DEVELOPMENT OF RATIONAL PAY FACTORS BASED ON CONCRETE COMPRESSIVE STRENGTH DATA

Final Report 608

Prepared by:
Busaba Laungrungrong, Ph.D. Student
Barzin Mobasher, CEE, Professor
Douglas Montgomery, IE, Professor
Ira A. Fulton School of Engineering
Arizona State University
Tempe, AZ, 85287-5306

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Arizona Department of Transportation
206 South 17th Avenue
Phoenix, Arizona 85007

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16. Abstract

This research project addresses the opportunity to contain the escalating costs of concrete materials in construction projects. Both statistical process control and rational acceptance criteria show that quality improvement and cost savings can be achieved. The report presents a comprehensive statistical evaluation of the compressive strength of concrete used in various sectors of the transportation infrastructure in Arizona. The proposed methodology is applicable to the concrete materials specified at other industrial sectors such as privately financed construction projects. Several case studies are conducted based on actual field data to show that performance based specification procedures can be used to improve the quality control process while decreasing the overall construction costs. Three sets of compressive data from various construction projects were selected. These data were evaluated by means of statistical process-control tools while state-of-the art procedures were utilized to evaluate the strength as a measure of quality. Several acceptance criteria based on the percent within limit (PWL) and operational-characteristic curves (OC) are proposed and evaluated. Various pay factor equations are considered and the historical records are evaluated based on hypothetical pay factor equations.

The report furthermore addresses the strengths and weaknesses associated with the present acceptance criteria in comparison to a PWL based method. Opportunities in sampling, optimization, operational-characteristics curves, and quality specification are discussed in detail. It is shown that the cost savings associated with both performance based-specification and quality control, sufficiently justify the amount of effort needed in order to implement these methodologies in the development of specifications.

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SI (MODERN METRIC) CONVERSION FACTORS*

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: Volumes greater than 1000L shall be shown in m^3.			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000lb)	0.907	megagrams (or "metric ton")	mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE AND PRESSURE OR STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
mg (or "t")	megagrams (or "metric ton")	1.102	short tons (2000lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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I. Executive Summary

Continuous development of civil infrastructure systems in support of population growth and economic productivity for the State of Arizona is a challenge faced by many decision makers in the planning, administrative, engineering, and executive branch of government. The State of Arizona utilizes more than 15 million cubic yards of concrete per year; a number that has been increasing at an annual rate of 15% during the past several years. This volume places a tremendous strain on the resources and the supply of cement and concrete products especially when one considers the increased demand for infrastructure development. It is therefore natural to expect that competition for resources and material shortages directly affects the escalating costs of construction projects and result in construction delays.

The rapid growth of the infrastructure has resulted in an ever increasing demand on the environment. For each ton of cement produced, a ton of carbon dioxide is emitted. Therefore, it would be advantageous to reduce the amount of cement, aggregates, and other natural materials that are used in construction projects without affecting the performance. Alkali-silica reactions and sulfate attack in concrete are among the major durability concerns in civil infrastructure systems. The corrosion of reinforcing steel, leading to the ultimate cracking of the concrete on highway bridges, was estimated to cost $8.29 billion in the U.S. A thorough understanding of the specifications will improve the decision making process in every stage of construction and maintenance, thus supporting a sustainable design approach.

This research project addresses areas of opportunity to contain the escalating costs of concrete materials in construction projects. The main objective for this project is to show that performance-based specification procedures can be used to improve the quality control process while decreasing the overall construction costs. Through the use of statistical process control and rational acceptance criteria, it can be shown that both a significant improvement in quality and cost savings can be achieved. By addressing the quality control measures, the incentives for payment based on early age or long term properties of concrete can be developed. Both sustainable and economical design methodologies can be addressed through proper specification guidelines.

New guidelines and cost structures for concrete materials are analyzed so that more economical alternatives can be evaluated and considered during the preliminary design of a project. As the cost of raw materials changes, many potential alternatives become cost effective. Examples include performance enhancing admixtures and/or supplementary cementitious materials, curing, and finally quality control (QC) parameters that affect the cost of a project. These alternatives, which have been addressed in a different report by the author [1], may not be regularly specified for highway structures due to the lack of available field data. The focus of the present work is based on a need to better understand the role of quality control and quality assurance in a sustainable design philosophy. The goal is directed toward generating cross-disciplinary tools to guide us toward more economical engineering and construction policies. Life cycle cost modeling, combined with statistical quality control measures, could identify potential savings. Enabling methodologies are proposed to help with statistical process control.

