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Investigation of Quality Control/ Quality Assurance Data to Review Current Specifications for Portland Cement Concrete Pavement Acceptance in Kansas

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16 Abstract

Quality control (QC) and quality assurance (QA) attributes of highway construction must be measured and achieved throughout each project. Statistical specifications are commonly used to ensure compliance of QC and QA attributes, and attribute data must be reviewed periodically to improve specifications for agencies and contractors. The Kansas Department of Transportation (KDOT) typically considers concrete compressive strength and slab thickness to be QC attributes for portland cement concrete (PCC) pavements. This study reviewed KDOT QC/QA data from 24 PCC projects to investigate the effects of statistical level of significance and sample size on pay adjustment. Pay adjustments were calculated based on current KDOT practices and practical performance models (PPMs). Results showed no significant differences between lot means for all projects at any significance level or for any sample size, and no specific patterns were observed in pay adjustments for changing sample sizes. The PPM yielded higher pay deductions compared to current KDOT practices. This study also implemented a multivariate control chart to monitor and regulate the KDOT QC/QA process.

Further investigation should explore why no significant differences were evident in lot means for strength and thickness; further research is also recommended to study the effect of sublot size on pay adjustment since pay adjustments can vary with the number of sublots. Coefficients of the PPM methods must be revisited if KDOT implements PPM methods for pay adjustments. Although use of a multivariate process control chart could be useful, especially when multiple variables are included in the QC process, further research is needed to effectively implement multivariate process control charts into the QC process.

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Abstract

Quality control (QC) and quality assurance (QA) attributes of highway construction must be measured and achieved throughout each project. Statistical specifications are commonly used to ensure compliance of QC and QA attributes, and attribute data must be reviewed periodically to improve specifications for agencies and contractors. The Kansas Department of Transportation (KDOT) typically considers concrete compressive strength and slab thickness to be QC attributes for portland cement concrete (PCC) pavements. This study reviewed KDOT QC/QA data from 24 PCC projects to investigate the effects of statistical level of significance and sample size on pay adjustment. Pay adjustments were calculated based on current KDOT practices and practical performance models (PPMs). Results showed no significant differences between lot means for all projects at any significance level or for any sample size, and no specific patterns were observed in pay adjustments for changing sample sizes. The PPM yielded higher pay deductions compared to current KDOT practices. This study also implemented a multivariate control chart to monitor and regulate the KDOT QC/QA process.

Further investigation should explore why no significant differences were evident in lot means for strength and thickness. Further research is also recommended to study the effect of sublot size on pay adjustment since pay adjustments can vary with the number of sublots. Coefficients of the PPM methods must be revisited if KDOT implements PPM methods for pay adjustments. Although use of a multivariate process control chart could be useful, especially when multiple variables are included in the QC process, further research is needed to effectively implement multivariate process control charts into the QC process.

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Chapter 1: Introduction

1.1 General

Highway pavement quality assurance (QA) programs encompass statistical specifications to regulate quality control (QC) attributes. Based on these specifications, disincentive pay factors, often called penalties or negative price adjustments, are utilized for products that fail to meet the standards (Hughes, 2005). QA programs commonly include three components: QC, acceptance, and independent assurance (IA). In general, the contractor is responsible for QC, the agency is responsible for acceptance, and an independent third party conducts IA (Hughes, 2005).

Kansas Department of Transportation (KDOT) Portland cement concrete (PCC) pavement QC/QA specifications include contractor quality control requirements, materials and construction requirements, and measurements and payment. Pay adjustments for mainline segments are calculated based on PCC thickness and compressive strength; pay adjustments for acceleration lanes are based on PCC thickness (Hossain, Khanum, Neil, & Ingram, 2006). Pay adjustment factors are determined lot by lot based on the percent-within-limits (PWL) approach. The pay adjustment reflects the amount of deduction or bonus and the optimized risk distributed between the agency and the contractor.

1.2 Problem Statement

KDOT maintains an updated database of as-constructed material properties for PCC pavements from the tests required for the QC/QA program. In addition, KDOT's Construction Management System (CMS) database contains selected attributes related to highway construction in Kansas. A Quality Assurance Stewardship Review by the Federal Highway Administration (FHWA) in the mid-2000s recommended that KDOT analyze data from the CMS and databases to validate specifications and calculate pay factors. Kansas State University reviewed KDOT QC/QA data in the K-TRAN: KSU-09-7 project in 2011 and investigated PWL specifications using payment lot sizes, acceptance of contractors' test results, a composite pay index, and changing levels of significance for statistical testing (Gedafa, Hossain, & Ingram, 2012). Another study developed a practical performance model (PPM) for PCC pavements in

Kansas in 2012 (Gedafa, Hossain, Ingram, & Kreider, 2012). Since development of that model, data have accumulated, and a new review is needed for continuous improvement. Therefore, the current study investigated the effects of changing sample sizes for strength and thickness for pay adjustments and compared lot- and sublot-wise means. Pay adjustment methods were investigated using current KDOT practice and the PPM.

1.3 Objectives of the Study

Main objectives of this study included the following:

- Investigate the consequences of changing sample sizes for strength and thickness.
- Study the effect of changing sample size on pay adjustment.
- Investigate the consequences of changing the level of significance (α) from 0.01 to 0.025.
- Compare several pay adjustment computation methods using QC data.
- Implement a multivariate process control chart to monitor the QC process.

Chapter 2: Data Analysis

2.1 Introduction

This chapter describes the data collection and statistical methodologies used to review QC/QA data of PCC pavements in Kansas. A total of 439 lots (each with five sublots) from 24 contracts were used in the statistical analysis.

2.2 Data Collection

PCC pavement compressive strength and slab thickness parameters were extracted from each construction contract form. Table 2.1 summarizes project and contract numbers for this study, and Figure 2.1 shows the variable number of lots for each contract. A total of 439 lots comprise one dataset, and one lot includes five sublots.

Table 2.1: Project Lots and Contract Numbers

No.	Total lots	Project No.	Contract No.
1	51	035-046 K 9014-01	508021011
2	50	70-91 KA0718-01	9511041353
3	44	61-78 K 8252-01	1509022525
4	41	035-046 K 9014-01	508021011
5	39	50-78- K7409-02	1511062555
6	36	54-1 KA 2202-01	513036414
7	27	54-76 K-8243.04	P513022535
8	27	I070-027 KA-0730-01	e511072292
9	21	I070-027 KA-0728-01	e511072272
10	20	KA 3529-01	514036241
11	18	54-48 K-8244-05	e511112515
12	14	90-105 KA 1003-05	513051111
13	10	400-37 KA 2375-05	515022434
14	7	54-48 K-8244-08	e511112535
15	7	54-480K-8244-10	P511112555
16	5	90-105 KA 1003-05	513051111
17	4	U050-009 KA 2683-01	512066232
18	4	KA 2040-01	512106675
19	3	54-48 K-8244-05	e511112515
20	3	70-91 KA 0718-01	9511041353
21	2	54-480K-8244-10	P511112555
22	2	54-76 K-8243.04	P513022535
23	2	400-103 KA 2375-06	515022514
24	2	KA 2040-01	512106675

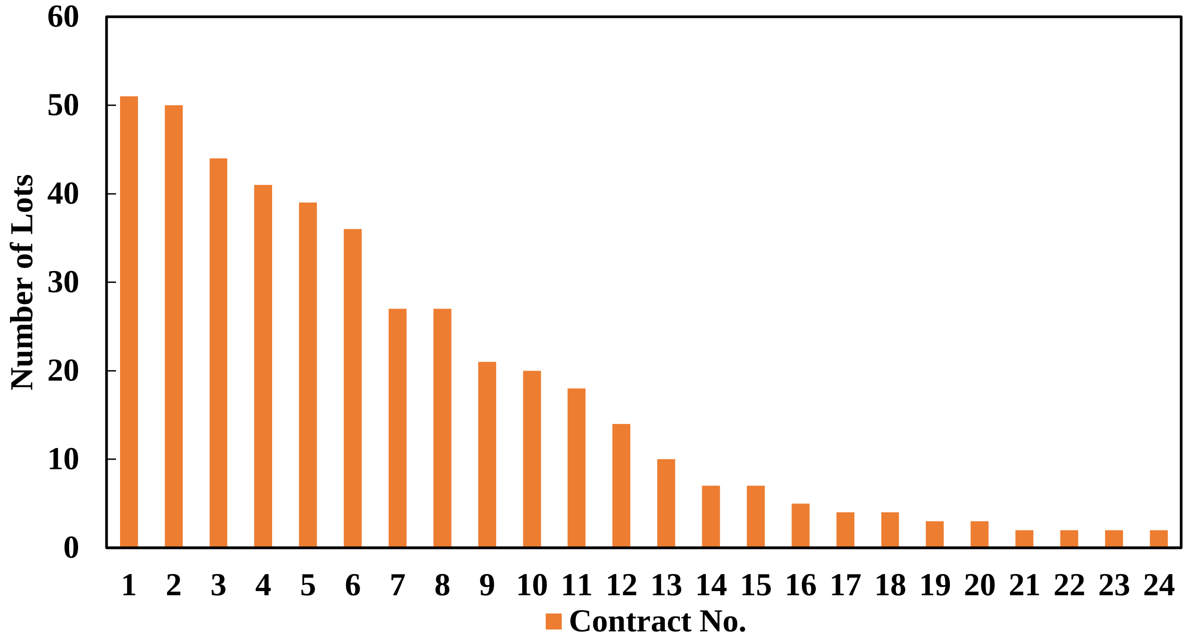
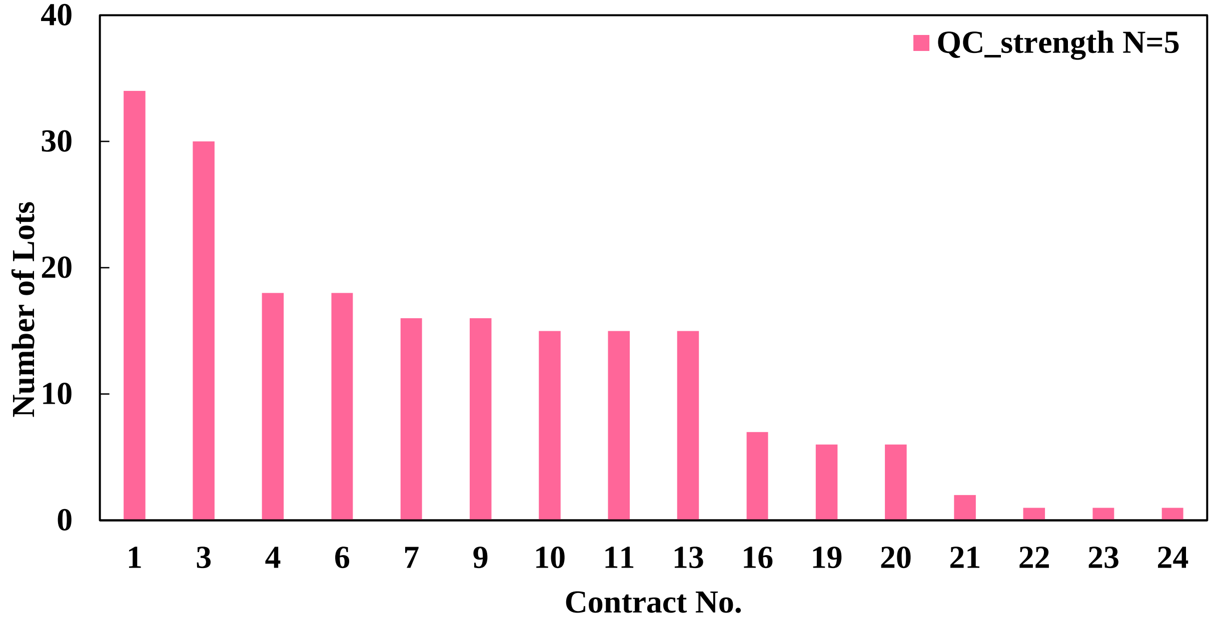
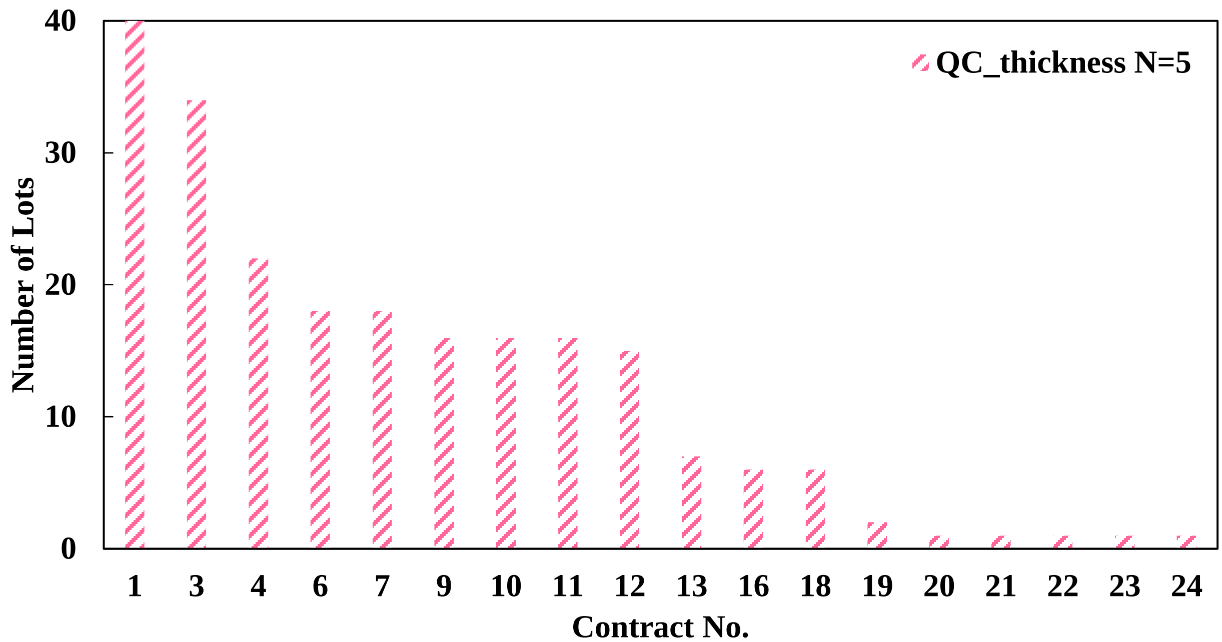


