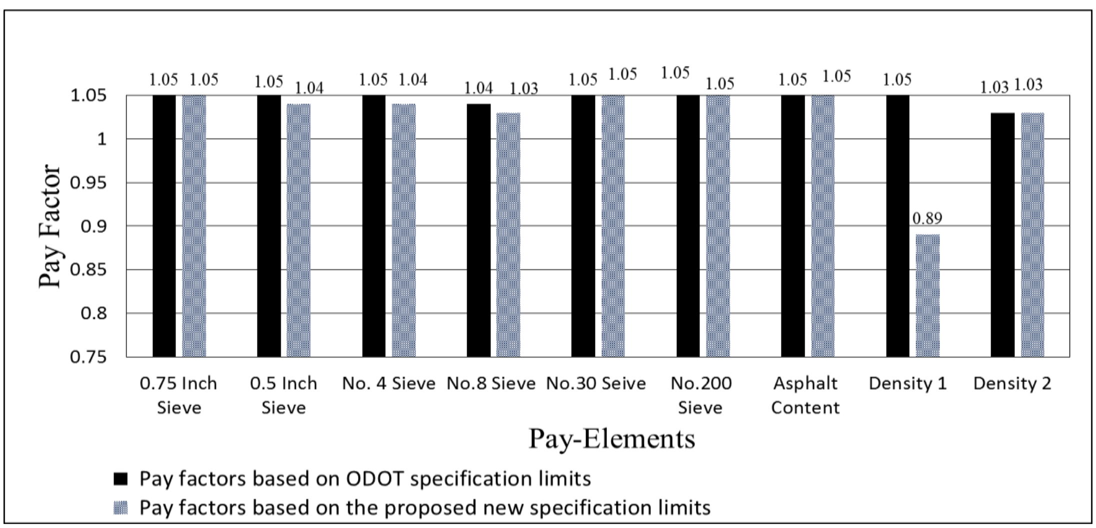

Figure 36 Project 2: PFs after Applying the Current ODOT Limits and the Proposed New Specification Limits

For project 3, applying the current specification limits leads to a pay factor of 0.81, while applying the new proposed specification limits would lead to a pay factor of 0.79 for the 0.75 inch sieve. In projects 1 and 2, the pay factor of the 0.75 inch sieve was not calculated since the STDEV values were zero. In project 3, the STDEV is 0.48 since one of the 17 tests results has a value of 98% (within specification limits) instead of 100%. According to ODOT specification, and regardless of PWL calculations, the contractor will receive full payment when QC data fall within specification limits after validation. For the 0.5 inch sieve, using the proposed new specification limits will lead to a reduction of the pay factor from 1.05 to 1.02. For the Nos. 4 and 8 sieves, the proposed new specification limits would reduce the pay factor from 0.97 to 0.80 and from 1.04 to 1.02, respectively. For the No. 30 sieve, the adoption of the proposed new specification limits will change the pay factor from 1.05 to 1.03. For the No.200 sieve, using the proposed specification limits will result in a pay factor of 1.02 instead of 1.05. For AC and density 1, the pay factor decreased from 1.04 to 1 and from 1.05 to 0.99, respectively. For density 2, using either limits will give a pay factor of 1.01. Figure 37 shows how the proposed new specification limits impact the PFs in project 3 “Lot” six. QC contractor data have been used to determine the PFs for all elements. Figure 37 shows how the proposed new specification limits impact the PFs for project 3.

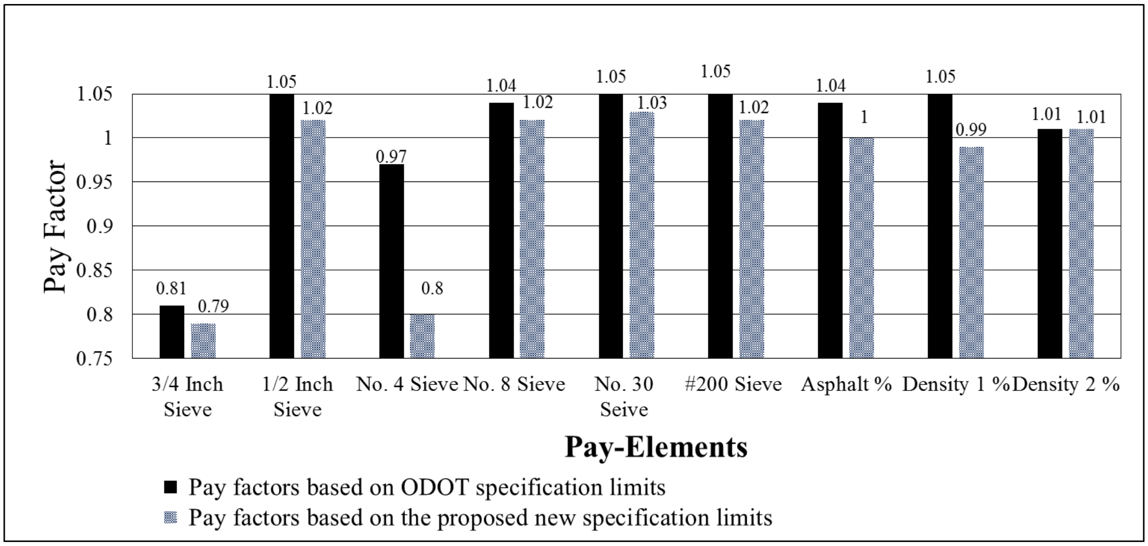

Figure 37 Project 3 PFs after Applying the Current ODOT Limits and the Proposed New Specification Limits

5. CONCLUSIONS AND RECOMMENDATIONS

The data points used to develop the proposed specification limits in this study represent eight contractors from 15 projects performed in Oregon in 2014 and 2015. The presented work indicates that the specification limits currently in use by ODOT lead predominantly to bonus payments being paid to contractors. It was concluded that a lower variability existed for most of the pay items using the current specifications to analyze the QC data that generated bonus payments to the same contractors. This indicates that a tighter proposed specification limit is possible. The proposed limits will give higher quality, as compared to the current ones. Contractors need to monitor their product and adjust it when necessary. This is essential to retain the HMA mixture properties as required in the JMF, which are built to give the highest quality. Contractors with low variability test results (i.e. project 2) can still obtain bonus since the proposed specification limits were developed based on the contractors' QC data and then rounded up to be more flexible.

Calculating the specification limits based on historical QC data helped to develop reasonable limits for contractors. Reducing the spread in these limits using a statistical analysis may assist in ensuring a higher-quality product. Contractors are able to produce a consistent product with acceptable variability in their test results will be rewarded with high PFs. Contractors unable to produce a consistent product with high variability in their test results will be penalized under tighter PWL specifications. Additionally, a PWL can assist highway agencies in identifying variations among contractors and encouraging the placement of high-quality materials by requesting them to focus on specific issues such as stockpiling practices, mix segregation, and field compaction.

In this study, three projects performed by three different contractors were presented as case studies to investigate the impact of changes to tighter specification limits. The comparison was made using the PFs based on the current and proposed new specification limits where the new specification limits resulted in lower PFs.

The following recommendations resulted from the work in this study:

- Highway agencies are encouraged to evaluate their specification limits when sampling techniques, materials, and construction practices change.
- Highway agencies who utilize QC data in PWL calculations are recommended to use the historical QC data to recalculate the specification limits for all PFs on a periodic basis (e.g., once every five years).
- Specification limits help balance the monetary risk to contractors and quality risk to the highway agency. This balance make the specification limits more realistic for pay elements and account for the practical variability that can be identified in QC test results.
- Elements currently used as pay elements should only be included if the variability is consistent in the test results. For example, ODOT can consider eliminating the 0.75 inch sieve from the pay elements list. This is recommended since the PWL cannot be calculated when the mean value equals the USL value and there is no standard deviation.
- Development of new specification limits is recommended to consider all sources of variability in the state highway agency. First, the agency need to determine within-process variability by calculate the typical STDEV within test results. Second, the agency need to make an assumption that contractors within the State are able to produce HMA "Lot" with a mean value similar to the target value in the JMF or not. The agency need to

take into account “target miss” variability if contractors cannot achieve mean value similar to the target value.

- Regardless of t-test and F-test results, ODOT use QC tests to determine PWL when the QC tests are fall within specification limits. Wide specification limits will lead always to use QC data in PWL calculation. Using proposed new specification limits in PWL specification may change this status. QA data may use in some cases to calculate the PWL and PFs.

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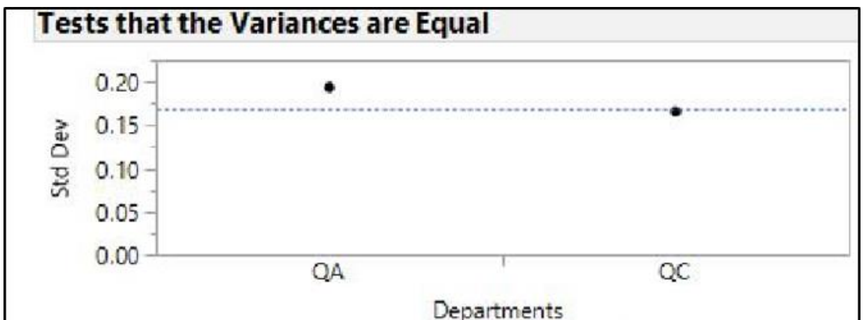
APPENDIX A
STATISTICAL ANALYSIS

Figure 40 through Figure 54 provide the statistical analysis details performed on projects 1, 2, and 3. JMP software (Thomas, 1999) has been used to run the F-test and independent t-tests. The variance of QC and QA datasets has been analyzed by F-test at 95 percent confidence interval. The variances in both two datasets are equal when P-value in F-test is greater than 0.05 while, the variances are unequal when P-value in F-test is less than 0.05. Figure 38 presents the F-test results of QC and QA AC tests for project 1. The P- value is 0.3423 which is greater than 0.05 and the two datasets have the same variance.



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
QA	17	0.1939375	0.1660900	0.1623529
QC	114	0.1659411	0.1354294	0.1353509

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	1.1691	1	129	0.2816
Brown-Forsythe	1.1152	1	129	0.2929
Levene	1.5552	1	129	0.2146
Bartlett	0.7211	1	.	0.3958
F Test 2-sided	1.3659	16	113	0.3432

Figure 38 P-Value calculated in F-test

The means of two datasets have been analyzed by t-test. The t-test shows if there is a significant difference between the means of two groups while the confident interval was 95 percent. Based on the F-test, t-tests are performed assuming either equal or unequal variances. When the means are equal, t-test is passed, when the t-test value is greater than 0.05. While, the t-test is failed when the t-test value is lower than 0.05. Figure 39 shows the t-test value for QC and QA data of asphalt content from project 1.

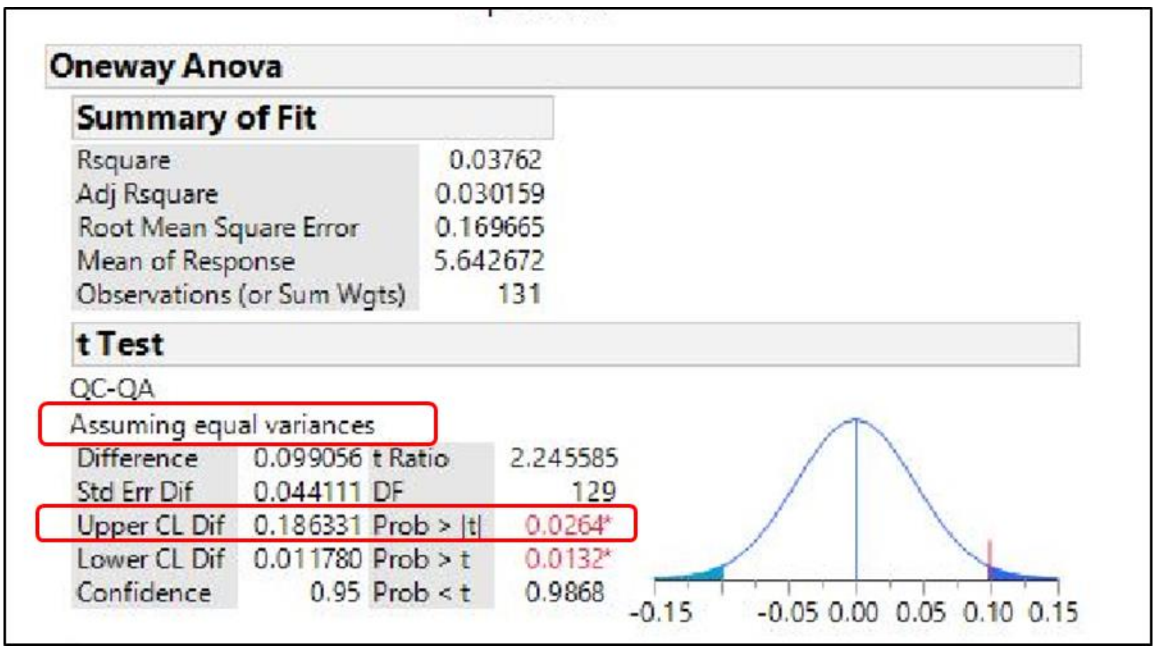


Figure 39 t-Test Value

In the following the results of all statistical analysis performed on QC and QA data for projects 1, 2, and 3 are presented.