This report presents a comprehensive statistical evaluation of the compressive strength of concrete used in various sectors of the transportation infrastructure in Arizona. The proposed methodology is also applicable to the concrete materials specified in other industrial sectors such as privately financed construction projects. The report furthermore addresses the strengths and weaknesses associated with the present acceptance criteria in comparison to the percent-within-limits (PWL) based methods. Opportunities in sampling, optimization, operational characteristics curves, and quality specification are discussed in detail. It can be shown that the cost savings associated with performance-based specification, together with good quality control, sufficiently justify the effort needed to implement these methodologies.

Three sets of compressive data from various construction projects were selected. The data, which were evaluated by means of statistical process control tools and state-of-the art procedures, were utilized to evaluate the strength as a measure of quality. Several acceptance criteria based on the percent-within-limits (PWL) and operational characteristic (OC) curves are proposed and evaluated. Various pay factor equations are considered and the historical records are evaluated based on hypothetical pay factor equations.

Results indicate that a majority of the samples evaluated meet and far exceed the strength requirements specified by the Arizona Department of Transportation (ADOT) specifications by as much as 30%-50%. There are excessive variations in the trends of the data which do not correlate with the specified strength of the concrete and the areas of its applications. These represent areas of potential opportunity to reduce both the average and standard deviations of the strength data. Reduction of the mean strength values delivered at the expense of better quality control will translate into significant raw materials savings.

Pay factor equations are used as the basis for payment, and they serve as a penalty or incentive to meet the specifications. The adherence to the pay factor equations often results in excessive over-strength design of the concrete mixtures. This study indicated that the total amount of penalties in comparison to the cost of many projects is insignificant. Out of a total materials cost of $13,590,000 for the projects studied, the total penalties assessed were $124,000 (0.91% of total) and $36,200 (0.26% of total) for the present and proposed ADOT formulas, respectively.

Several methods were employed to better understand the acceptance criteria. The Federal Highway Administration (FHWA) approach utilizes a PWL penalty based on many factors such as the Q-value table and the specification upper and lower limit. The FHWA approach should be employed carefully because of the sensitivity of the method. Six bridge cases were studied where each case had rejected lots by the current ADOT, new proposed ADOT, FHWA, and California Department of Transportation (Caltrans) methods. Various penalty factors for these cases were determined.

A comparison of two different pay factors- the PWL and the Kentucky OC curve shows that the two methods are quite similar. The PWL computed by Kentucky OC curve was generally friendlier to suppliers as compared to the FHWA's Category II which is based on an acceptance quality limit (AQL) of 90% specification. In addition, the Kentucky OC curve provided an award or bonus to the supplier whereas there was no extra payment by using Category II. The FHWA method results in a higher penalty than the other methods (1.38% of the total cost of the projects), whereas the Caltrans method shows a lower penalty (0.81%). The huge penalty is attributed to the rejection of several sublots. The penalties are less than 1% for current ADOT, proposed ADOT, and the Caltrans methods.

Comparing the current and proposed ADOT methods, the penalties were assessed in all six bridge cases. The average level of penalty was in the range of 6.9%. This level of penalty could be reduced to 2.2% upon adoption of the new ADOT cost factor policy. Average cost comparisons between the current and proposed ADOT equations indicate that the approximate penalties in the new ADOT method are in the range of 26% of the present penalty levels. The FHWA method with pay factor Category II, showed only three cases that were penalized. The penalties given by FHWA, current ADOT, and Caltrans methods were similar and averaged 6% of the total costs. The penalty from the new ADOT method was the lowest and resulted in 2.2% penalty.

The proposed ADOT method seems to be friendlier to suppliers while still providing a stable penalty. The penalty is 0.27% and is slightly lower than the current ADOT method (0.92%). Applying methods with quality control criteria would benefit projects by reducing out-of-spec concrete on jobsites, retaining required strength, and minimizing materials consumption.

While the proposed modifications to the specifications provide reasonable and justifiable changes to the current pay factor equations used by ADOT, real materials savings can be realized when the cost of raw materials used is reduced through the implementation of a balanced and comprehensive statistical quality control acceptance criteria.