Figure 2.1: PCC Contracts

All lots were grouped into three categories to investigate the consequences of changing sample sizes for strength and thickness. Each category contained a certain number of sublots. For example, Category 1 had five sublots, Category 2 had four sublots, and Category 3 had three sublots. Figure 2.2 shows the number of lots for each contract with five sublots.



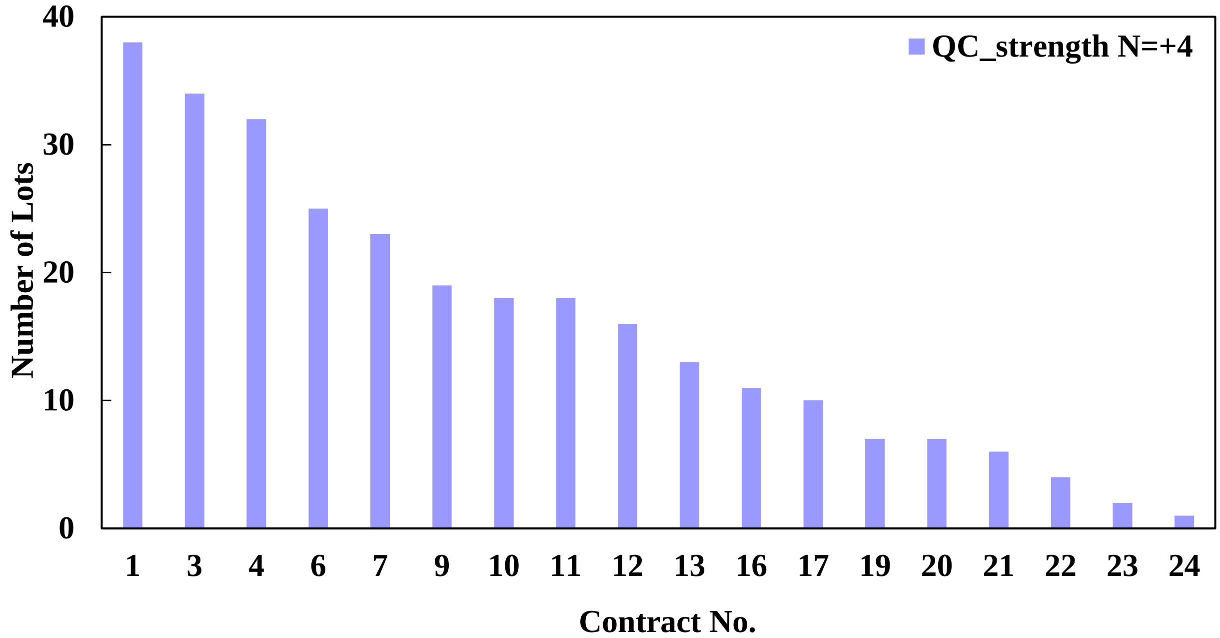
(a) QC Strength



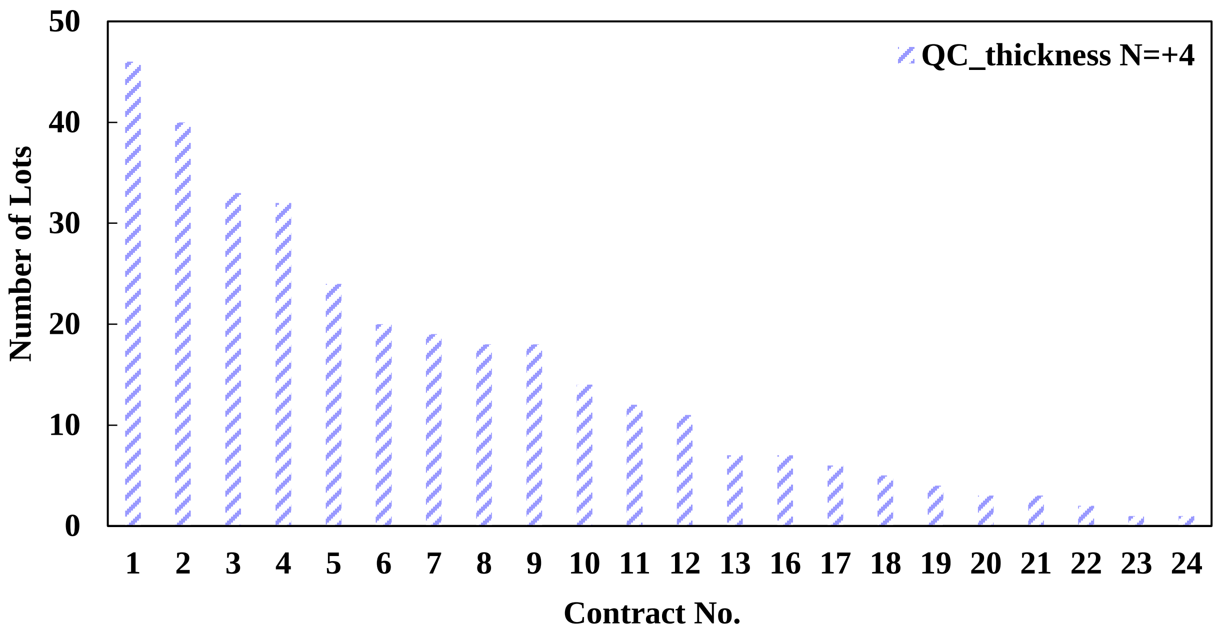
(b) QC Thickness

Figure 2.2: Number of Lots with Five Sublots

Figure 2.3 and Figure 2.4 illustrate the number of lots for each contact with four and three sublots, respectively. In the figures, "+4" represents the first four sublots from each lot, while "-4" represents the last four sublots from each lot. Three sublots are named similarly. For lots with only four sublots, if the last sublot from a lot is missing, then that lot is classified into the "+4" sublot group; otherwise, it is classified into the "-4" sublot group. Lots with only three sublots are denoted as "+3" sublots if the last two sublots are missing from one lot, and "-3" sublots if the first two sublots are missing from one lot.