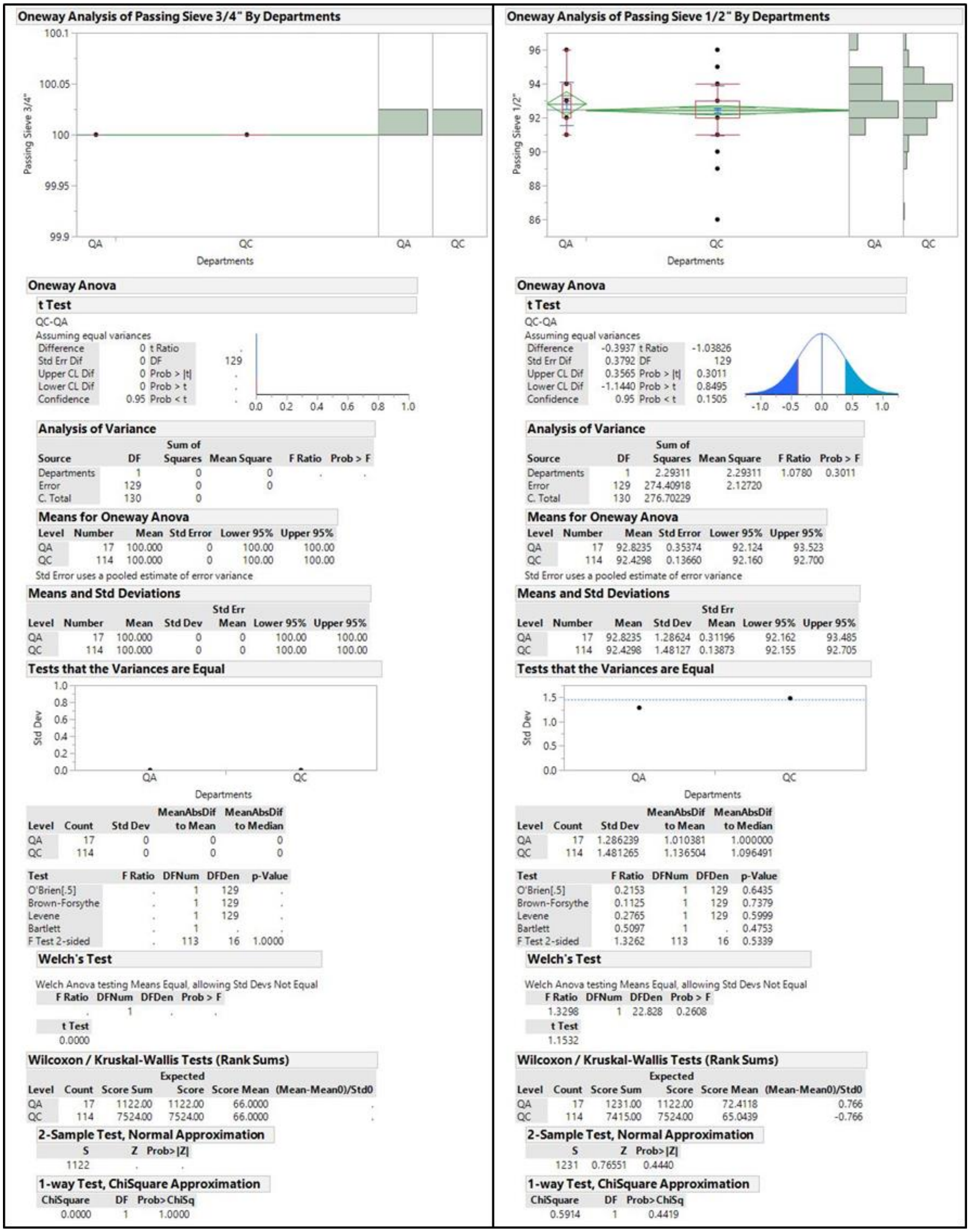
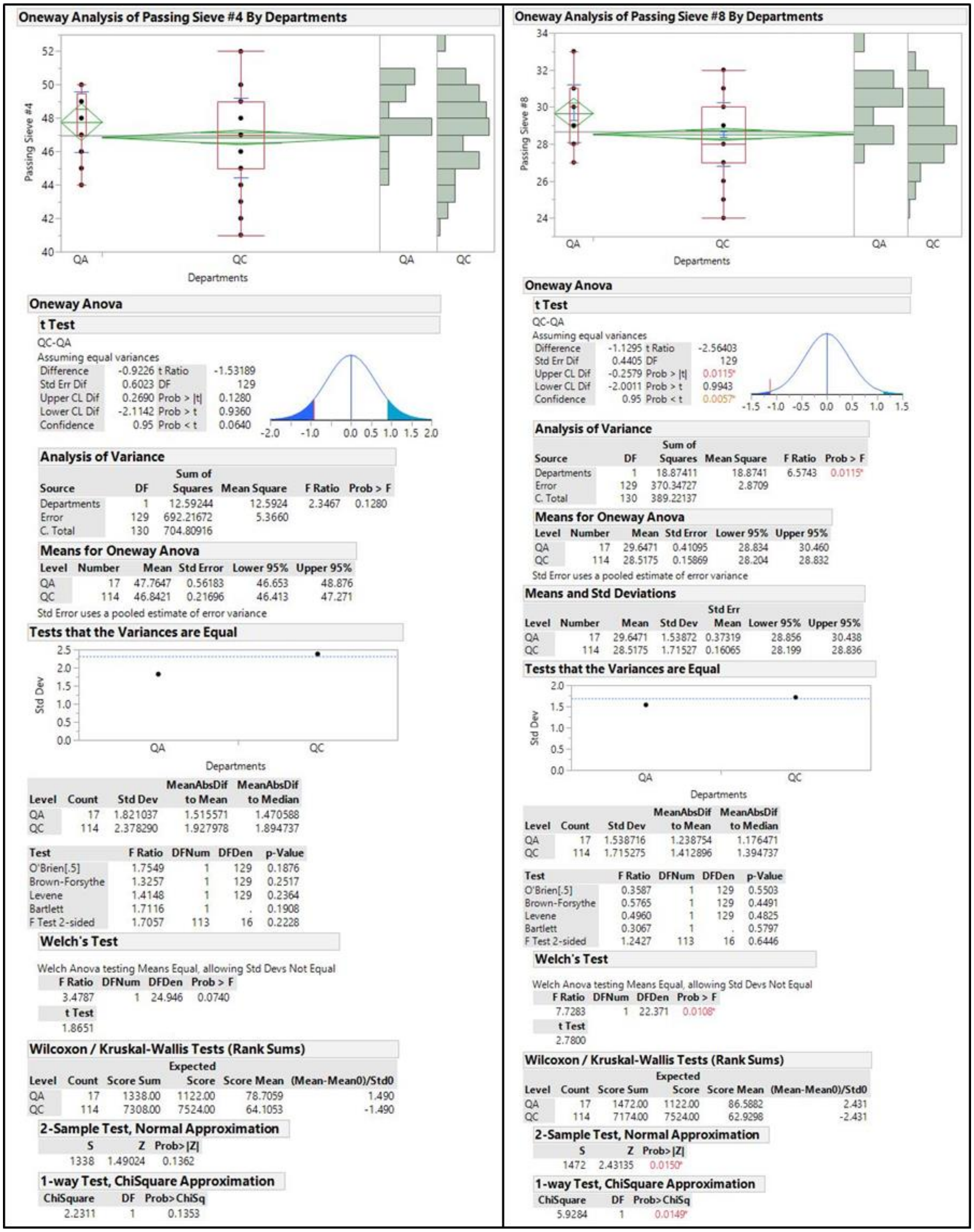


Figure 40 Project 1: Statistical Analysis for 0.75 and 0.5 Inch Sieves



Oneway Analysis of Passing Sieve #4 By Departments

Oneway Anova

t Test

QC-QA

Assuming equal variances

Difference	-0.9226	t Ratio	-1.53189
Std Err Dif	0.6023	DF	129
Upper CL Dif	0.2690	Prob > |t|	0.1280
Lower CL Dif	-2.1142	Prob > t	0.9360
Confidence	0.95	Prob < t	0.0640

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Departments	1	12.59244	12.5924	2.3467	0.1280
Error	129	692.21672	5.3660		
C. Total	130	704.80916			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
QA	17	47.7647	0.56183	46.653	48.876
QC	114	46.8421	0.21696	46.413	47.271

Std Error uses a pooled estimate of error variance

Tests that the Variances are Equal

Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
QA	17	1.821037	1.515571	1.470588
QC	114	2.378290	1.927978	1.894737

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	1.7549	1	129	0.1876
Brown-Forsythe	1.3257	1	129	0.2517
Levene	1.4148	1	129	0.2364
Bartlett	1.7116	1	.	0.1908
F Test 2-sided	1.7057	113	16	0.2228

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
3.4787	1	24.946	0.0740

t Test

1.8651

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
QA	17	1338.00	1122.00	78.7059	1.490
QC	114	7308.00	7524.00	64.1053	-1.490

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1338	1.49024	0.1362

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
2.2311	1	0.1353

Oneway Analysis of Passing Sieve #8 By Departments

Oneway Anova

t Test

QC-QA

Assuming equal variances

Difference	-1.1295	t Ratio	-2.56403
Std Err Dif	0.4405	DF	129
Upper CL Dif	-0.2579	Prob > |t|	0.0115*
Lower CL Dif	-2.0011	Prob > t	0.9943
Confidence	0.95	Prob < t	0.0057*

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Departments	1	18.87411	18.8741	6.5743	0.0115*
Error	129	370.34727	2.8709		
C. Total	130	389.22137			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
QA	17	29.6471	0.41095	28.834	30.460
QC	114	28.5175	0.15869	28.204	28.832

Std Error uses a pooled estimate of error variance

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
QA	17	29.6471	1.53872	0.37319	28.856	30.438
QC	114	28.5175	1.71527	0.16065	28.199	28.836

Tests that the Variances are Equal

Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
QA	17	1.538716	1.238754	1.176471
QC	114	1.715275	1.412896	1.394737

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.3587	1	129	0.5503
Brown-Forsythe	0.5765	1	129	0.4491
Levene	0.4960	1	129	0.4825
Bartlett	0.3067	1	.	0.5797
F Test 2-sided	1.2427	113	16	0.6446

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
7.7283	1	22.371	0.0108*

t Test

2.7800

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
QA	17	1472.00	1122.00	86.5882	2.431
QC	114	7174.00	7524.00	62.9298	-2.431