II. Introduction

Continuous development of civil infrastructure systems in support of the population growth and economic productivity of the State of Arizona is a challenge faced by many decision makers in the planning, administra tive, engineering, and executive branches of our state.

Concrete is the most commonly used building material in the world. Its production in the United States has almost doubled from 220 million cubic yards per year in the early 1990's to more than 430 million cubic yards in 2004. Arizona's share has been about 15 million cubic yards of concrete per year; a number that is increasing at an annual rate of 15% during the past several years. This has placed a tremendous strain on the suppliers when one considers the increased demand for infrastructure development. Construction delays and material shortages have resulted in escalating costs.

A significant amount of energy is required to produce cement. For each ton of cement produced, a ton of carbon dioxide is emitted into the environment. Therefore, it would be advantageous to reduce the amount of cement and other virgin materials that are used in cement-based composites. Chemical attack such as corrosion and alkali silica reaction (ASR) in concrete is among the major durability concerns in civil infrastructure systems. These mechanisms affect the service life and long term maintenance costs. For example, the average annual direct cost of corrosion for highway bridges was estimated by Yunovich to be $8.29 billion in the U.S.[2] A better understanding of how the environment influences concrete performance will improve the decision making process in every stage of construction and maintenance. The initial design of a structure must consider the entire service life, and any new proposals for modification of the formulations should consider the materials science aspects of the performance. This report, however, addresses methods that can be used to better understand the quality control measures and incentives for the payment based on early age properties of concrete.

One of the reasons for the extensive use of cement-based systems is the design versatility which can be tailored to each application. Based on the intended use, varying constituent materials and processing techniques can be used to achieve performance metrics from fresh state properties to superior mechanical properties and durability. From a technical perspective, numerous challenges remain in promotion and use of blended cements as sustainable and cost saving alternatives. It would be beneficial to utilize and recycle waste by-products such as class C fly ash as value added ingredients for concrete production, according to Roy.[3] One must however appreciate the complexity of integration of cement chemistry, early age properties, and specifications when using blended cements in construction projects, per Mobasher and Ferraris.[4]

It is imperative that new guidelines and cost structures for concrete materials be analyzed so that more economical alternatives can be evaluated and considered during the preliminary design of a project. As the cost of raw materials changes, many potential alternatives become cost effective, such as the use of performance enhancing admixtures and/or supplementary cementitious materials, curing, and finally quality control (QC). These alternatives may not be regularly specified for highway structures due to the lack of avail-able field data. The focus of the present work is based on a need to better understand the role of quality control and quality assurance in a sustainable design philosophy. The goal is directed toward generating cross-disciplinary tools to guide us toward more economical engineering and construction policies. Life cycle cost modeling combined with statistical quality control measures could identify potential savings, claim Burati et al. [5]

The interaction of various choices for an appropriate cost reduction strategy is especially important in hot, arid regions where special attention must be paid to the materials design with respect to curing, early shrinkage, and cracking. These will ultimately affect the durability and quality of the concrete. Not all loading cases, applications, and specifications can be translated into compressive strength values of concrete; hence this parameter cannot and should not be used as the sole measure of concrete quality and performance. Knowledge of various alternatives would allow state officials to make cost-effective decisions when specifying concrete and provide contractors greater flexibility in meeting design requirements and future needs.

Objectives

The objective of this work is to promote better quality and economy when using concrete materials by focusing on:

- Evaluation of the acceptance criteria and current pay factor adjustment methods based on bonus/penalty factors in order to improve quality control and specification procedures.
- Use of a mix design formulation that is based on the principles of economy but still improves the durability of the finished product.

This report addresses recommendations drafted in consideration of the concerns of various stakeholders, including state and federal transportation officials, local cement suppliers, concrete ready mix plants, and construction companies. The opportunities developed in earlier reports addressed both the quality and economy of concrete materials used locally.