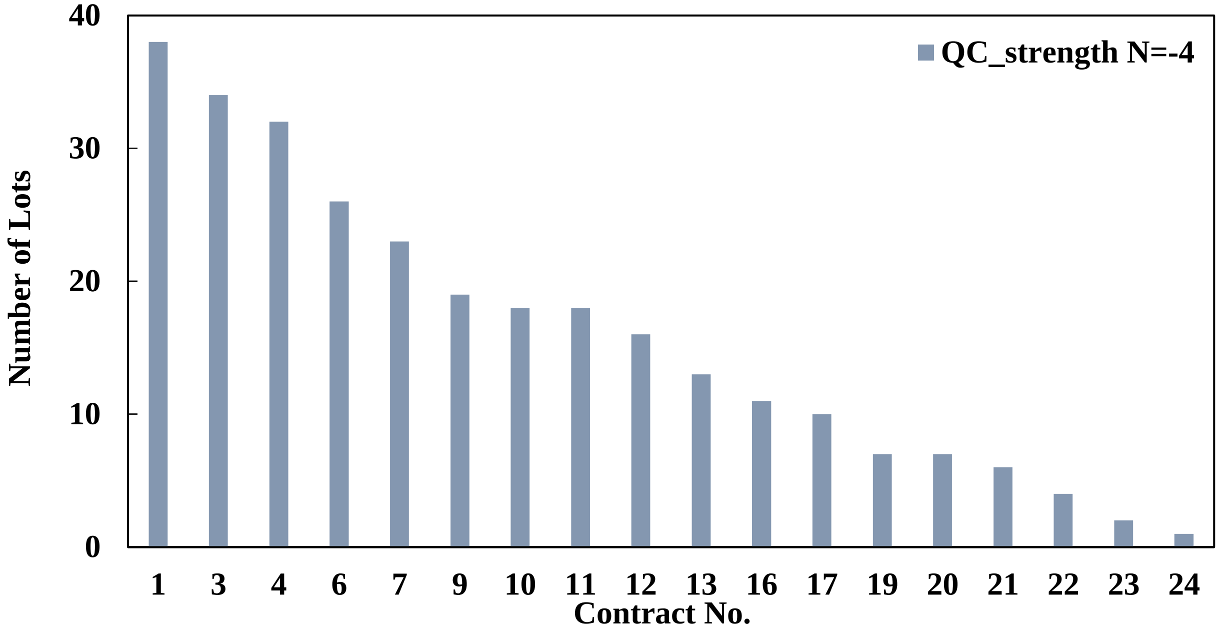


(a) QC Strength for N = +4

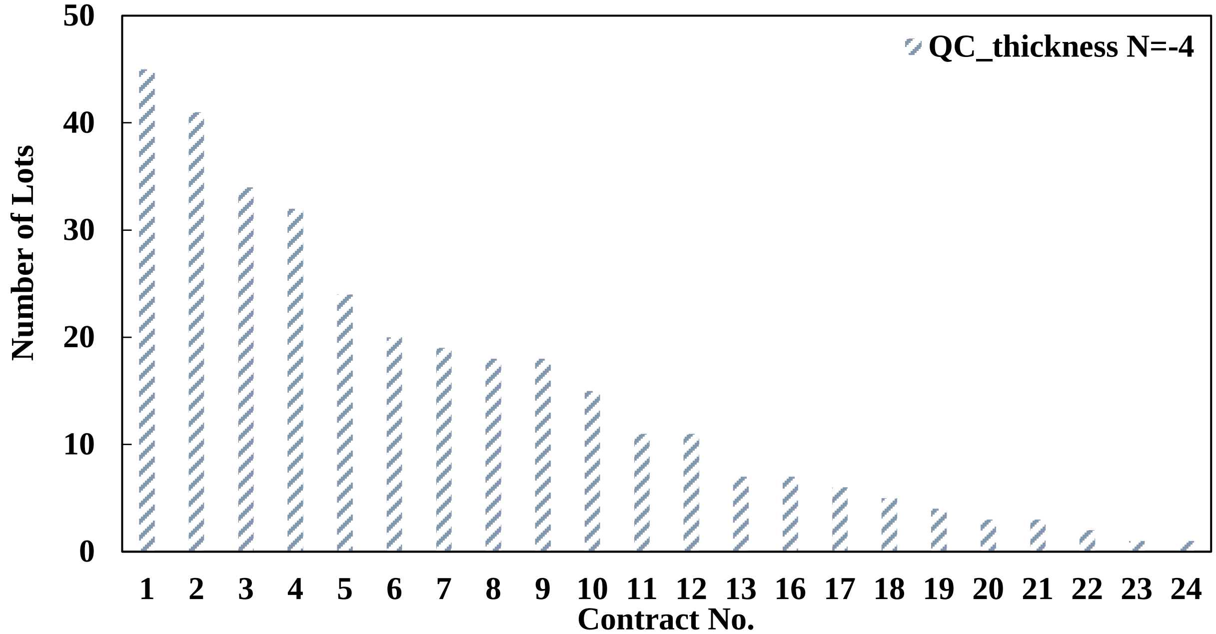


(b) QC Thickness for N = +4

Figure 2.3: Number of Lots with Four Sublots

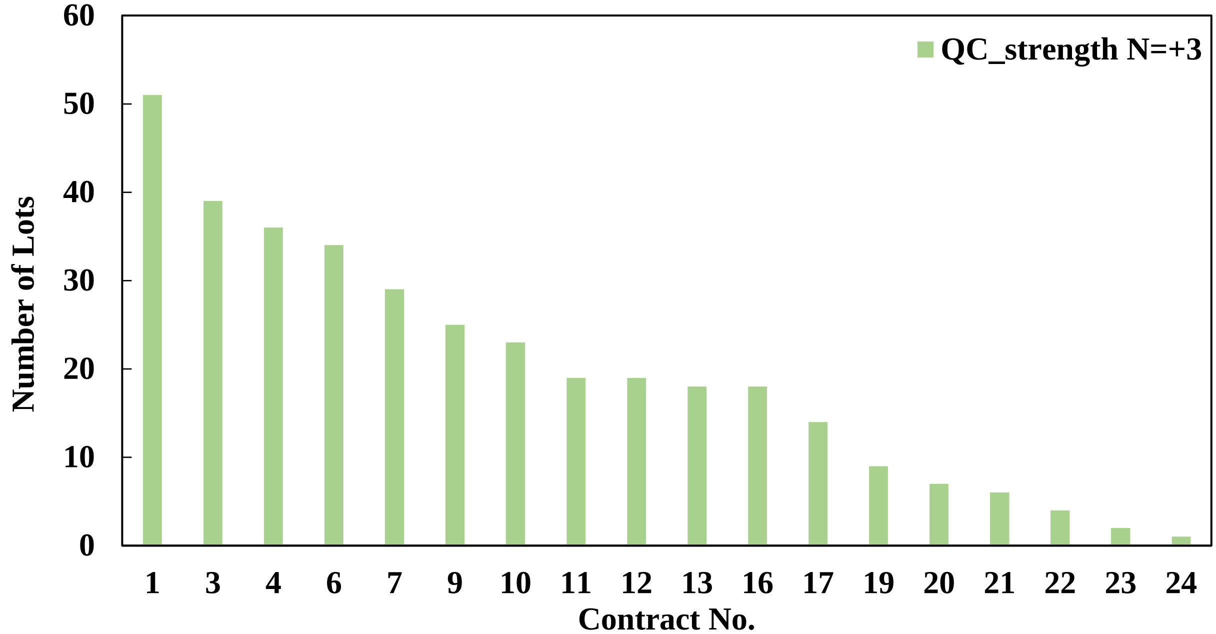


(c) QC Strength for N = -4

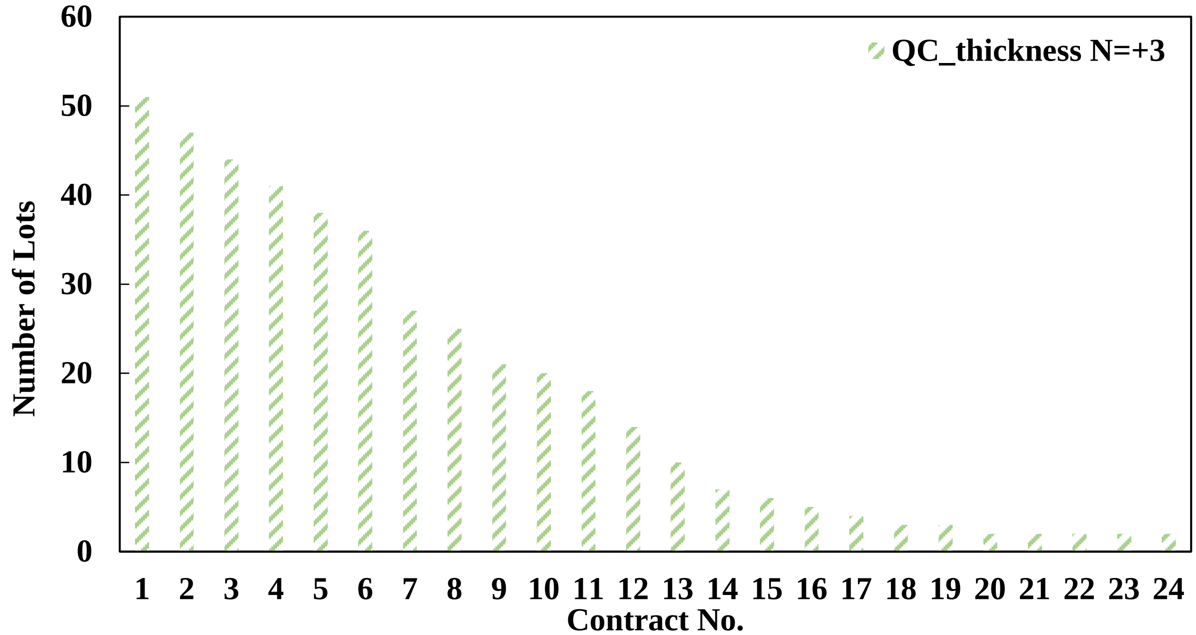


(d) QC Thickness for N = -4

Figure 2.3: Number of Lots with Four Sublots (Continued)

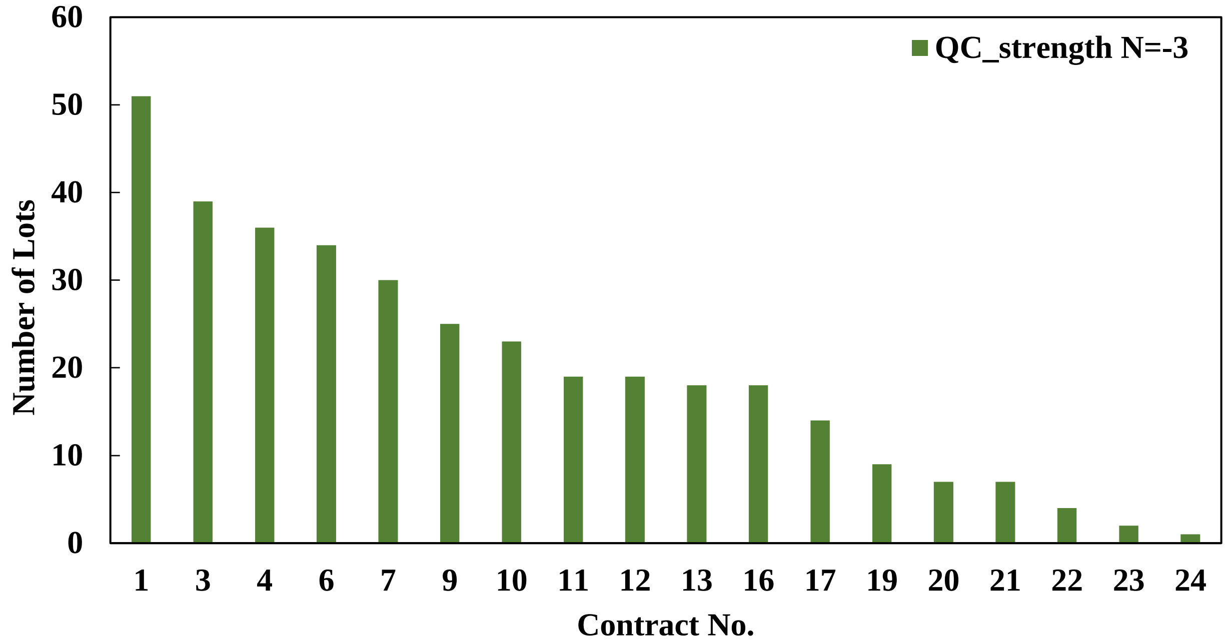


(a) QC Strength for N = +3

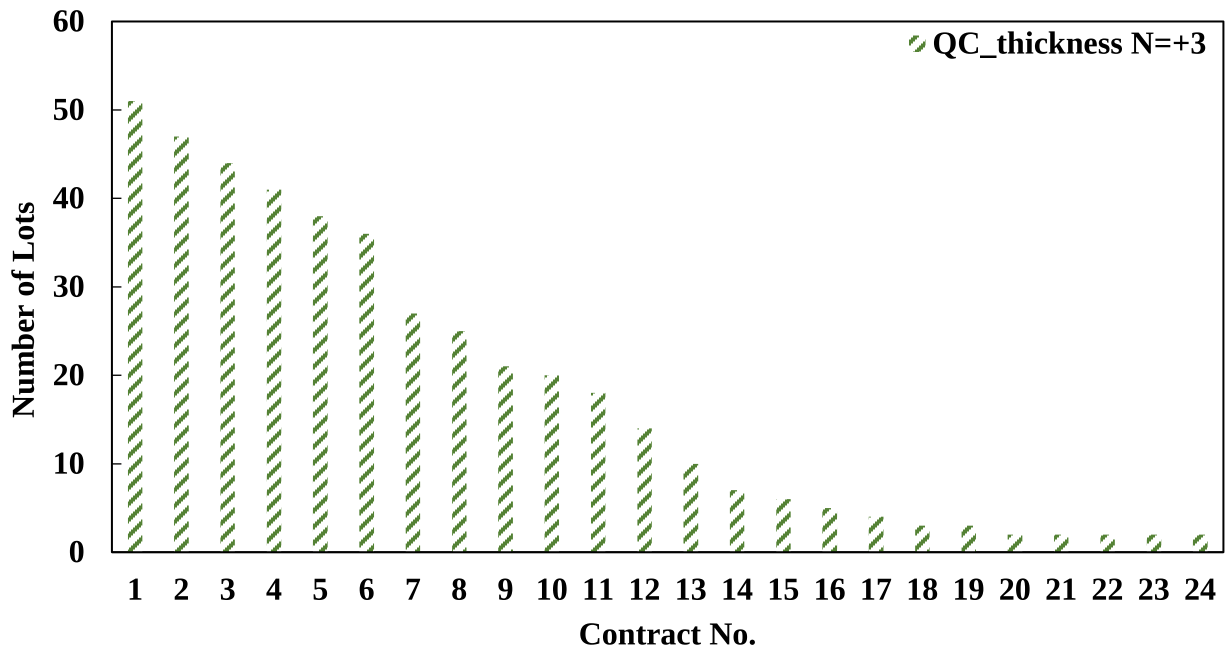


(b) QC Thickness for N = +3

Figure 2.4: Number of Lots with Three Sublots



(c) QC Strength for N = -3



(d) QC Thickness for N = -3

Figure 2.4: Number of Lots with Three Sublots (Continued)

2.3 Methodologies

2.3.1 Lot-Wise and Sublot-Wise Comparison

Statistical analysis software programs RStudio and SPSS were used in this analysis. The first approach consisted of methodologies introduced by Gedafa et al. (2012) to determine whether lot-wise and sublot-wise QC strength and thickness means are similar for the 24 contracts. Fisher's least significant difference (LSD), Tukey's honestly significant difference (HSD), Student-Newman-Keuls (SNK), and Scheffe's test methods were programmed into RStudio for statistical analysis. A detailed discussion about the four methods is presented in the study by Gedafa et al. (2012).