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1472	2.43135	0.0150*

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
5.9284	1	0.0149*

Figure 41 Project 1: Statistical Analysis for No.4 and No.8 Sieves

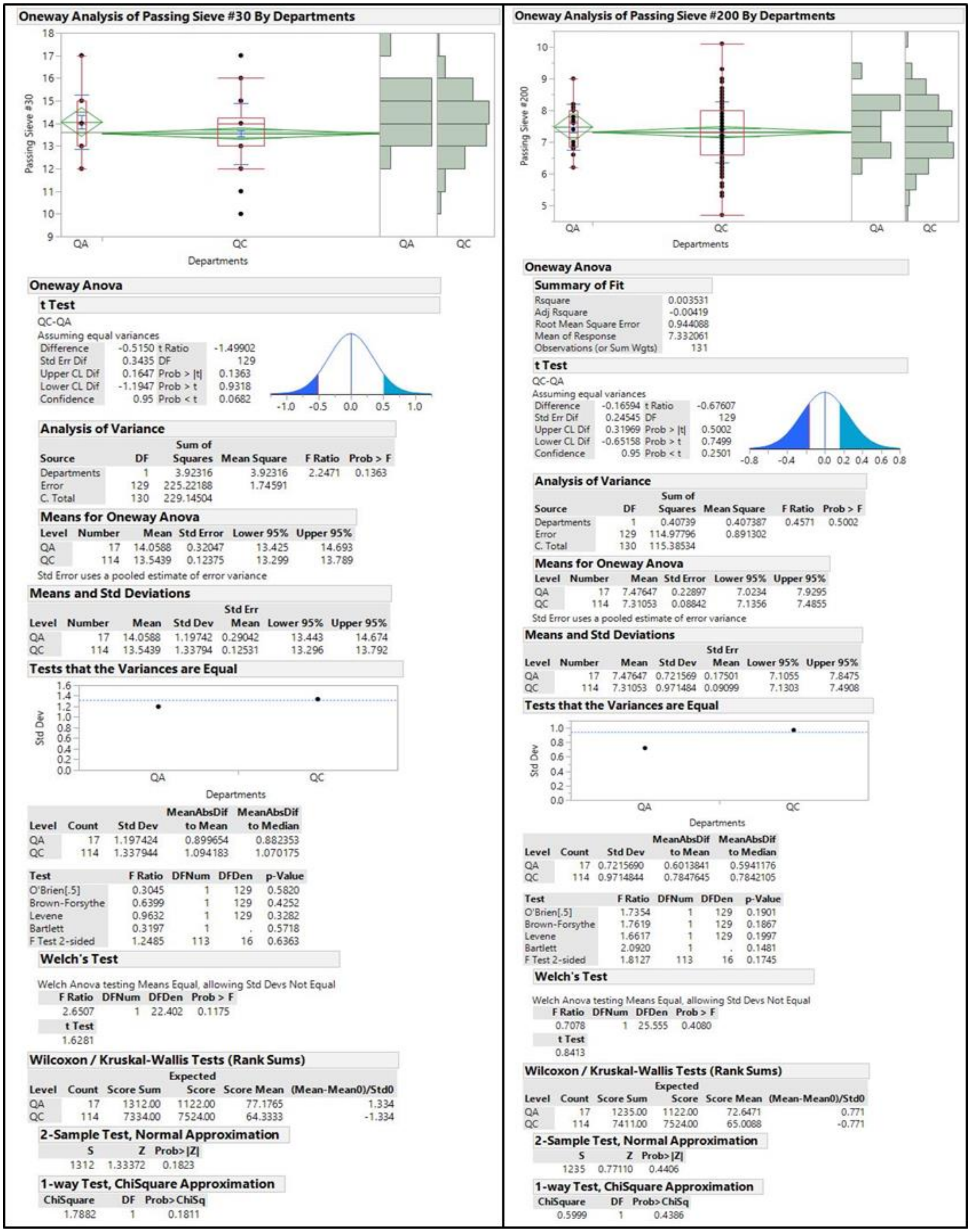
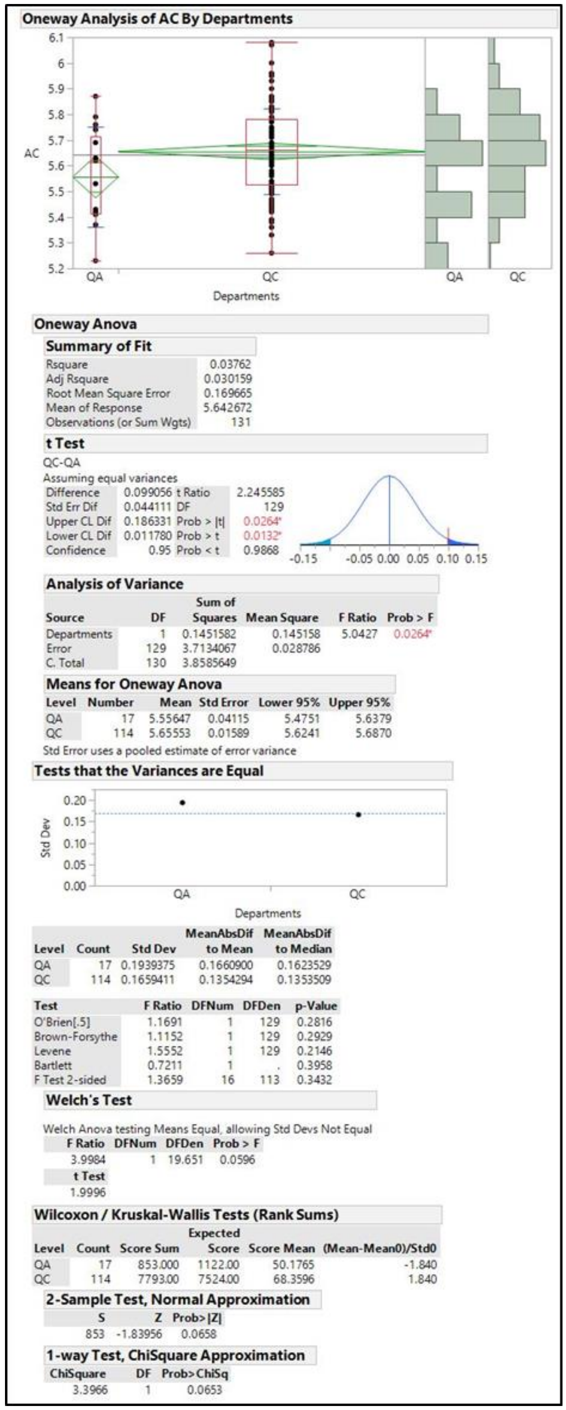


Figure 42 Project 1: Statistical Analysis for No. 30 and No. 200 Sieve s



Oneway Anova

Summary of Fit

Rsquare	0.03762
Adj Rsquare	0.030159
Root Mean Square Error	0.169665
Mean of Response	5.642672
Observations (or Sum Wgts)	131

t Test

QC-QA

Assuming equal variances

Difference	0.099056	t Ratio	2.245585
Std Err Dif	0.044111	DF	129
Upper CL Dif	0.186331	Prob > |t|	0.0264*
Lower CL Dif	0.011780	Prob > t	0.0132*
Confidence	0.95	Prob < t	0.9868

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Departments	1	0.1451582	0.145158	5.0427	0.0264*
Error	129	3.7134067	0.028786		
C. Total	130	3.8585649			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
QA	17	5.55647	0.04115	5.4751	5.6379
QC	114	5.65553	0.01589	5.6241	5.6870

Std Error uses a pooled estimate of error variance

Tests that the Variances are Equal

Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
QA	17	0.1939375	0.1660900	0.1623529
QC	114	0.1659411	0.1354294	0.1353509

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	1.1691	1	129	0.2816
Brown-Forsythe	1.1152	1	129	0.2929
Levene	1.5552	1	129	0.2146
Bartlett	0.7211	1	.	0.3958
F Test 2-sided	1.3659	16	113	0.3432

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
3.9984	1	19.651	0.0596

t Test
1.9996

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
QA	17	853.000	1122.00	50.1765	-1.840
QC	114	7793.00	7524.00	68.3596	1.840