Preliminary Results

Results from a preliminary study conducted for a committee consisting of members of Arizona Rock Products Association and the Arizona Department of Transportation (herein referred to as the ARPA/ADOT committee) are discussed first. Figure 1 presents data from a single concrete manufacturer that was obtained from ADOT's Field office Automation SysTem (FAST) database. The plot shows specified strength vs. the strength of concrete delivered to the job-site. Each data point represents a single compressive strength value for a representative volume of material. Assuming that each cylinder represents a lot of 50 cubic yards on average, the data represents approximately 300,000 cubic yards of concrete. For a major portion of the materials delivered, the strength value delivered far exceeded that required for the job. It is clearly shown that quite often, the strength of concrete delivered is approximately 1100-1500 psi higher than the specified values. As such, the amount of cement that could be saved by reducing the total cement content in the mixture is significant. The worksheet cost analysis model has been developed which shows the potential cost savings of cement substitution by supplementary cementitious products. By implementing a quality control process for the acceptance of concrete, it is clear that one can reduce both the standard deviations and the mean strength values while maintaining the same level of risk. The net result would be realized in the reduction of the average cement dosage requirements. Figure 2 shows the running average strength value for a 2-year period of a single supplier for a 3000 psi class of concrete. Note that the over-strength conservatism is significantly higher with as much as 1500 psi mean over-strength values.

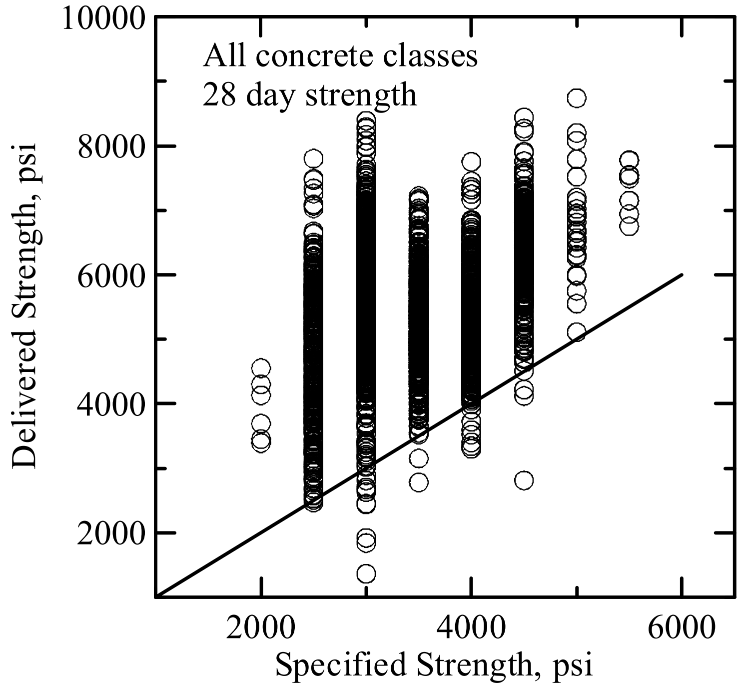


Figure 1. Correlation of data from both the specified strength and the actual strength of concrete delivered to the job site from a single ready mix producer. The solid line represents a 1:1 correlation.

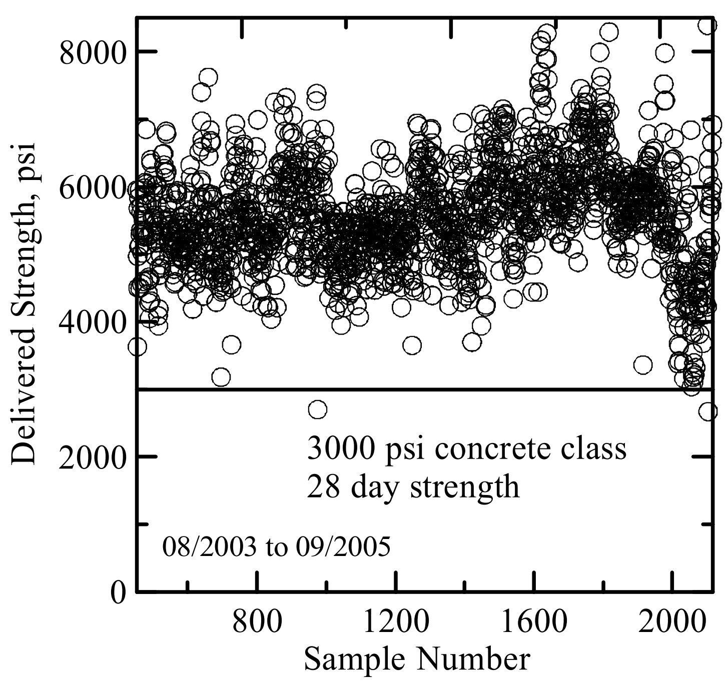


Figure 2. Data from a single ready mix producer during a two year cycle representing the amount of over-strength concrete delivered.