The second part of the analysis investigated whether sublot size and selection order cause statistically significant differences between QC and QA results. The one-sample t-test utilizes computed p-value to determine whether the mean value of a selected sample is equal to a certain value at a defined level of significance (Johnson, 2017). The current study utilized modified one-sample t-test methodology. SPSS software was also used to compute the statistical parameters for each lot at three significance levels (0.01, 0.025, and 0.05) with three sublot numbers (5, 4, and 3). The parameters included mean QC value, QC standard deviation, and the standard error (SE) of the sample mean. Furthermore, the lower and upper limits for certain lots were computed by substituting the parameters into Equations 2.1 and 2.2 (Johnson, 2017).

$$\mathrm{LCL} = \bar{\mathrm{x}} - \mathrm{t}_{1-\frac{\alpha}{2},\mathrm{df}} \times \mathrm{Se}$$ **Equation 2.1**

$$\mathrm{UCL} = \bar{\mathrm{x}} + \mathrm{t}_{1-\frac{\alpha}{2},\mathrm{df}} \times \mathrm{Se}$$ **Equation 2.2**

Where: *LCL* is the lower control limit, *UCL* is the upper control limit, $\bar{x}$ is the mean of the sublot, $t_{1-\alpha/2,df}$ is a selected value from the t-distribution table, and *Se* is the standard error of the mean.

The QA value for each sublot was compared to its corresponding upper control limit (UCL) and lower control limit (LCL) range. If the QA value fell within the range, then it was not significantly different from the QC values; otherwise, it was statistically different. Another ratio was introduced to represent the number of lots outside this range, and this ratio was computed by the number of lots with significant statistical differences divided by the total number of corresponding lots.

2.3.2 Pay Adjustment

KDOT currently uses a combined pay adjustment equation for thickness and compressive strength lot by lot based on contractors' QC test results if the statistical check against KDOT results is favorable. The combined pay factor (*P*) is determined using Equation 2.3, and the pay adjustment is computed by multiplying *P* times the lot size (number of square yards in the lot) times the bid price per square yard. Equation 2.3 presents the combined pay factor (*P*) for a lot.

$$P = \left(\frac{(PWL_{TH} + PWL_{ST}) * 0.60}{200}\right) - 0.54$$ **Equation 2.3**

Where: PWL_{TH} is the thickness percentage within limits value which is a function of thickness quality index (Q_T), and PWL_{ST} is the strength percentage within limits value which is a function of strength quality index (Q_S).

Q_T is calculated for a lot using the following equation:

$$Q_T = \frac{\overline{X} - LSL}{S}$$ **Equation 2.4**

Where: $\overline{x}$ is the average measured core length of all QC samples representing a lot, *LSL* is the lower specification limit for thickness (defined as 0.2 in. less than plan thickness), and *S* is the sample standard deviation of the measured core lengths.

Q_S is calculated for a lot using the following equation:

$$Q_S = \frac{\overline{X} - LSL}{S}$$ **Equation 2.5**

Where: $\overline{x}$ is the average measured compressive strength of all QC samples representing a lot, *LSL* is the lower specification limit for compressive strength (defined as 3,900 psi), and *S* is the sample standard deviation of the measured compressive strengths.

Gedafa, Hossain, and Ingram (2012) developed the PPM and composite index for PCC pavements in Kansas under the K-TRAN: KSU-09-7 project. The objective was to relate performance with QC and QA attributes. PPMs were developed using two (PCC thickness and strength) and three (thickness, strength, and air content) quality characteristics. KDOT generally employs two quality characteristics for pay adjustment calculation. In this study, pay adjustments were calculated using KDOT's current method and the previously developed PPM and composite index.

Composite index PWL^* was developed for quality characteristics of thickness and strength. Pay adjustment was calculated based on the composite index, and the composite index was developed with and without considering the interaction between the two quality characteristics. Equations 2.6 and 2.7 present the composite $PWL*$ for strength and thickness with and without considering the cross product, respectively.

$$\mathrm{PWL}^* = 0.0687\mathrm{PWL}_{\mathrm{TH}} - 0.137\mathrm{PWL}_{\mathrm{ST}} + 0.0107\mathrm{PWL}_{\mathrm{TH}} * \mathrm{PWL}_{\mathrm{ST}}$$ **Equation 2.6**

$$\mathrm{PWL}^* = 0.556\mathrm{PWL}_{\mathrm{TH}} + 0.444\mathrm{PWL}_{\mathrm{ST}}$$ **Equation 2.7**

2.3.3 Multivariate Process Control Chart

Statistical process control charts are used to ensure final product quality and to examine QC attributes individually. KDOT typically utilizes a univariate moving average control chart to identify systematic bias in the production process. Moving average control charts are prepared for PCC thickness and strength, and simultaneous monitoring of a large number of individual plots is required. This process is further complicated by a combination of many variables.

This study attempted to implement the bivariate normal control ellipsoid chart to analyze KDOT QC data. This type of process control is especially useful if quality characteristics are correlated. Statgraphics (2017) software Version 18 was used to generate the multivariate process control chart and infer the capability of the control chart to analyze the KDOT QC process.

Chapter 3: Results and Discussion

3.1 Fisher’s LSD, Tukey’s HSD, SNK, and Scheffe’s Test Methodologies

Fisher’s LSD, Tukey’s HSD, SNK, and Scheffe’s test methods were used to determine if lot-wise QC and QA strength and thickness means were similar for the 24 contracts at three levels of significance (α = 0.01, 0.025, and 0.05). The four tests were programmed into RStudio. Figure 3.1 shows RStudio codes for the four test methods. Detailed information about the RStudio codes is presented in the Appendix. Statistically significant testing results are summarized in Table 3.1, in which output codes “0” and “99” mean that no statistically significant difference was found using the four statistical methods. Results showed no significant differences between the lot means for all contracts at three levels of significance.

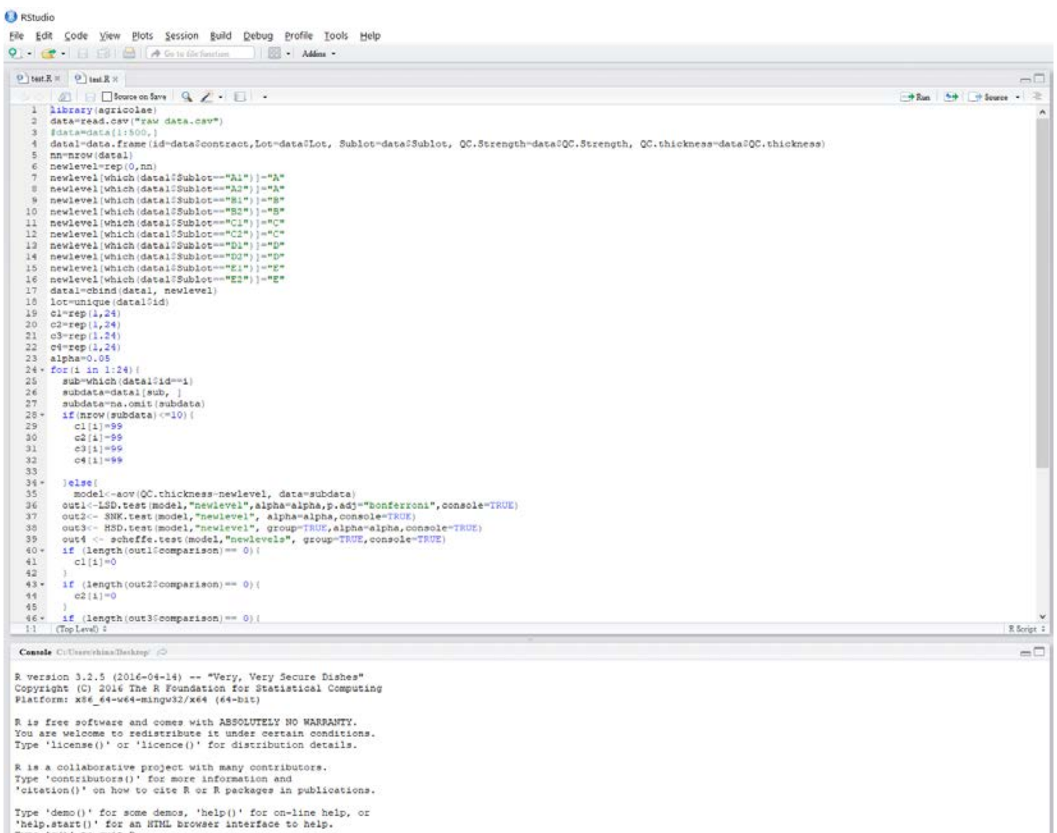


Figure 3.1: RStudio Codes for Fisher’s LSD, Tukey’s HSD, SNK, and Scheffe’s Tests

Table 3.1: Fisher's LSD, Tukey's HSD, SNK, and Scheffe's Tests Results

Methodologies / Contract No.	α = 0.01				α = 0.025				α = 0.05			
	Fisher's LSD	Tukey's HSD	SNK	Scheffe's test	Fisher's LSD	Tukey's HSD	SNK	Scheffe's test	Fisher's LSD	Tukey's HSD	SNK	Scheffe's test
1	0	0	0	0	0	0	0	0	0	0	0	0
2	99	99	99	99	99	99	99	99	99	99	99	99
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	99	99	99	99	99	99	99	99	99	99	99	99
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	99	99	99	99	99	99	99	99	99	99	99	99
9	0	0	0	0	0	0	0	0	0	0	0	0
10	99	99	99	99	99	99	99	99	99	99	99	99
11	0	0	0	0	0	0	0	0	0	0	0	0
12	99	99	99	99	99	99	99	99	99	99	99	99
13	0	0	0	0	0	0	0	0	0	0	0	0
14	99	99	99	99	99	99	99	99	99	99	99	99
15	99	99	99	99	99	99	99	99	99	99	99	99
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	99	99	99	99	99	99	99	99	99	99	99	99
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0

3.2 Modified One-Sample t-Test Methodology

The modified one-sample t-test method requires that the independent variables (QC strength and thickness) are approximately normally distributed within each lot, as based on Shapiro-Wilk test results at the significance level of 0.05 for each lot. If the computed significance value is greater than 0.05, then the sublots are normally distributed. This study used SPSS to compute the significance value of each lot, and normality ratios were used to calculate the number of normal distributed lots divided by the number of lots. Table 3.2 summarizes the results for each sample size, and Figure 3.2 shows normality ratios for the lots. Normality test results indicated that most sublots within each lot are normally distributed.

Table 3.2: Summary of Normality Tests

Parameter	Total	Sublot Nos.	Normality	Non-Normality	Normality Ratio
QC strength	201	n = 5	191	10	0.95
	284	n = +4	266	18	0.94
	285	n = -4	271	14	0.95
	54	n = +3	336	18	0.95
	56	n = -3	336	20	0.94
QC thickness	21	n = 5	202	19	0.91
	26	n = +4	289	37	0.89
	27	n = -4	293	34	0.90
	30	n = +3	368	62	0.86
	32	n = -3	366	66	0.85