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
853	-1.83956	0.0658

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
3.3966	1	0.0653

Figure 43 Project 1: Statistical Analysis for AC

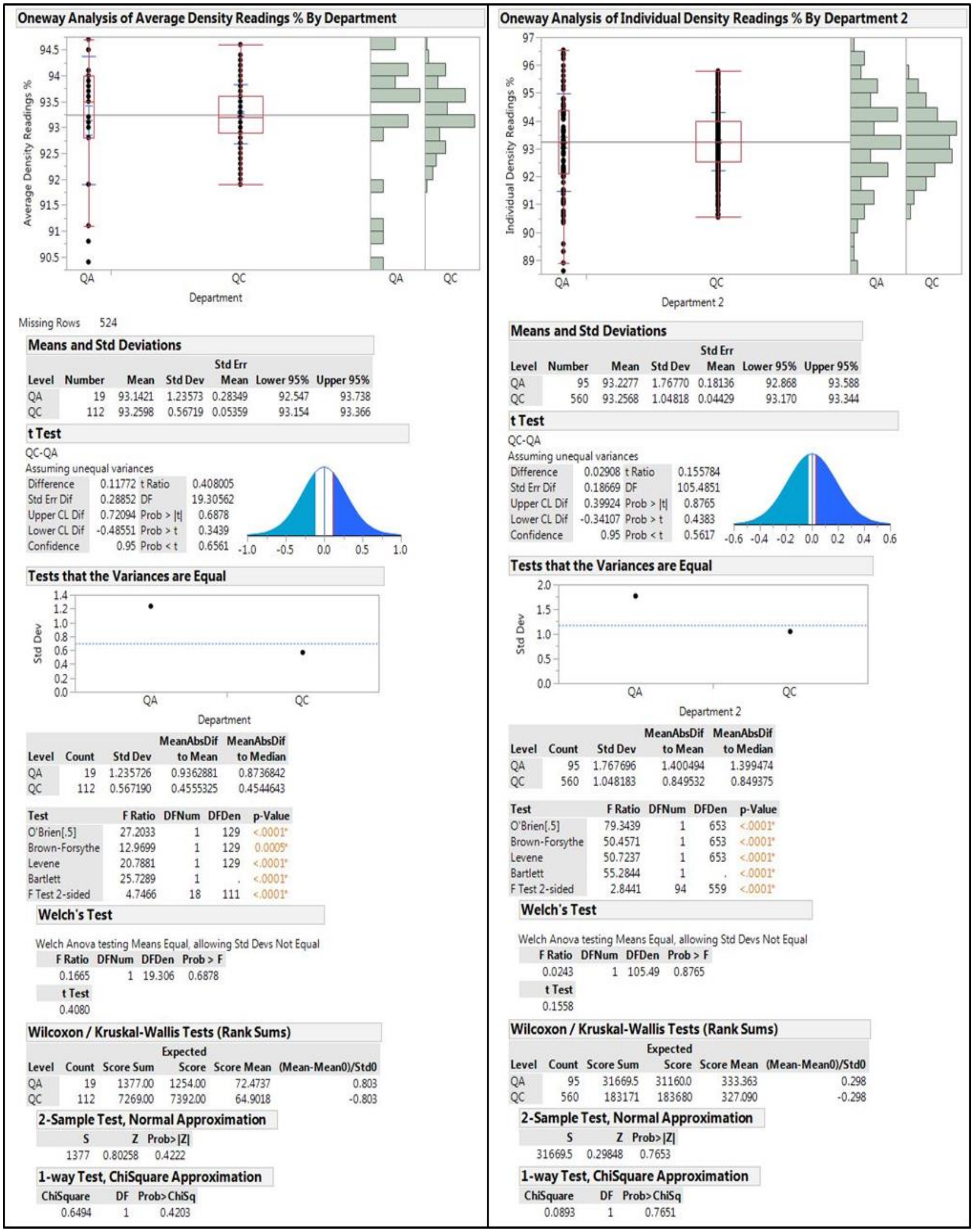


Figure 44 Project 1: Statistical Analysis for Density 1 and 2

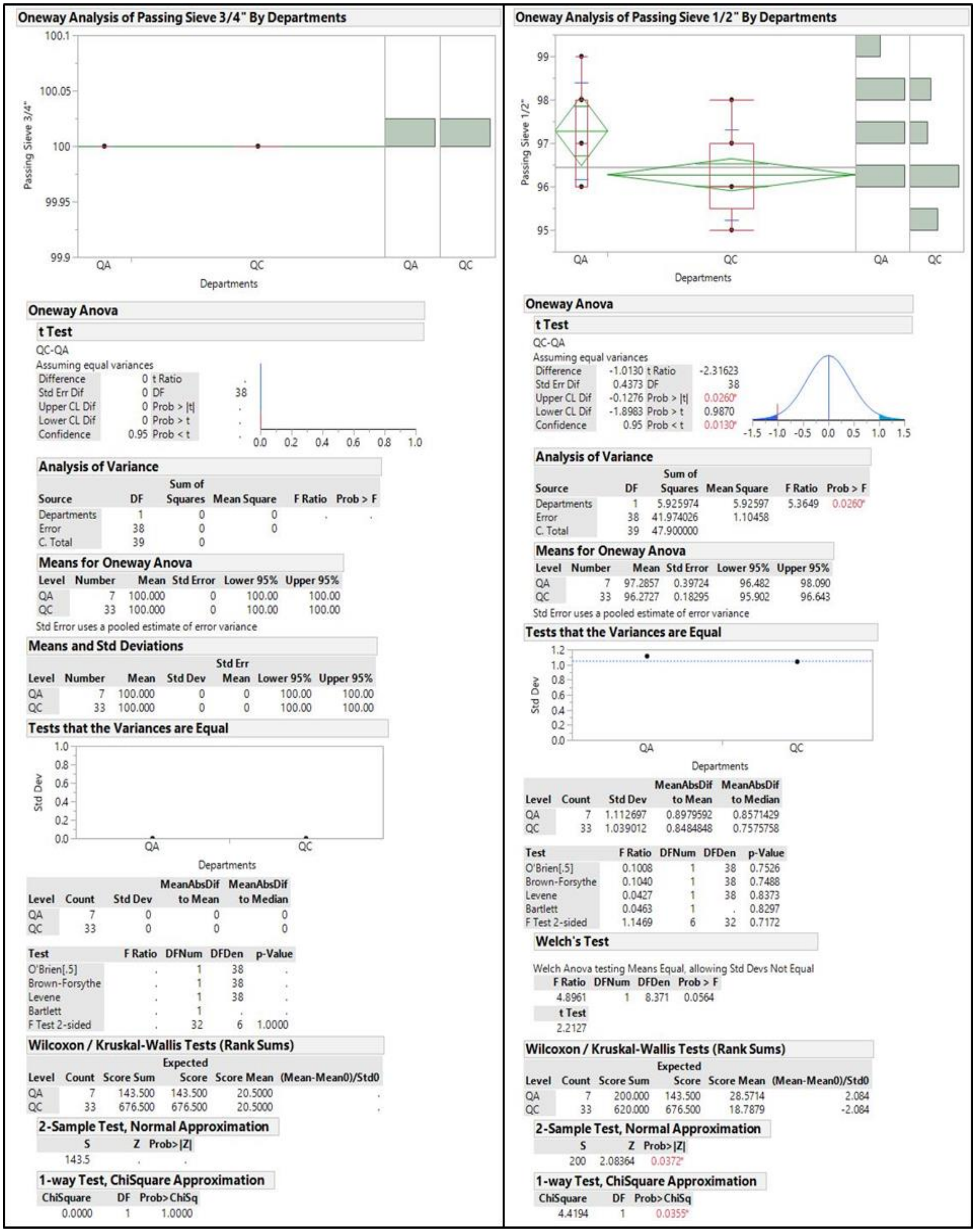


Figure 45 Project 2: Statistical Analysis for 0.75 and 0.5 Inch Sieves

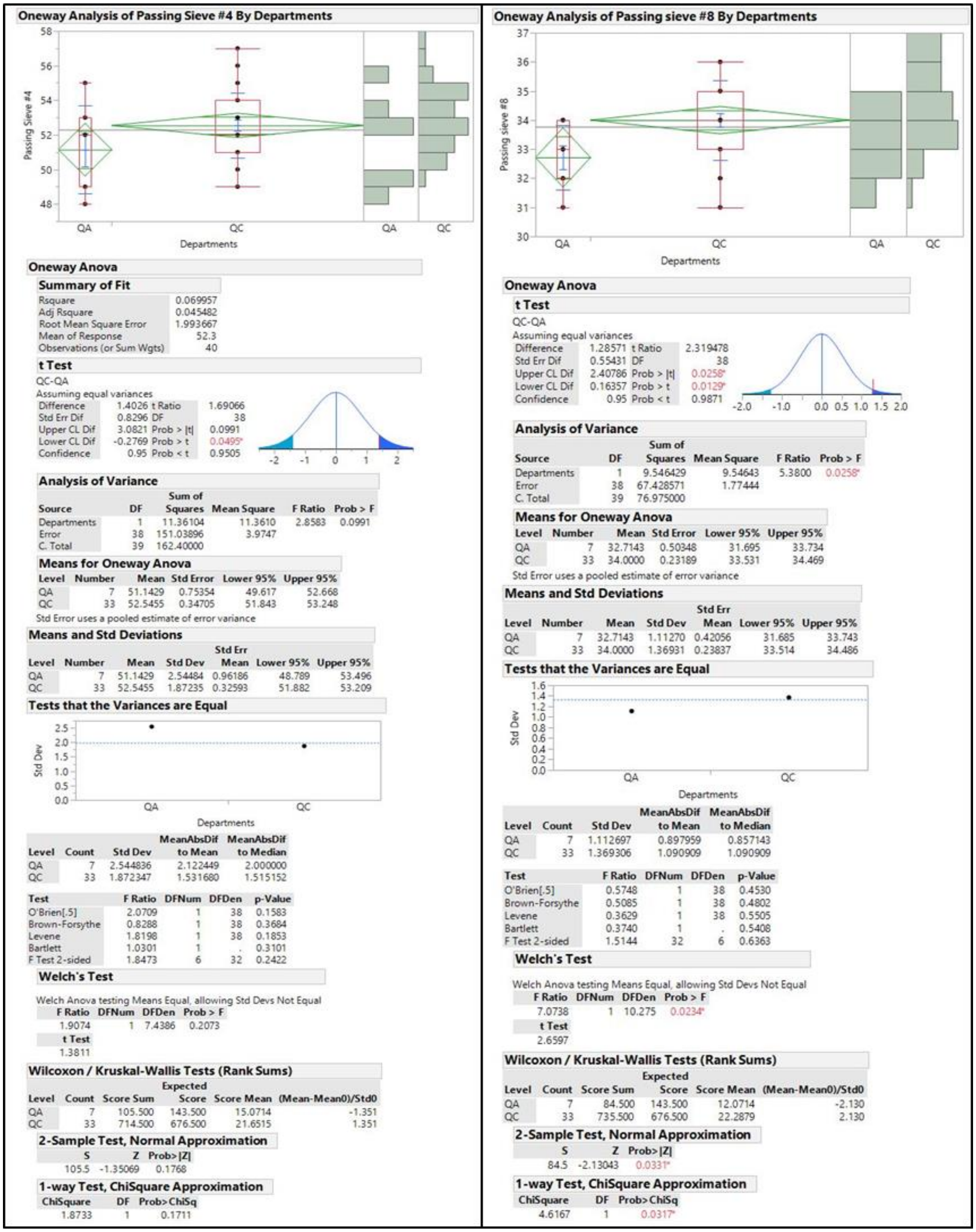


Figure 46 Project 2: Statistical Analysis for Nos. 4 and 8 Sieves

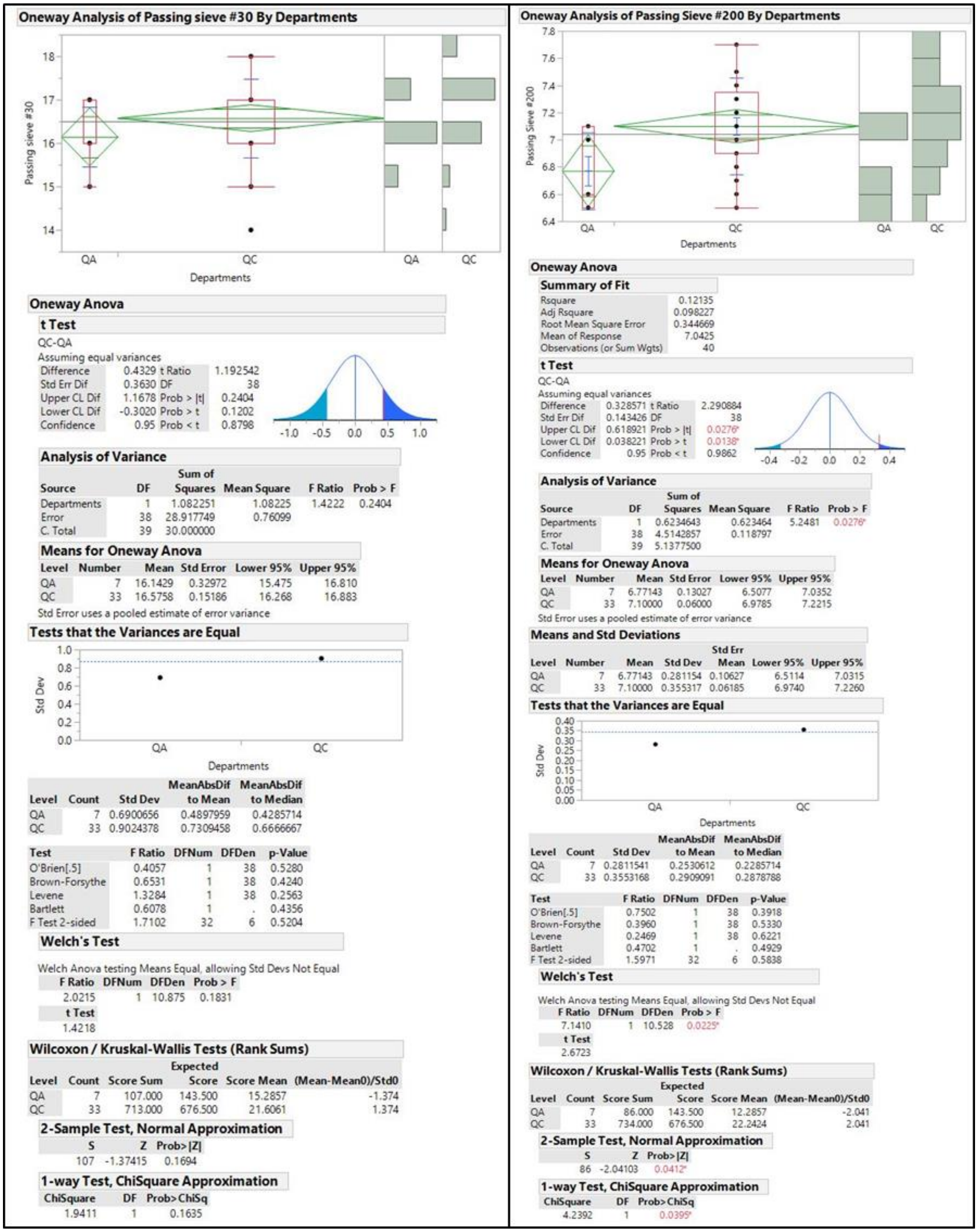


Figure 47 Project 2: Statistical Analysis for Nos. 30 and 200 Sieves

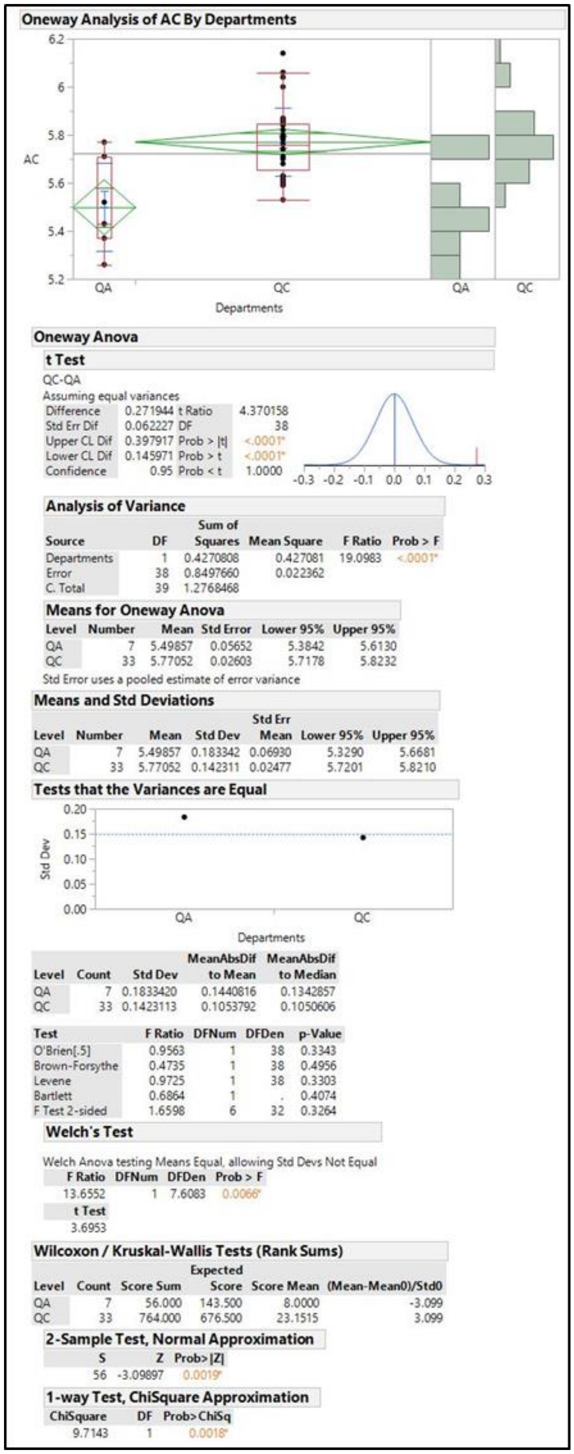


Figure 48 Project 2: Statistical Analysis for AC

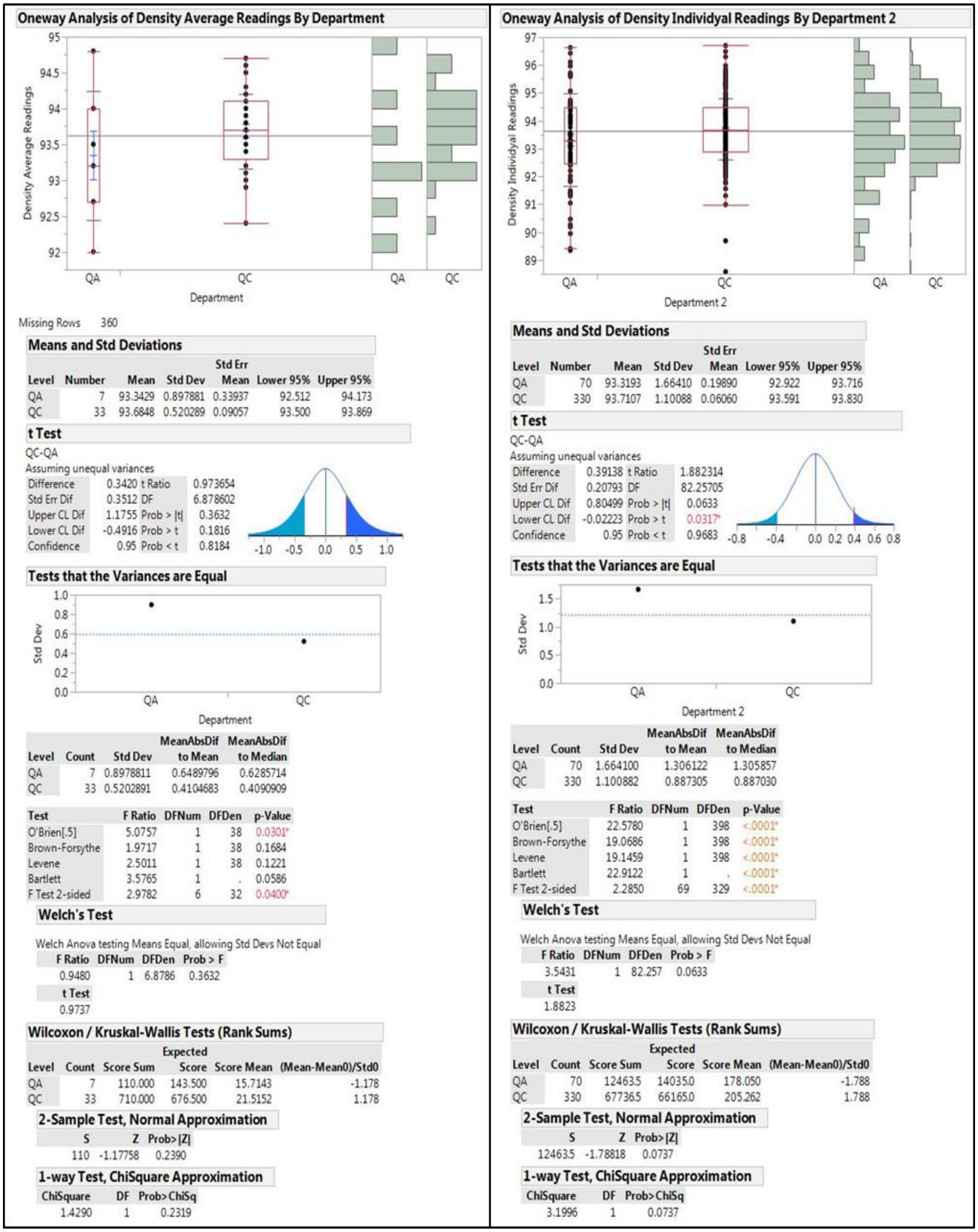


Figure 49 Project 2: Statistical Analysis for Density 1 and 2

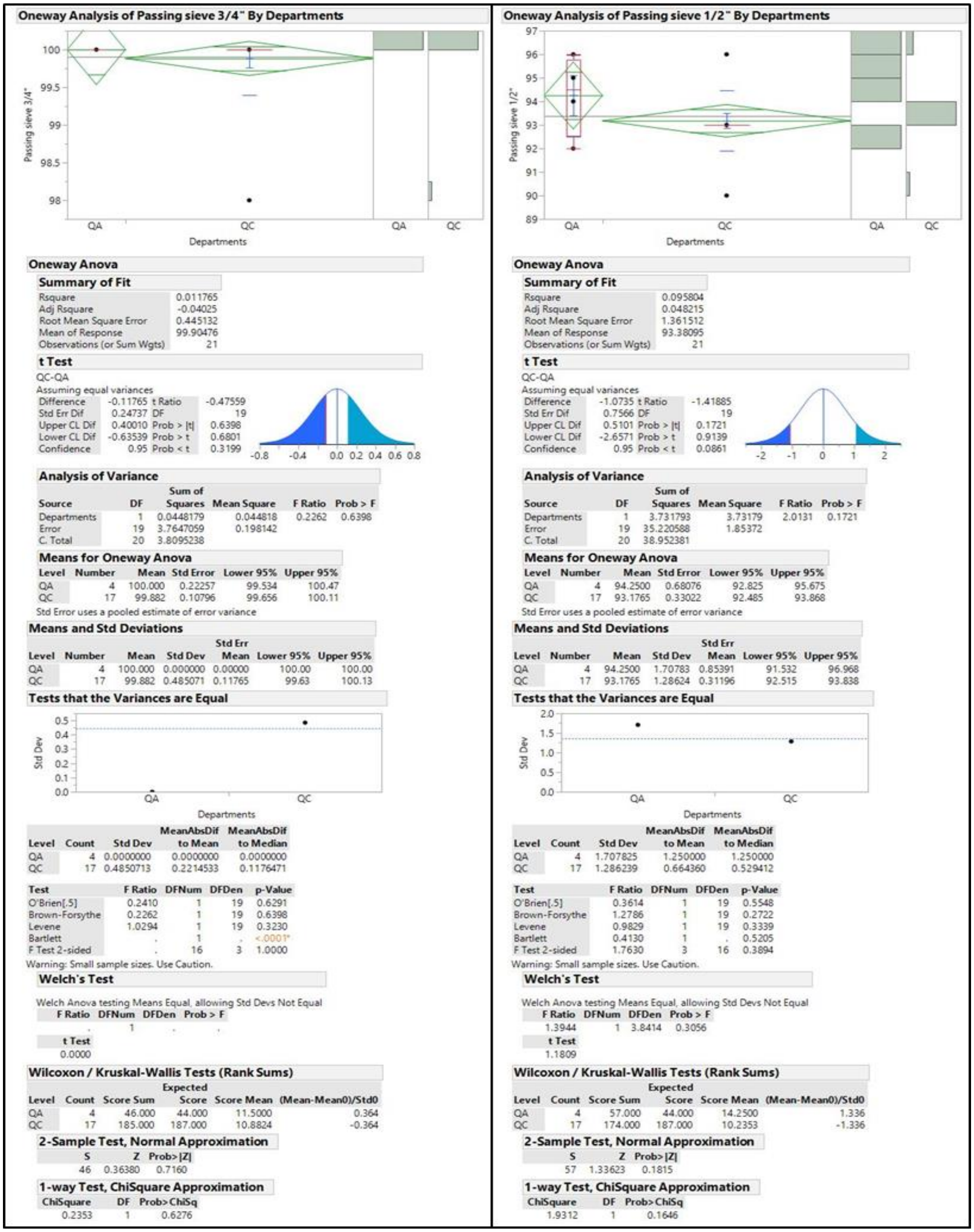


Figure 50 Project 3: Statistical Analysis for 0.75 and 0.5 Inch Sieves

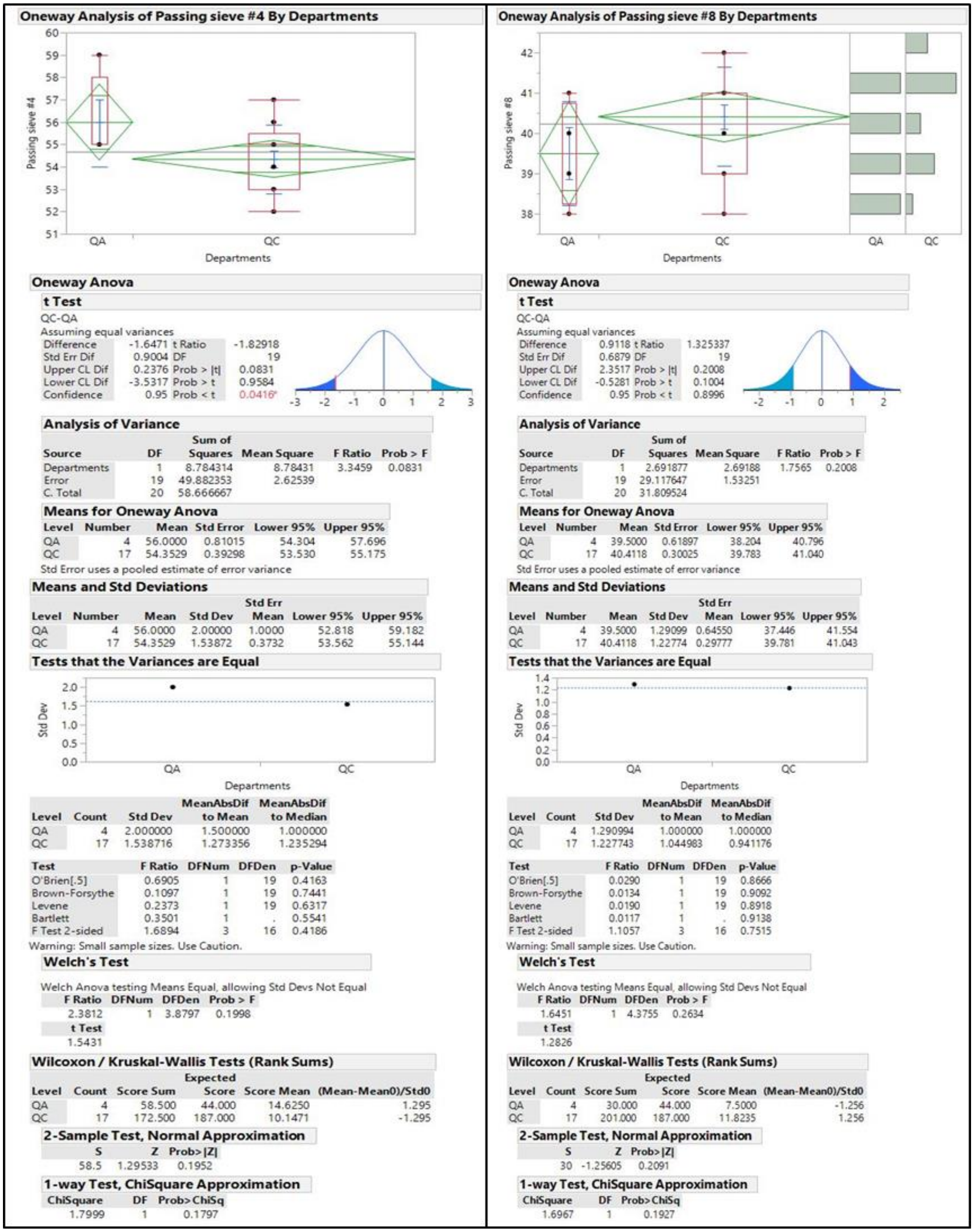


Figure 51 Project 3: Statistical Analysis for Nos. 4 and 8 Sieves

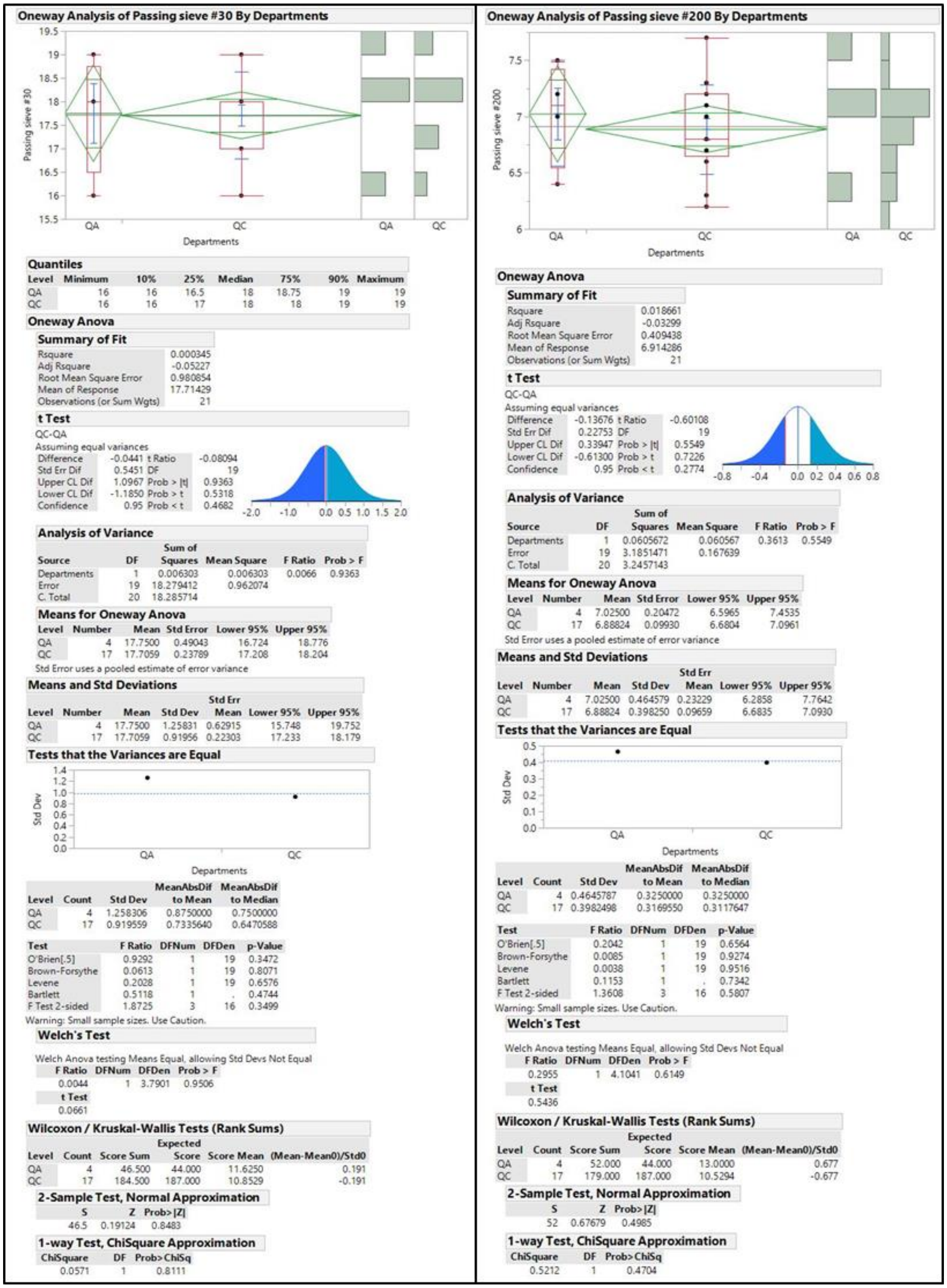
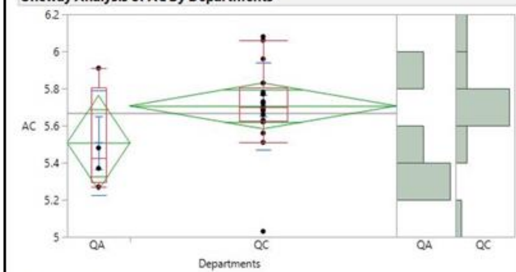


Figure 52 Project 3: Statistical Analysis for Nos. 30 and 200 Sieves

Oneway Analysis of AC By Departments



Oneway Anova

Summary of Fit

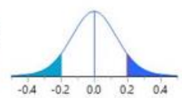
Rsquare	0.102174
Adj Rsquare	0.05492