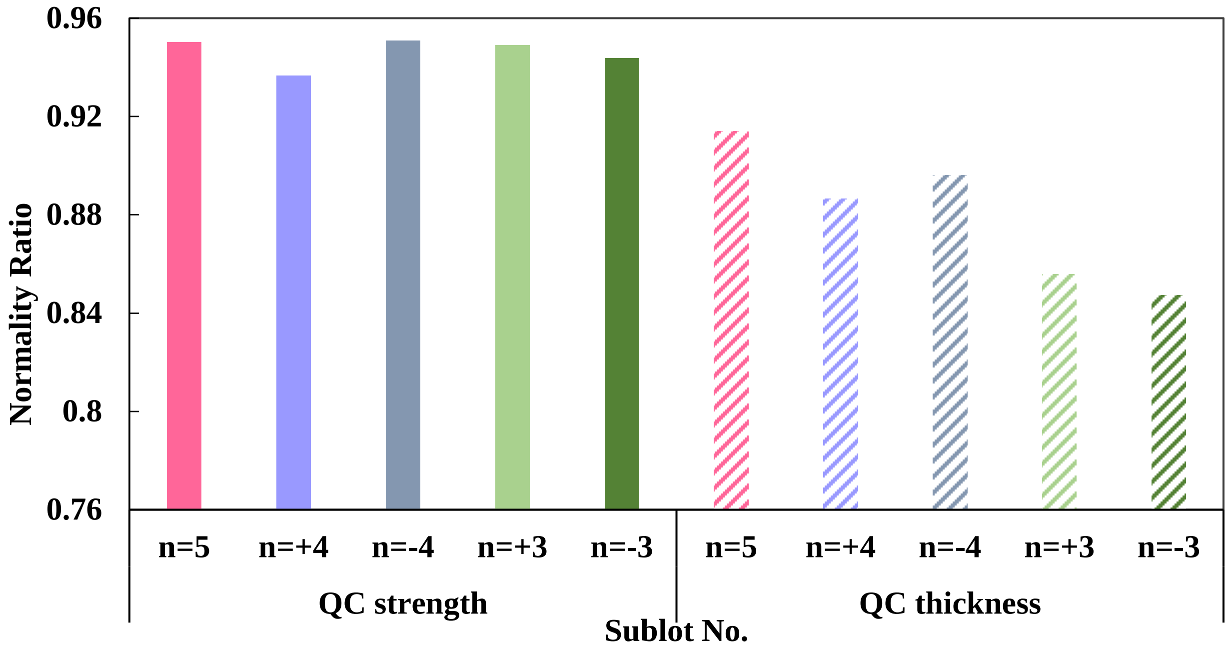
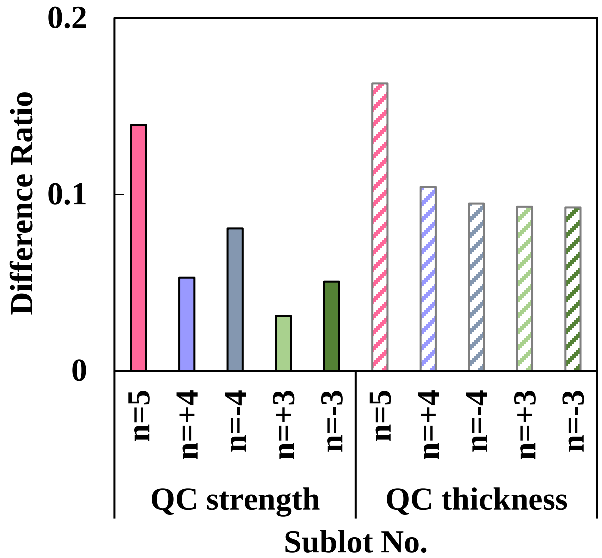
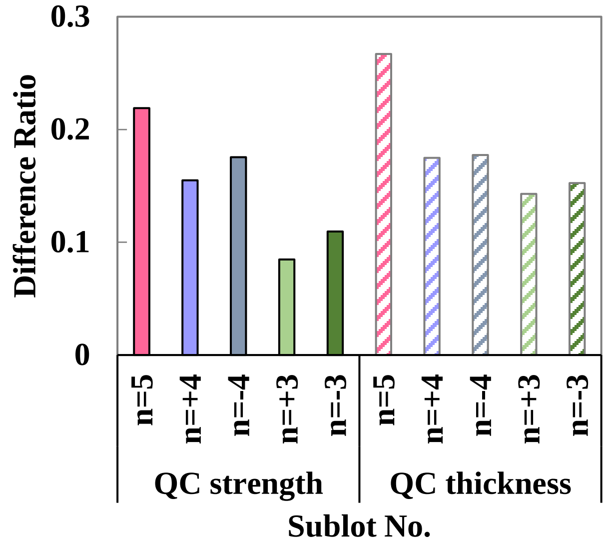


Figure 3.2: Results of Normality Tests

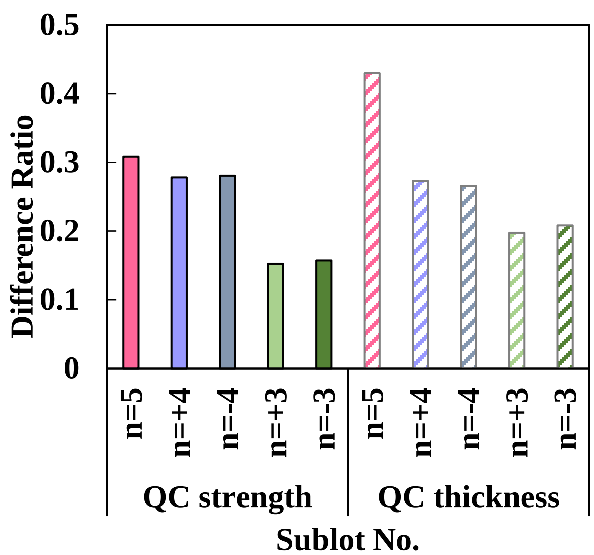
Results of the modified one-sample t-test can be summarized in two parts. The first part includes investigation of the consequences of changing the sublot size for strength and thickness at three levels of significance (α = 0.01, 0.025, and 0.05). Figure 3.3 illustrates the effect of the confidence interval (CI). Each bar in the figure represents the number of lots that are significantly different from their corresponding QA values. The significance level of 0.05 has a corresponding confidence level of 95%. Results showed that QC strength and thickness at three levels of significance have similar trends: reducing the number of sublots results in decreasing different ratios.



(a) 99% CI



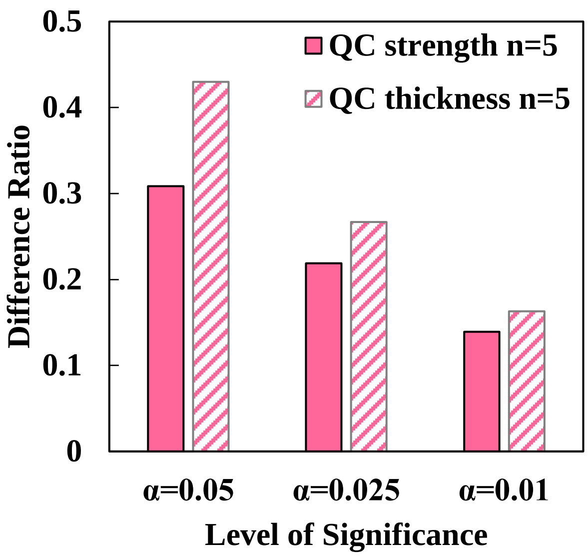
(b) 97.5% CI



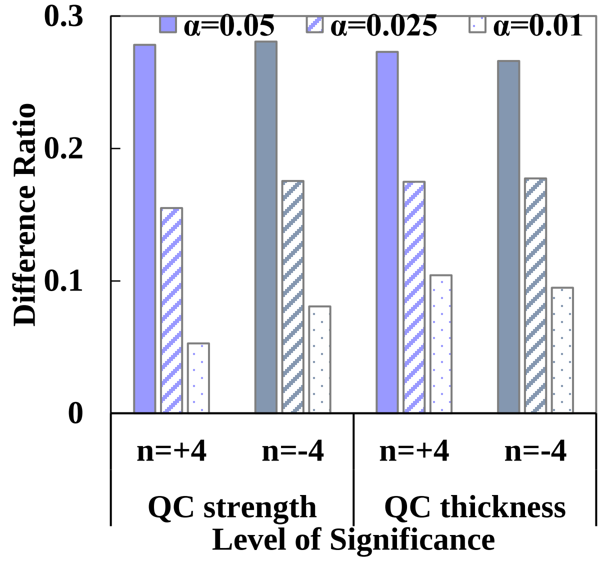
(c) 95% CI

Figure 3.3: Effect of Confidence Interval

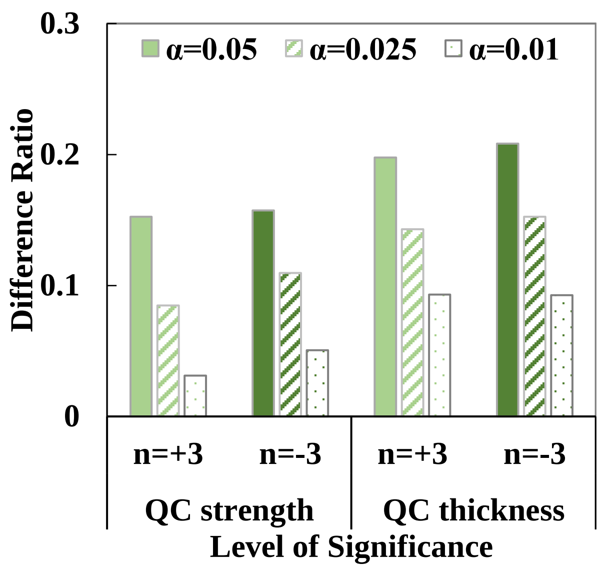
The second component of t-test results includes investigation of the consequences of changing the significance levels (α = 0.01, 0.025, and 0.05) for a certain number of sublots (5, 4, and 3). Figure 3.4 illustrates a similar trend in the strength and thickness test results for three types of sublots. The ratios decreased as the level of significance decreased, whereas results from the QC thickness test showed relatively higher ratios than the QC strength groups. Moreover, as shown in the figure, sublots with sample sizes of “+4” and “-4” have similar difference ratios. A comparable phenomenon was observed for “+3” and “-3” sublots.



(a) Five Sublots



(b) Four Sublots



(c) Three Sublots

Figure 3.4: Effect of Sublots Size

3.3 Effect of Sample Size on Pay Adjustment

This study sought to investigate the effect of changing sample size or number of sublots on pay adjustments. PWLs for strength and thickness were calculated for lots with five sublots. Four and three sublots were selected randomly from the five sublots, and then PWL was recalculated. The current KDOT method was used to calculate the pay adjustments. Figure 3.5 shows computed pay adjustments for lots in a project on US-54 in Allen County, Kansas. This project was completed in 2014; plan thickness was 9 inches.

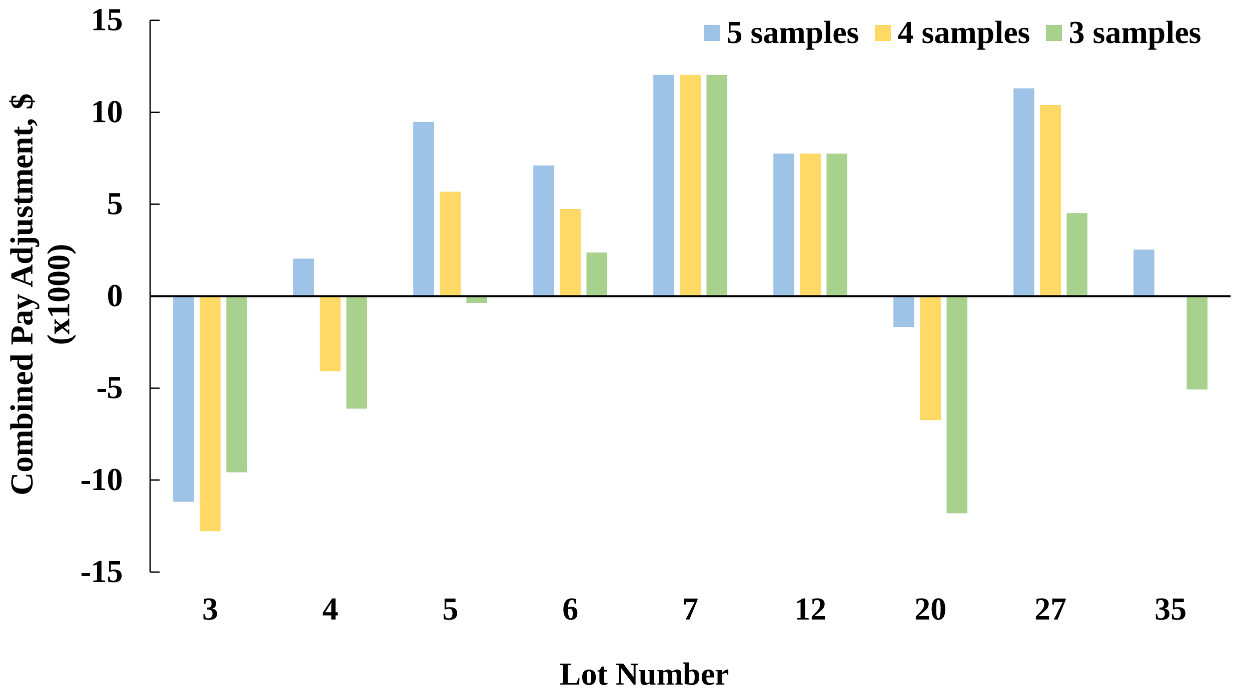


Figure 3.5: Effect of Sublot Size on Pay Adjustment for US-54 (Allen County) Project Contract

Figure 3.5 shows that pay adjustments vary depending on the number of sublots. For example, the pay deduction for Lot 20 was $12,000 when three sublots were considered, but the pay deduction was only $1,500 for five sublots. Lot 5 demonstrated a pay increase of $10,000 when considering five sublots but a penalty of $500 with three sublots. Figure 3.6 shows computing pay adjustments on K-61 project in Reno County, Kansas. This project was constructed in 2012; the planned thickness was 8.5 inches.