Root Mean Square Error	0.24349
Mean of Response	5.668571
Observations (or Sum Wgts)	21

t Test

QC-QA

Assuming equal variances

Difference	0.19897	t Ratio	1.470456
Std Err Dif	0.13531	DF	19
Upper CL Dif	0.48218	Prob > |t|	0.1578
Lower CL Dif	-0.08424	Prob > t	0.0789
Confidence	0.95	Prob < t	0.9211



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Departments	1	0.1281939	0.128194	2.1622	0.1578
Error	19	1.1264632	0.059288		
C. Total	20	1.2546571			

Means for Oneway Anova

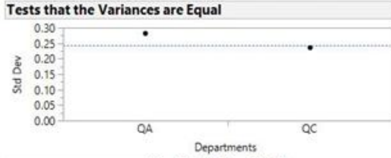
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
QA	4	5.50750	0.12175	5.2527	5.7623
QC	17	5.70647	0.05906	5.5829	5.8301

Std Error uses a pooled estimate of error variance

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
QA	4	5.50750	0.281706	0.14085	5.0592	5.9558
QC	17	5.70647	0.235636	0.05715	5.5853	5.8276

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
QA	4	0.2817061	0.2012500	0.1875000
QC	17	0.2356359	0.1503806	0.1500000

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.1205	1	19	0.7323
Brown-Forsythe	0.1371	1	19	0.7153
Levene	0.2745	1	19	0.6064
Bartlett	0.1566	1	.	0.6923
F Test 2-sided	1.4293	3	16	0.5422

Warning: Small sample sizes. Use Caution.

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
1.7134	1	4.0485	0.2599

t Test
1.3090

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