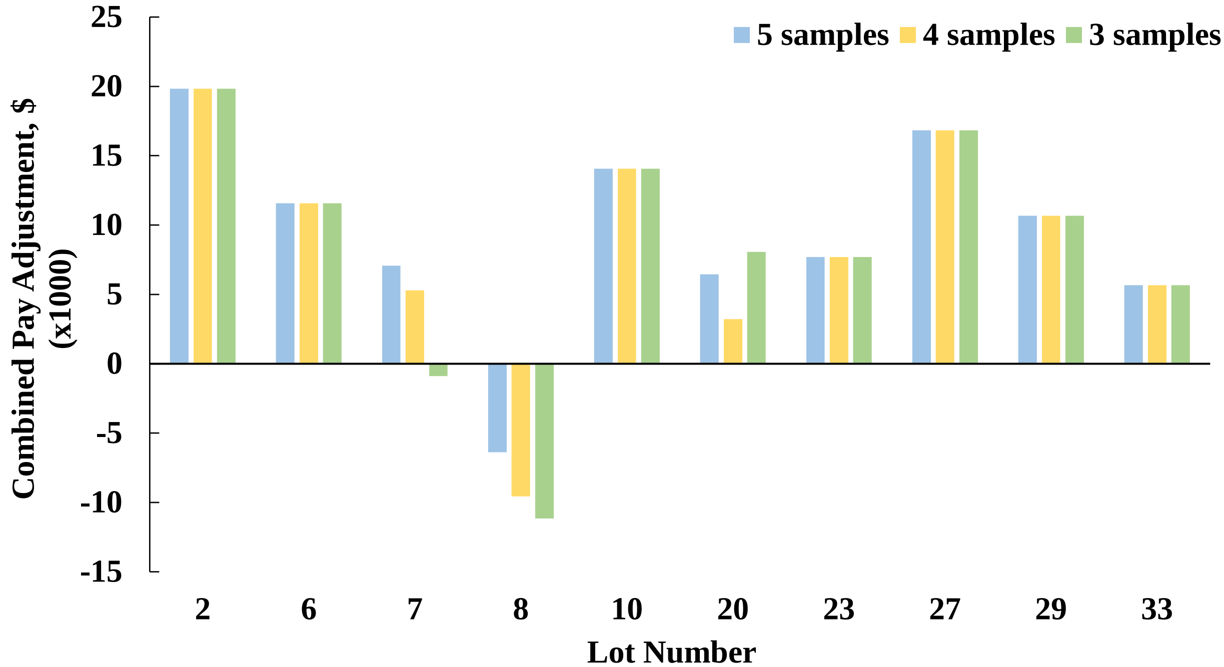


Figure 3.6: Effect of Sublot Size in Pay Adjustment for K-61 (Reno County) Project Contract

PWLs estimated from five sublots were very similar to PWLs computed from three or four sublots. In most cases, the PWLs were 100.00 irrespective of the number of sublots. However, standards deviation caused decreased PWL values in proportion to the various sample sizes, thereby affecting pay factor calculation and potential major changes in pay adjustment. Figure 3.7 shows computed pay adjustments for the project on US-54 in Kingman County, Kansas. This project was completed in 2014; plan thickness was 9.5 inches. Pay deduction was found to be higher for Lot 3 with five sublots compared to the same lot with four sublots.

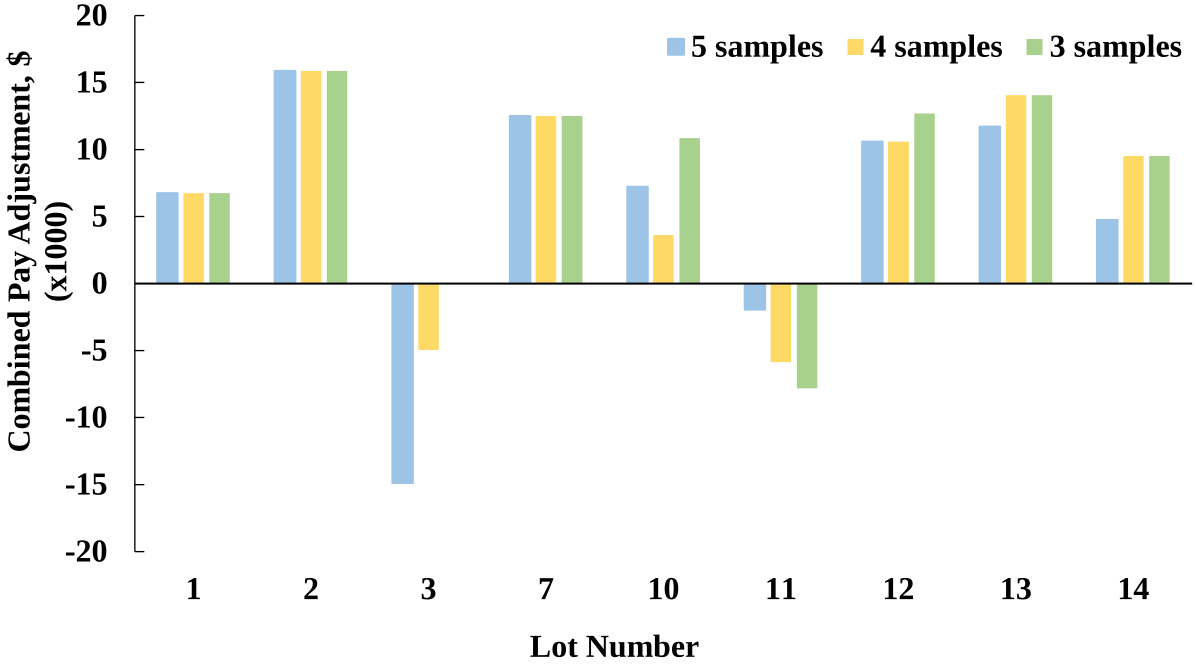


Figure 3.7: Effect of Sublot Size on Pay Adjustment for US-54 (Kingman County) Project Contract

3.4 Differences in Pay Adjustment Computation Method

This study also examined the effect of the pay adjustments method. Three pay adjustment methods were considered for this analysis: the current KDOT method, the PPM method that considers the cross product between strength and thickness, and the PPM method that does not consider the cross product between strength and thickness. Figure 3.8 shows differences in pay adjustments in these three approaches for the US-54 project in Allen County. As shown, the pay adjustment was lowest when the PPM with interaction was considered. This model seems to be extremely punishing when the lot material is out of specification.

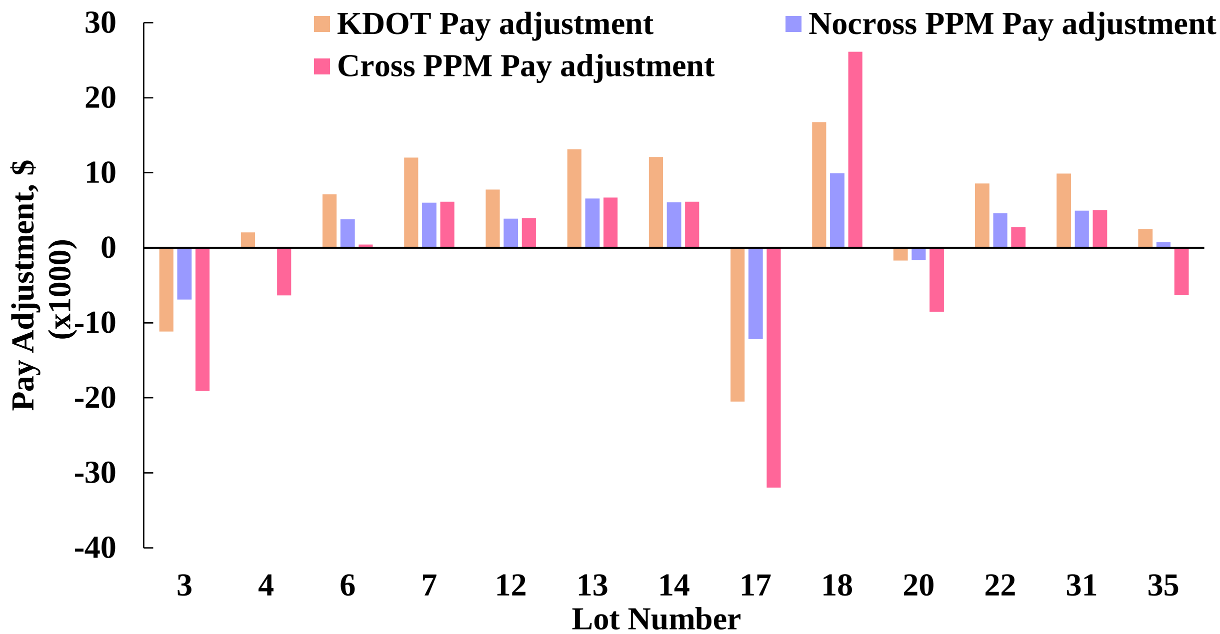


Figure 3.8: Differences in Pay Adjustments for US-54 (Allen County) Project Contract

Figure 3.9 shows differences in pay adjustments for the three pay adjustment methods for K-61 project in Reno County. The PPM methods were less rewarding than the current KDOT pay adjustment method.

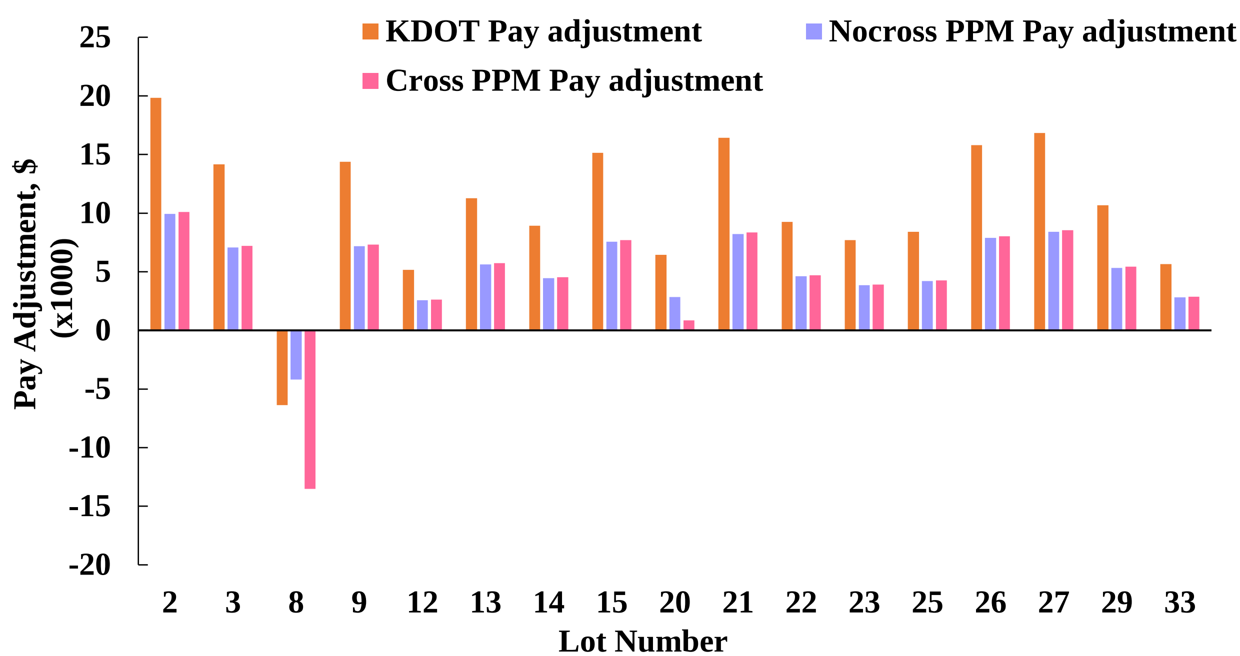


Figure 3.9: Differences in Pay Adjustments for K-61 (Reno County) Project Contract

3.5 Control Chart

This study utilized Statgraphics software Version 18 to develop a multivariate ellipsoid process control chart. This type of chart is useful for two quality characteristics, especially correlating characteristics. The lower specification limit (LSL) was 3,900 psi and the plan thickness was -0.2 in. for quality attributes strength and thickness, respectively. Figure 3.10 shows the 99.73 capability ellipse for the K-61 project in Reno County. This capability ellipse refers to 99.73% of the probability, the same percentage area within mean ±3 standard deviation. Table 3.3 presents analysis results developed with data from 172 sublots. The analysis showed that approximately 1.15% of the sublots were beyond the LSL. However, the control ellipse did not fit within the specification limits, indicating that the process cannot fully meet the specifications.