QA	4	27.000	44.000	6.7500	-1.478
QC	17	204.000	187.000	12.0000	1.478

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
27	-1.47778	0.1395

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
2.3182	1	0.1279

Figure 53 Project 3: Statistical Analysis for AC

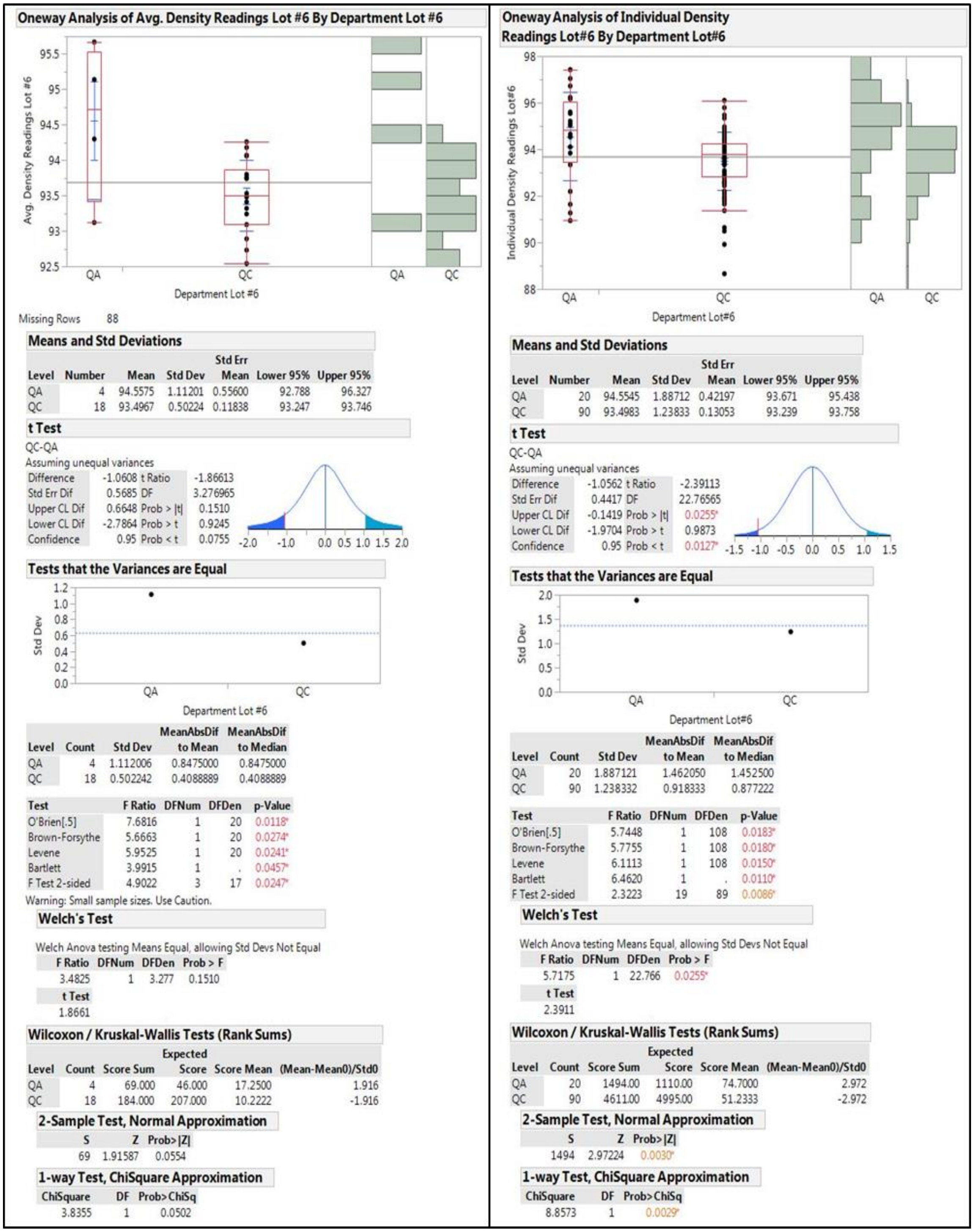


Figure 54 Project 3: Statistical Analysis for Density 1 and 2

APPENDIX B

QC AND QA DATA

Table 40 Project 1: QC Test Results of Aggregate Gradation and AC

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
1	100	93	50	30	15	8.4	5.93
2	100	93	47	28	13	7.4	5.60
3	100	93	52	32	17	10.1	5.63
4	100	92	47	30	15	8.6	5.44
5	100	91	50	31	15	8.9	5.39
6	100	93	52	32	16	9.0	5.85
7	100	92	47	25	10	4.7	5.86
8	100	90	48	28	15	8.9	5.38
9	100	94	49	28	13	5.6	5.64
10	100	94	49	30	13	7.0	5.46
11	100	94	49	24	10	5.3	5.60
12	100	92	46	28	12	5.9	5.69
13	100	92	47	29	14	7.3	5.69
14	100	93	45	27	12	6.2	5.74
15	100	94	47	28	13	7.0	5.75
16	100	93	47	28	13	6.9	5.82
17	100	94	47	29	14	8.0	5.78
18	100	94	49	30	14	7.5	5.73
19	100	91	48	30	15	8.0	5.82
20	100	93	50	30	15	7.9	5.75
21	100	93	48	30	14	6.9	5.85
22	100	93	48	29	14	7.0	5.81
23	100	94	49	30	14	7.2	6.08
24	100	93	49	30	14	7.6	5.87
25	100	94	50	30	13	6.5	5.52
26	100	95	50	32	15	8.1	5.53
27	100	93	47	28	13	7.1	5.63
28	100	92	48	28	13	7.0	5.57
29	100	94	48	29	13	6.8	5.61
30	100	93	44	27	12	6.2	5.42
31	100	94	48	28	11	6.3	5.83

Table 40 Continued

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
32	100	94	50	31	14	7.7	5.82
33	100	91	49	30	14	7.9	5.53
34	100	94	48	27	12	6.7	5.79
35	100	86	46	28	14	7.6	5.58
36	100	93	46	28	14	7.7	5.49
37	100	93	49	29	14	7.6	5.90
38	100	91	44	27	13	7.1	5.36
39	100	93	52	31	15	8.4	6.07
40	100	93	50	32	16	8.9	6.00
41	100	95	48	29	14	8.6	5.66
42	100	94	47	28	14	7.5	5.66
43	100	92	47	29	15	8.1	5.57
44	100	93	48	29	15	8.3	5.73
45	100	93	47	28	13	7.0	5.73
46	100	93	47	30	14	7.3	5.74
47	100	93	42	27	13	6.5	5.49
48	100	92	46	28	13	6.5	5.62
49	100	93	46	28	13	7.1	5.26
50	100	93	47	29	14	7.9	5.58
51	100	92	45	27	13	6.5	5.46
52	100	92	48	29	14	7.6	5.54
53	100	93	50	31	15	8.1	5.78
54	100	93	50	31	15	8.5	5.85
55	100	93	46	29	14	7.8	5.56
56	100	91	45	28	14	7.3	5.47
57	100	93	49	30	15	8.7	5.44
58	100	93	49	31	16	8.9	5.38
59	100	93	49	31	16	8.9	5.42
60	100	92	49	31	15	8.2	5.47
61	100	92	49	31	15	8.7	5.47
62	100	95	50	31	15	8.1	5.57
63	100	92	50	31	16	9.0	5.67
64	100	90	45	28	14	7.8	5.46
65	100	93	44	28	13	7.1	5.65
66	100	93	48	30	15	8.1	5.73
67	100	91	43	26	12	5.7	5.60
68	100	91	48	29	14	8.4	5.81
69	100	93	46	28	12	6.2	5.56
70	100	92	47	29	12	5.7	5.77

Table 40 Continued

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
71	100	92	43	26	12	6.5	5.46
72	100	93	45	28	13	7.3	5.42
73	100	96	48	30	15	8.4	5.50
74	100	91	45	28	13	7.1	5.58
75	100	91	43	27	12	6.2	5.74
76	100	91	43	27	13	6.6	5.79
77	100	91	45	27	12	6.3	5.63
78	100	92	43	26	11	5.6	5.62
79	100	91	42	25	12	6.6	5.33
80	100	92	49	30	15	8.0	5.72
81	100	89	44	27	14	7.5	5.61
82	100	89	44	27	13	7.1	5.67
83	100	91	41	25	11	5.4	5.46
84	100	92	47	29	12	6.7	5.72
85	100	91	42	26	13	6.7	5.50
86	100	92	43	27	13	6.9	5.62
87	100	95	45	27	13	6.5	5.95
88	100	91	45	27	12	6.1	5.85
89	100	92	48	29	14	7.3	5.86
90	100	89	42	25	11	6.0	5.54
91	100	93	47	29	14	7.5	5.83
92	100	93	48	30	15	8.4	5.72
93	100	93	47	30	14	7.5	5.51
94	100	92	45	27	13	6.5	5.78
95	100	92	44	27	13	6.7	5.63
96	100	92	45	27	13	6.6	5.68
97	100	94	48	30	15	8.3	5.66
98	100	91	46	28	14	7.5	5.78
99	100	92	45	28	14	7.5	5.73
100	100	92	46	28	14	7.6	5.77
101	100	93	45	26	11	6.3	5.71
102	100	93	47	28	13	6.4	5.68
103	100	91	44	27	14	7.7	5.43
104	100	92	46	29	14	7.8	5.69
105	100	92	45	26	12	6.8	5.69
106	100	94	49	29	13	6.9	5.95
107	100	93	49	29	14	7.0	5.82
108	100	94	48	28	13	6.7	5.64

Table 40 Continued

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
109	100	93	47	29	13	7.4	5.60
110	100	91	45	28	14	7.7	5.51
111	100	90	47	27	12	6.6	5.96
112	100	91	43	26	12	6.2	5.71
113	100	96	48	30	15	9.3	5.45
114	100	90	45	27	12	6.7	5.72

Table 41 Project 1: QA Test Results of Aggregate Gradation and AC

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
1	100	92	50	33	17	9.0	5.23
2	100	91	50	30	14	6.8	5.69
3	100	91	45	28	13	6.9	5.69
4	100	92	49	31	15	7.7	5.87
5	100	94	49	31	15	8.2	5.63
6	100	93	44	27	12	6.2	5.42
7	100	93	47	28	13	6.6	5.53
8	100	93	49	30	14	7.4	5.62
9	100	96	50	31	15	8.0	5.76
10	100	93	48	30	14	7.6	5.63
11	100	94	50	31	15	8.0	5.37
12	100	92	47	30	14	7.8	5.42
13	100	92	47	29	13	7.0	5.43
14	100	92	47	30	15	8.1	5.79
15	100	92	47	29	13	6.8	5.41
16	100	94	47	28	13	7.0	5.74
17	100	94	46	28	14	8.0	5.23

Table 42 Project 1: QC Density Data

Test No.	Density 1,%	Density 2,%				
1	94.03	94.45	93.71	94.33	94.02	93.64
2	93.37	93.52	93.67	93.92	92.43	93.30
3	93.53	93.67	93.55	93.24	92.81	94.36
4	93.76	93.43	92.81	93.61	94.42	94.54
5	93.64	93.75	93.81	93.81	93.19	93.63
6	94.05	94.12	94.55	94.06	94.00	93.50
7	93.38	93.63	93.32	93.19	93.56	93.20
8	92.82	93.08	92.58	91.59	94.50	92.34
9	92.57	92.34	92.65	92.21	92.65	93.02
10	92.84	92.58	93.20	92.58	92.40	93.45
11	92.01	92.54	91.99	91.74	91.68	92.11
12	92.71	92.17	91.92	91.99	93.46	94.02
13	93.38	93.03	93.22	94.14	93.90	92.60
14	93.13	93.90	92.73	93.34	93.83	91.86
15	93.49	94.14	92.23	91.00	95.07	95.01
16	94.03	93.22	95.62	92.42	94.20	94.69
17	94.17	93.64	94.63	94.38	93.95	94.26
18	94.11	94.38	93.40	94.20	94.51	94.07
19	94.17	93.95	94.26	92.71	94.81	95.12
20	94.12	93.58	94.50	94.01	95.31	93.21
21	93.85	92.96	94.19	94.69	94.63	92.77
22	94.45	94.11	95.11	94.73	94.24	94.05
23	94.62	94.67	95.42	95.42	92.87	94.73
24	93.88	93.87	94.55	93.68	94.73	92.57
25	93.50	93.74	94.79	92.68	93.06	93.24
26	93.61	93.12	93.30	92.87	94.48	94.30
27	93.01	94.17	93.56	92.94	92.26	92.14
28	92.27	91.70	91.83	92.14	93.00	92.69
29	93.37	94.98	92.20	93.44	93.00	93.25
30	92.40	92.83	92.27	91.47	92.83	92.58
31	93.41	93.39	93.02	91.72	98.39	90.54
32	91.88	90.91	90.91	91.10	94.87	91.59
33	93.40	95.18	93.51	90.98	93.70	93.63
34	93.40	95.18	93.51	90.98	93.70	93.63
35	93.34	95.12	93.45	90.92	93.64	93.58
36	93.63	93.76	93.02	92.53	93.70	95.12
37	93.55	91.29	93.33	93.89	94.63	94.63
38	93.07	92.16	93.95	93.58	92.96	92.71
39	93.01	92.10	93.89	93.52	92.90	92.65

Table 42 Continued

Test No.	Density 1,%	Density 2,%				
40	93.09	92.90	92.96	92.96	93.27	93.33
41	93.09	92.90	92.96	92.96	93.27	93.33
42	93.88	93.46	94.08	94.08	93.83	93.95
43	93.67	93.77	92.97	93.71	94.02	93.89
44	93.71	94.63	93.71	93.58	93.95	92.66
45	93.15	92.60	92.66	93.15	93.40	93.96
46	92.95	93.40	93.34	93.16	93.59	91.25
47	93.19	94.27	93.09	93.09	91.99	93.53
48	94.03	94.82	93.59	94.33	94.20	93.22
49	92.56	94.88	93.59	91.50	92.17	90.63
50	92.74	91.50	92.48	93.10	94.52	92.11
51	93.28	93.78	93.84	93.04	92.79	92.98
52	93.07	92.17	93.84	93.59	92.91	92.85
53	93.58	93.04	93.84	93.78	93.34	93.90
54	93.22	93.03	93.65	92.54	92.23	94.64
55	92.87	93.90	91.55	94.33	92.79	91.80
56	93.37	93.28	94.33	92.36	92.79	94.08
57	92.85	91.80	94.02	92.29	93.35	92.79
58	93.70	92.54	94.52	94.27	94.09	93.10
59	93.12	93.59	92.23	93.71	92.36	93.71
60	93.09	92.97	92.97	93.22	93.83	92.48
61	93.44	92.48	93.83	92.60	95.37	92.90
62	92.60	94.07	92.65	91.79	92.90	91.60
63	93.52	94.32	94.38	93.33	92.53	93.02
64	92.75	92.10	93.33	92.84	93.07	92.39
65	92.69	93.63	91.65	92.76	93.88	91.53
66	92.79	92.52	92.70	94.00	91.96	92.76
67	92.33	93.01	93.20	92.39	91.59	91.47
68	92.20	92.02	91.03	92.21	92.76	92.95
69	92.75	93.20	93.32	91.65	90.79	94.81
70	92.59	92.83	92.70	92.27	93.01	92.15
71	93.04	93.26	92.89	93.07	91.16	94.81
72	92.11	92.58	92.58	91.59	91.65	92.14
73	93.54	94.99	92.95	92.64	92.88	94.25
74	93.06	93.01	91.65	93.19	93.81	93.63
75	92.60	92.51	93.63	91.34	92.33	93.19
76	93.27	92.33	92.70	93.01	92.82	95.48
77	93.09	92.57	92.20	93.19	93.19	94.30
78	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

Table 42 Continued

Test No.	Density 1,%	Density 2,%				
79	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
80	93.78	94.43	92.94	94.43	91.95	95.17
81	93.73	95.29	92.07	95.67	91.33	94.30
82	93.19	95.79	93.75	93.75	90.65	92.01
83	92.41	91.89	91.33	93.50	92.82	92.51
84	93.08	91.33	92.32	93.19	94.12	94.43
85	93.37	93.07	94.55	92.76	93.07	93.44
86	92.50	93.50	92.01	93.99	91.64	91.33
87	93.11	93.62	92.26	93.68	92.88	93.13
88	93.54	93.06	93.25	94.36	92.69	94.36
89	93.97	92.07	94.30	94.73	94.80	93.93
90	94.32	93.99	94.49	94.49	94.11	94.55
91	93.23	93.18	92.81	95.48	92.38	92.32
92	93.33	93.31	91.83	91.96	94.25	95.30
93	93.09	93.94	91.34	93.07	93.63	93.50
94	93.11	92.76	92.08	94.12	93.69	92.88
95	93.04	93.01	93.13	93.94	93.69	91.46
96	93.60	91.96	95.29	93.87	93.19	93.68
97	93.91	92.51	94.55	95.11	92.07	95.29
98	93.14	93.25	93.99	94.86	92.57	91.02
99	93.46	93.68	93.81	94.55	93.62	91.64
100	94.15	94.50	94.56	93.51	94.43	93.75
101	94.17	94.62	94.56	93.51	94.43	93.75
102	92.67	92.64	92.39	92.21	94.12	91.96
103	92.41	92.58	92.46	92.89	92.15	91.96
104	93.68	91.84	95.54	93.87	95.05	92.08
105	93.06	93.63	92.76	94.31	91.71	92.88
106	93.12	92.88	95.54	92.45	93.19	91.52
107	93.56	92.02	92.51	95.05	93.81	94.43
108	92.84	92.39	93.57	92.08	92.52	93.63
109	92.43	93.26	91.47	92.52	92.64	92.27
110	93.44	92.27	94.00	93.88	95.49	91.59
111	93.84	91.96	93.07	95.73	95.05	93.38
112	93.56	92.58	94.06	94.62	93.44	93.07
113	93.48	91.71	94.19	95.42	92.39	93.68
114	93.12	93.74	93.18	92.81	92.63	93.25