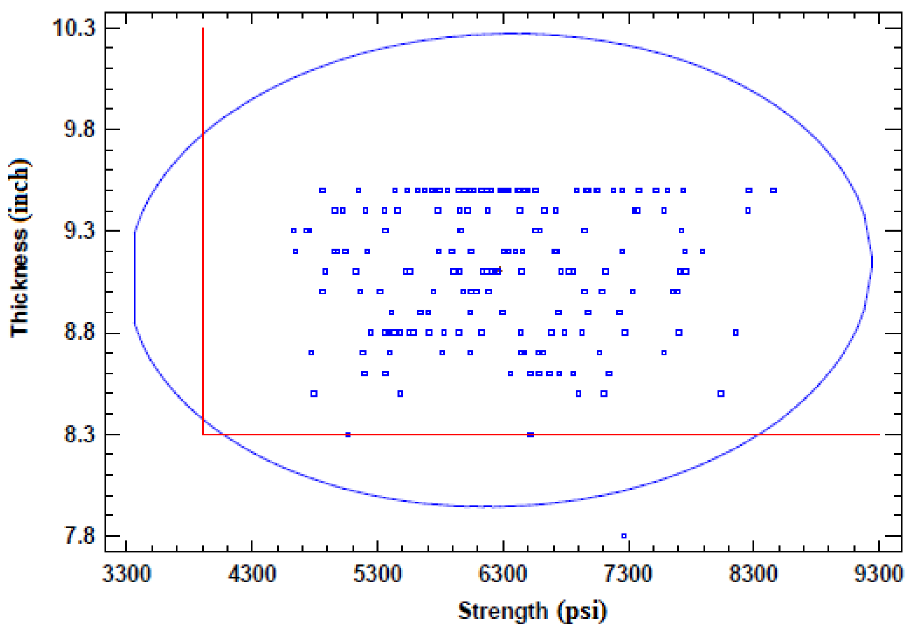


Figure 3.10: Control Chart for K-61 (Reno County) Project Contract

Table 3.3: Multivariate Capability Analysis for K-61 (Reno County) Project Contract

Variable	Sample mean	Sample standard deviation	Lower specification limit	Nominal value
Strength	6273.33	863.0	3900.0	
Thickness	9.11	0.34	8.3	8.5

	Observed	Estimated	Estimated
Variable	Beyond specification	Beyond specification	Defects per million
Strength	0.0%	0.3%	2,979
Thickness	0.6%	0.85%	8,560
Both	0.6%	1.15%	11,514

Table 3.3 shows that the estimated frequencies of non-conformities for strength and thickness are 2,979 and 8,560 per million, respectively. Their combined estimated frequency of non-conformities per million is 11,514, which is almost the sum of their individual frequencies, thus indicating that the variables are not correlated to each other and non-conformity of one of them may not affect the other variable. The 99.73% capability ellipse and analysis results for several other projects are shown in Figures 3.11 to 3.17, and Tables 3.4 to 3.10.

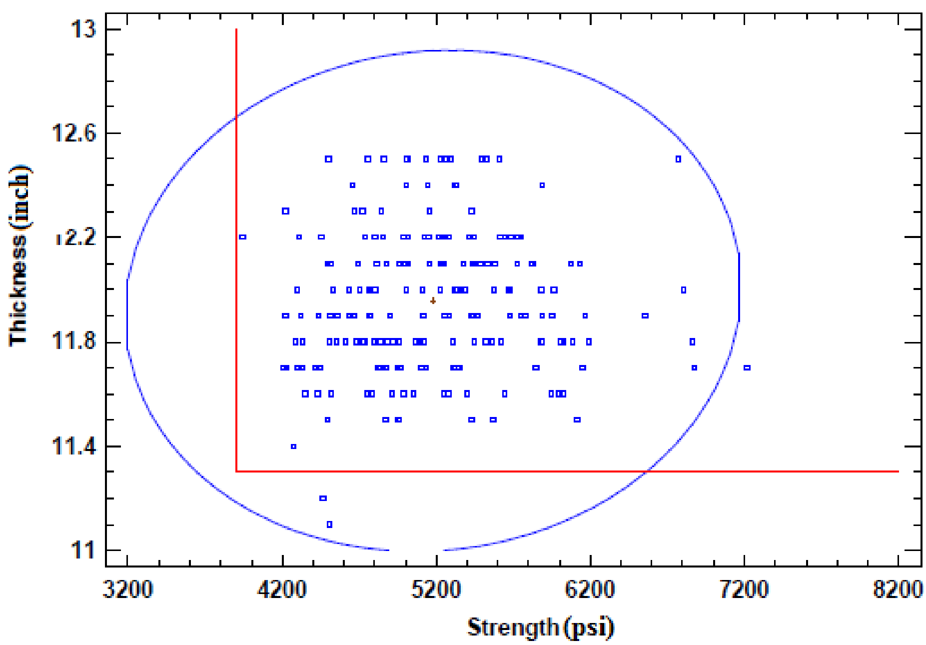


Figure 3.11: Control Chart for I-70 (Sherman County) Project Contract

Table 3.4: Multivariate Capability Analysis for I-70 (Sherman County) Project Contract

Variable	Sample mean	Sample standard deviation	Lower specification limit	Nominal value
Strength	5179.60	581.40	3900.0	
Thickness	11.96	0.28	11.30	11.50

Variable	Observed Beyond specification	Estimated Beyond specification	Estimated Defects per million
Strength	0.0%	1.39%	13,871
Thickness	1.04%	0.94%	9,360
Combined	1.04%	2.31%	23,098

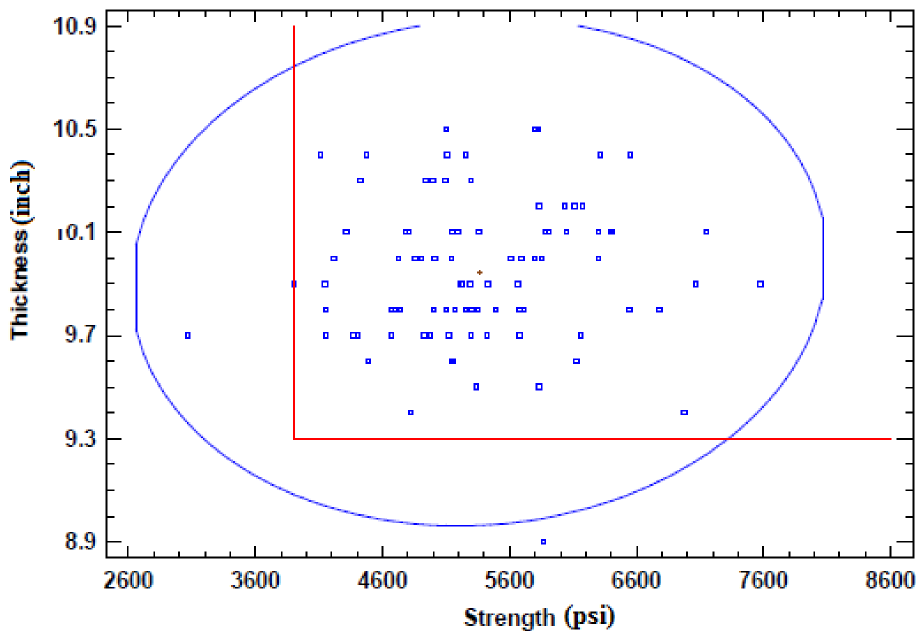


Figure 3.12: Control Chart for US-54 (Kingman County) Project Contract (1)

Table 3.5: Multivariate Capability Analysis for US-54 (Kingman County) Project Contract (1)

Variable	Sample mean	Sample standard deviation	Lower specification limit	Nominal value
Strength	5,360.69	796.61	3,900.0	
Thickness	9.94	0.29	9.30	9.50

Variable	Observed Beyond specification	Estimated Beyond specification	Estimated Defects per million
Strength	1.15%	3.35%	33354
Thickness	1.15%	1.21%	12101
Joint	2.30%	4.50%	45043

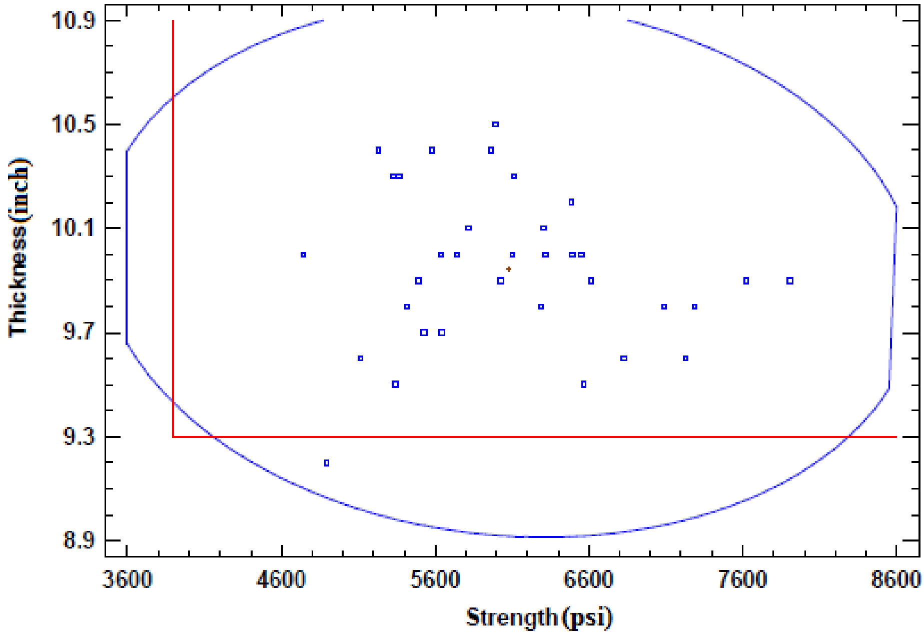


Figure 3.13: Control Chart for US-54 (Kingman County) Project Contract (2)

Table 3.6: Multivariate Capability Analysis for US-54 (Kingman County) Project Contract (2)

Variable	Sample mean	Sample standard deviation	Lower specification limit	Nominal value
Strength	6,077.63	772.81	3,900.0	
Thickness	9.94	0.30	9.30	9.50

	Observed	Estimated	Estimated
Variable	Beyond specification	Beyond specification	Defects per million
Strength	0.00%	0.24%	2,418
Thickness	2.94%	1.58%	15,805
Combined	2.94%	1.82%	18,183

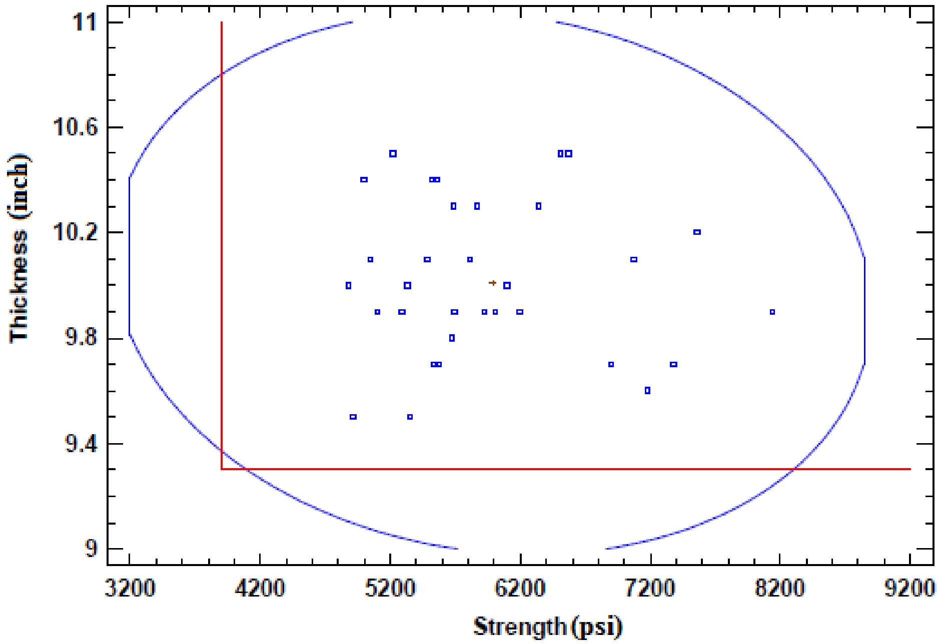


Figure 3.14: Control Chart for US-54 (Kingman County) Project Contract (3)