Table 43 Project 1: QA Density Data

Test No.	Density 1,%	Density 2,%				
1	93.60	95.98	93.57	90.42	93.63	94.62
2	93.90	94.75	92.22	92.28	95.80	93.45
3	90.80	91.12	91.37	90.57	91.12	89.58
4	90.40	88.90	94.08	92.85	92.79	93.16
5	94.50	95.62	96.36	92.78	95.25	92.59
6	93.50	94.19	93.02	96.54	92.16	91.79
7	91.10	92.26	90.77	88.61	93.44	90.34
8	91.90	89.31	92.15	90.61	93.26	94.07
9	94.70	93.33	96.42	94.56	95.43	93.58
10	94.10	93.03	95.13	93.28	94.76	94.51
11	92.80	92.11	93.04	91.99	94.21	92.54
12	93.80	94.39	93.22	92.11	93.78	95.44
13	93.10	90.70	94.33	93.65	91.19	95.44
14	93.70	92.89	93.69	94.19	94.06	93.69
15	93.50	95.24	92.08	91.53	94.37	93.26
16	93.20	93.19	92.01	94.80	92.38	94.18
17	94.00	95.24	94.25	96.23	91.47	93.02
18	94.10	96.41	94.25	93.19	94.25	92.33
19	93.00	91.08	91.02	95.42	93.06	94.30

Table 44 Project 2: QC Data of Aggregate Gradation and AC

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
1	100	97	52	33	16	6.7	5.78
2	100	98	54	35	17	7.2	5.71
3	100	96	53	34	17	7.0	5.86
4	100	96	52	34	17	7.4	5.85
5	100	95	51	33	17	7.0	5.80
6	100	98	53	34	17	7.0	5.79
7	100	95	52	34	17	7.1	5.76
8	100	96	53	35	17	7.2	5.78
9	100	98	55	36	17	7.7	5.84
10	100	97	54	36	18	7.7	5.80
11	100	96	54	34	16	7.0	5.87
12	100	98	53	34	17	7.0	6.04
13	100	96	50	32	17	7.7	6.14
14	100	97	50	33	18	7.7	6.06
15	100	95	49	32	15	6.6	5.60
16	100	96	50	31	14	6.5	5.63
17	100	96	54	35	17	7.3	5.74
18	100	96	54	36	18	7.5	5.76
19	100	98	55	36	17	7.2	5.70
20	100	95	53	35	16	6.9	5.62
21	100	96	54	35	16	6.6	5.62
22	100	96	56	36	17	7.5	5.85
23	100	97	57	36	18	7.3	5.82
24	100	96	50	33	16	6.9	5.59
25	100	96	51	33	15	6.6	5.71
26	100	96	51	33	16	6.9	5.76
27	100	95	51	32	16	6.5	5.68
28	100	96	51	33	16	6.8	5.74
29	100	98	54	35	17	7.4	5.78
30	100	95	52	33	16	7.0	6.00
31	100	95	52	34	16	6.9	5.61
32	100	95	52	34	16	7.2	5.53
33	100	97	52	33	17	7.3	5.60

Table 45 Project 2: QA Data of Aggregate Gradation and AC

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
1	100	99	55	34	17	7.1	5.71
2	100	97	49	31	15	6.5	5.37
3	100	97	49	32	16	6.6	5.52
4	100	98	52	33	16	7.0	5.43
5	100	98	53	33	16	6.6	5.77
6	100	96	52	34	17	7.1	5.43
7	100	96	48	32	16	6.5	5.26

Table 46 Project 2: Density 1 and 2 QC Data

Test No.	Density 1,%	Density 2,%									
1	93.6	92.98	94.15	92.79	94.22	94.28	94.22	94.15	93.37	93.24	92.72
2	93.4	94.35	93.57	93.37	93.96	93.37	93.37	93.83	91.81	93.44	92.53
3	93.9	93.69	93.04	94.47	92.78	94.53	92.78	94.60	96.29	94.01	93.23
4	93.8	92.26	93.75	92.91	94.34	92.91	94.47	94.53	93.62	95.71	93.95
5	94.3	95.38	94.21	92.26	94.47	94.22	96.49	93.70	93.25	94.48	94.94
6	93.7	93.70	94.16	92.86	92.21	95.00	94.55	92.60	93.18	95.00	93.96
7	93.5	94.16	93.31	94.35	92.86	94.74	92.73	94.09	94.09	94.48	92.08
8	92.9	93.38	94.03	92.92	92.79	95.71	91.56	93.12	93.31	93.38	94.09
9	94.0	93.64	92.27	95.84	93.96	92.47	93.31	95.13	95.00	93.18	95.26
10	93.2	93.38	92.27	94.61	92.14	93.51	94.16	92.47	93.77	92.53	92.73
11	93.9	94.03	93.38	94.09	92.60	94.16	93.84	94.94	95.52	93.12	93.12
12	93.7	94.94	93.71	94.22	92.73	94.81	93.25	92.73	93.19	93.06	93.96
13	94.1	93.96	94.87	95.26	94.09	93.84	92.80	92.61	95.27	94.10	94.36
14	93.8	94.36	94.29	94.42	93.77	93.39	95.14	93.06	94.36	94.03	91.31
15	93.2	95.27	93.19	92.61	94.03	93.51	92.87	93.13	92.35	92.80	92.48
16	94.7	95.40	93.58	94.94	93.46	94.75	96.70	94.04	94.49	94.43	95.40
17	94.1	94.56	94.17	93.33	95.34	93.59	95.21	93.65	92.88	94.30	93.78
18	93.8	92.62	92.94	92.81	94.75	92.81	92.81	94.95	93.33	95.66	95.01
19	93.8	95.53	93.59	92.29	93.01	93.52	93.84	92.68	94.75	93.20	95.46
20	93.4	94.23	92.09	92.55	95.27	92.61	93.26	92.55	93.13	94.23	94.62
21	93.6	94.56	91.96	93.32	92.35	93.77	95.33	93.84	93.00	95.33	92.48
22	93.1	93.90	92.87	92.93	93.71	92.41	94.29	92.15	93.71	91.96	93.00
23	93.2	93.32	93.90	93.19	92.35	93.19	93.90	94.62	93.90	88.58	95.46
24	94.5	92.86	94.29	94.16	95.46	93.25	94.74	94.94	95.85	94.68	94.61
25	93.0	92.86	92.54	92.86	94.16	92.47	94.81	92.21	92.41	92.80	92.93
26	94.1	94.87	96.30	92.21	92.15	94.22	93.58	95.78	94.74	93.32	93.58
27	94.6	93.32	95.20	93.51	94.87	93.96	95.13	94.03	95.98	95.26	94.74
28	94.2	93.71	94.68	93.06	94.94	94.35	94.68	95.59	93.12	95.32	93.51

Table 46 Continued

Test No.	Density 1,%	Density 2,%									
29	94.1	95.00	93.31	94.81	95.84	93.12	92.53	95.13	93.77	93.18	93.90
30	93.6	94.09	95.13	92.92	93.51	93.12	92.73	92.53	95.26	94.09	92.92
31	93.4	93.25	93.31	92.92	94.87	94.48	93.45	93.26	91.76	93.71	92.74
32	92.4	94.16	90.99	95.27	89.69	92.54	92.54	91.96	92.02	92.93	92.28
33	93.0	93.39	92.48	94.16	92.41	92.54	93.58	93.64	92.41	92.87	92.09

Table 47 Project 2: Density 1 and 2 QA Data

Test No.	Density1, %	Density 2,%									
1	93.2	93.76	94.41	89.41	91.42	94.67	94.54	93.18	91.49	93.31	95.65
2	93.2	93.18	93.12	95.06	93.44	94.09	93.18	92.73	92.21	92.53	92.66
3	93.5	96.43	92.40	92.60	94.74	93.96	93.57	92.47	93.25	92.40	92.73
4	94.8	96.11	96.63	93.00	95.07	95.72	94.10	94.49	94.03	94.42	94.36
5	92	89.95	93.51	93.06	94.16	91.05	90.47	92.02	93.77	90.27	91.37
6	94	95.59	94.61	96.11	94.68	94.74	92.54	92.47	91.82	92.86	94.22
7	92.7	94.55	92.79	95.97	91.88	93.51	90.19	91.30	93.90	93.12	89.35

Table 48 Project 3: Aggregate Gradation and AC QC Data

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
1	98	90	52	39	17	6.7	5.03
2	100	93	53	40	17	6.6	5.69
3	100	96	56	40	18	7.1	5.63
4	100	93	52	39	16	6.3	5.66
5	100	93	55	39	17	6.8	5.68
6	100	93	54	41	18	7.2	5.62
7	100	93	56	41	18	6.8	5.83
8	100	93	57	42	19	7.7	6.08
9	100	96	54	41	19	7.1	5.56
10	100	93	55	41	18	6.8	5.96
11	100	93	55	41	18	6.8	6.06
12	100	93	55	42	18	7.2	5.72
13	100	93	55	41	18	7.2	5.78
14	100	93	56	42	19	7.3	5.73

Table 48 Continued

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
15	100	93	52	38	16	6.2	5.51
16	100	93	53	39	17	7.0	5.70
17	100	93	54	41	18	6.3	5.77

Table 49 Project 3: Aggregate Gradation and AC QA Data

Test No.	0.75 inch	0.5 inch	No.4	No.8	No.30	No.200	AC %
1	100	96	59	41	18	7.2	5.37
2	100	94	55	38	16	6.4	5.27
3	100	92	55	40	19	7.5	5.91
4	100	95	55	39	18	7.0	5.48

Table 50 Project 3: Density 1 and 2 QC Data

Test No.	Density 1,%	Density 2,%				
1	93.09	94.79	92.09	91.83	91.96	94.79
2	94.07	94.35	94.41	94.97	93.78	92.84
3	93.74	92.59	94.28	93.40	94.10	94.35
4	93.09	90.64	94.03	95.79	93.09	91.90
5	93.24	92.53	93.53	94.10	92.21	93.84
6	93.32	94.03	93.91	93.40	91.65	93.59
7	94.06	94.22	93.02	96.10	93.33	93.65
8	94.26	93.77	93.96	95.47	94.59	93.52
9	92.89	94.59	94.65	93.08	93.46	88.66
10	92.73	90.49	93.83	91.75	93.83	93.77
11	93.41	94.14	94.71	92.07	93.70	92.44
12	92.54	89.92	91.37	93.45	94.08	93.89
13	93.76	94.02	91.81	95.34	92.75	94.90
14	94.18	94.14	94.58	93.89	94.01	94.27
15	93.48	92.88	93.70	94.39	93.82	92.63
16	93.80	93.70	92.94	93.57	94.96	93.82
17	93.53	92.63	94.20	92.75	93.64	94.45
18	93.75	94.51	92.56	94.01	94.01	93.69

Table 51 Project 3: Density 1 and 2 QA Data

Test No.	Density 1,%	Density 2,%				
1	94.30	91.27	95.54	93.34	96.23	95.10
2	95.67	95.60	94.10	96.17	97.42	95.04
3	93.12	90.94	91.64	93.84	94.53	94.65
4	95.14	97.04	92.19	96.72	95.21	94.52