Table 3.7: Multivariate Capability Analysis for US-54 (Kingman County) Project Contract (3)

Variable	Sample mean	Sample standard deviation	Lower specification limit	Nominal value
Strength	5,988	847.34	3,900.0	
Thickness	10.01	0.30	9.30	9.50

	Observed	Estimated	Estimated
Variable	Beyond specification	Beyond specification	Defects per million
Strength	0.00%	0.69%	6864
Thickness	0.00%	0.89%	8921
Joint	0.00%	1.57%	15718

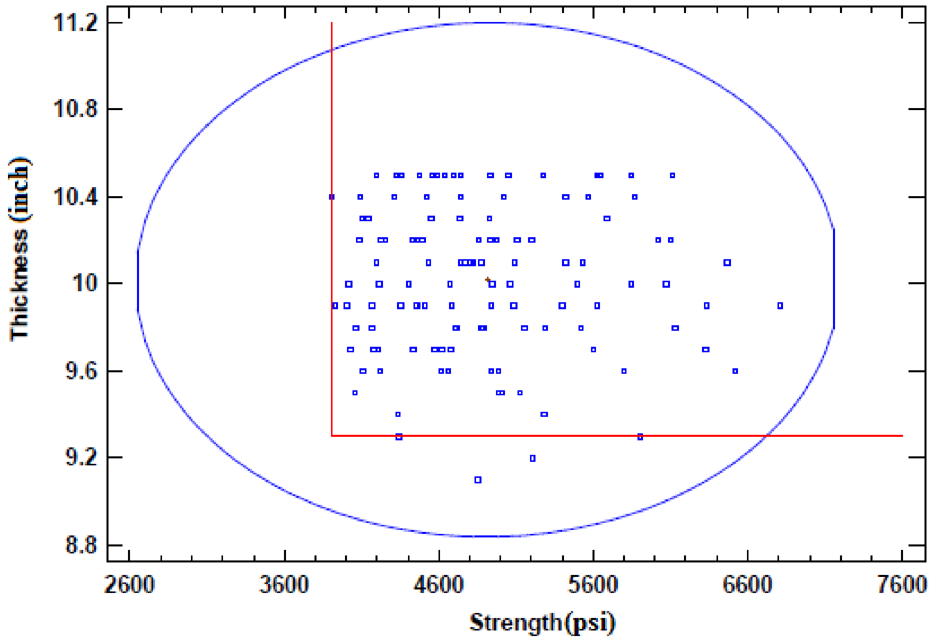


Figure 3.15: Control Chart for US-54 (Pratt County) Project Contract

Table 3.8: Multivariate Capability Analysis for US-54 (Pratt County) Project Contract

Variable	Sample mean	Sample standard deviation	Lower specification limit	Nominal value
Strength	4,916.5	663.18	3,900.0	
Thickness	10.02	0.34	9.30	9.50

	Observed	Estimated	Estimated
Variable	Beyond specification	Beyond specification	Defects per million
Strength	0.00%	6.27%	62,667
Thickness	1.71%	1.80%	18,027
Combined	1.71%	7.96%	79,565

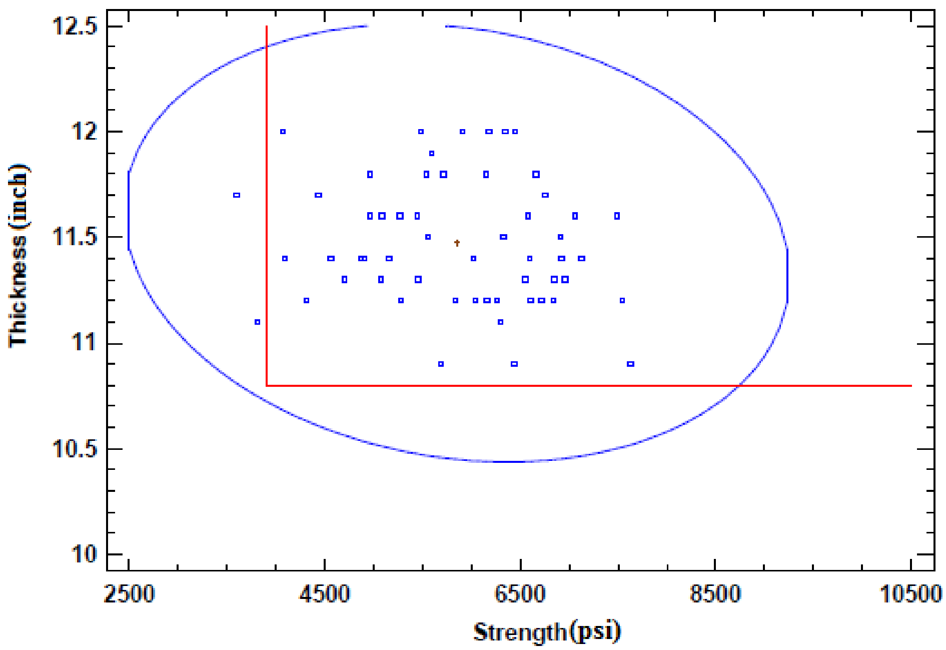


Figure 3.16: Control Chart for I-70 (Wyandotte County) Project Contract

Table 3.9: Multivariate Capability Analysis for I-70 (Wyandotte County) Project Contract

Variable	Sample mean	Sample standard deviation	Lower specification limit	Nominal value
Strength	5,851.03	990.18	3,900.0	
Thickness	11.47	0.30	10.80	11.00

	Observed	Estimated	Estimated
Variable	Beyond specification	Beyond specification	Defects per million
Strength	3.64%	2.44%	24,398
Thickness	0.0%	1.27%	12,685
Joint	3.64%	3.67%	36,727

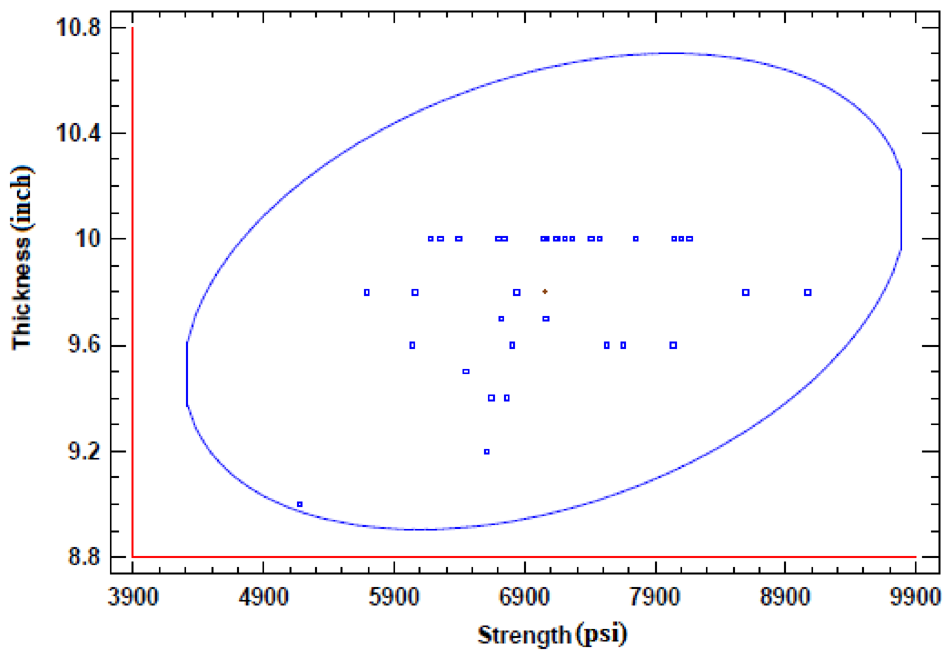


Figure 3.17: Control Chart for US-400 (Greenwood County) Project Contract

Table 3.10: Multivariate Capability Analysis for US-400 (Greenwood County) Project Contract

Variable	Sample mean	Sample standard deviation	Lower specification limit	Nominal value
Strength	7,057.11	805.30	3,900.0	
Thickness	9.80	0.26	8.80	9.00

	Observed	Estimated	Estimated
Variable	Beyond specification	Beyond specification	Defects per million
Strength	0.0%	0.0044%	44.21
Thickness	0.0%	0.0062%	62.13
Joint	0.0%	0.0163%	106.3

Figure 3.17 shows the control chart for the US-400 project in Greenwood County. As shown, the control ellipse fits nicely well the specification limits, indicating that the process can meet the specifications.

Chapter 4: Conclusions and Recommendations

4.1 Conclusions

The following conclusions are based on this study:

- No statistically significant differences between lot means were observed for all contracts with any significance level (0.01, 0.025, and 0.05) or sublot numbers (3, 4, and 5).
- QC/QA strength and thickness groups have similar trends, but the QC thickness group has a larger difference ratio than the strength group.
- At a certain confidence level, the statistically significant difference ratios of lots decrease as the number of sublots decreases.
- When one sample size remains constant, the statistically significant difference ratio decreases as the confidence level increases. In addition, statistical inferences remain unchanged when the sample sizes are reduced to four, either by eliminating the first or the last sublot. Similar results are evident for the samples sizes of three sublots.
- No definite pattern in pay adjustments is evident for changing sample size; however, significant pay reduction occurs for some contracts when three sublots are used in a lot instead of five sublots.
- The PPM method that considers the interaction between strength and thickness is extremely punishing.

4.2 Recommendations

- Further investigation should explore why no significant differences were evident in lot means for strength and thickness.
- Further research is recommended to study the effect of sublot size on pay adjustment since pay adjustments can vary with the number of sublots.
- Coefficients of the PPM methods must be revisited if KDOT implements PPM methods for pay adjustments.
- Although use of a multivariate process control chart could be useful, especially when multiple variables are included in the QC process, further research is needed to effectively implement multivariate process control charts into the QC process.

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Appendix: RStudio Codes for Fisher's LSD, Tukey's HSD, SNK, and Scheffe's Tests

```
library(agricolae)

data=read.csv("raw data.csv")

#data=data[1:500,]

data1=data.frame(id=data$contract,Lot=data$Lot, Sublot=data$Sublot,
QC.Strength=data$QC.Strength, QC.thickness=data$QC.thickness)

nn=nrow(data1)

newlevel=rep(0,nn)

newlevel[which(data1$Sublot=="A1")]="A"

newlevel[which(data1$Sublot=="A2")]="A"

newlevel[which(data1$Sublot=="B1")]="B"

newlevel[which(data1$Sublot=="B2")]="B"

newlevel[which(data1$Sublot=="C1")]="C"

newlevel[which(data1$Sublot=="C2")]="C"

newlevel[which(data1$Sublot=="D1")]="D"

newlevel[which(data1$Sublot=="D2")]="D"

newlevel[which(data1$Sublot=="E1")]="E"

newlevel[which(data1$Sublot=="E2")]="E"

data1=cbind(data1, newlevel)

lot=unique(data1$id)

c1=rep(1,24)

c2=rep(1,24)

c3=rep(1.24)
```

```
c4=rep(1,24)
alpha=0.05
for(i in 1:24){
 sub=which(data1$id==i)
 subdata=data1[sub, ]
 subdata=na.omit(subdata)
 if(nrow(subdata)<=10){
  c1[i]=99
  c2[i]=99
  c3[i]=99
  c4[i]=99
 }else{
  model<-aov(QC.thickness~newlevel, data=subdata)
 out1<-LSD.test(model,"newlevel",alpha=alpha,p.adj="bonferroni",console=TRUE)
 out2<- SNK.test(model,"newlevel", alpha=alpha,console=TRUE)
 out3<- HSD.test(model,"newlevel", group=TRUE,alpha=alpha,console=TRUE)
 out4 <- scheffe.test(model,"newlevels", group=TRUE,console=TRUE)
 if (length(out1$comparison)== 0){
  c1[i]=0
 }
 if (length(out2$comparison)== 0){
  c2[i]=0
 }
```

```
 if (length(out3$comparison)== 0){
   c3[i]=0
 }
 if (length(out4$comparison)== 0){
   c4[i]=0
 }
 }
}
c1
c2
c3
c4
```


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