It would also be ideal to evaluate the 7-day strength results and use that information as a basis to determine if the 28-day strength results are capable of meeting the design objectives or not. In Figure 3, red dots represent the 7-day strength values whereas the black dots represent the 28-day strength values. The specified strength of the concrete is 2500 psi at 28 days. It is clear that the 28-day strength is greater than the 7-day strength; however, no correlation is apparent in the trend of the data. While it is true that the strength might be improved by the extended curing time, there is no methodology to correlate the 28-day strength with 7-day strength. Subsequently, there is no way to determine if the trend and variations in the 28-day strength are too large to be statistically significant.

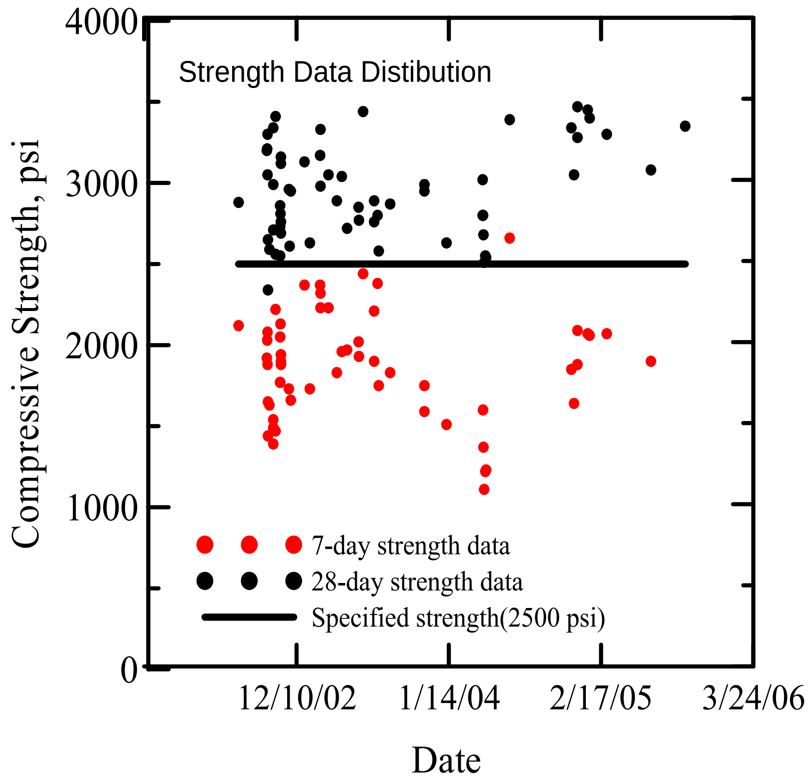


Figure 3. Plot of the Comparison of Strength Data Distribution to Specification

II. Sample Collection and Analysis Procedures

1. Preliminary Data Selection

Three types of data sets were used in this survey. These included data provided by industry in cases of previous dispute which had been resolved using the pay factor equations. Data was also provided by ADOT resident engineers based on their prior experience with cases which required additional investigation. The third set of data involved a random selection of a range of available data within the FAST data base. Three sets of various data bases were addressed. These data were categorized in the following case studies.

1.1 ADOT Supplied Test Cases (Series 1)

Six projects using a total of nine mixes were identified as cases which required further statistical evaluation. They were identified by ADOT Resident Engineers as test cases for analysis and in depth evaluation. These cases were identified as problem projects which had historically required further investigation such as coring and additional testing (for example, H407601C, H416001C, H552501, and H576801C). The following Transportation Accounting (TRACs) numbers are used within the Series 1 category and further investigated:

Table 1: Series 1 Data Set

Project	TRACs number	Supplier	Plant number	Product number	Required strength (psi)	Age (days)
1	H576801C	Rinker	33341	1333115	4500	28
2	H552501C	Sunshine Concrete	Kingman	S3000A	3000	28
3A	H407601C	Rinker	55041	14016	3500	28
3B	H407601C	Rinker Materials	60141	1332439	4000	28
4A	H416001C	Campbell Redi-mix	Lake Havasu	2500S	2500B	28
4B	H416001C	Campbell Redi-mix	Lake Havasu	2500S	3500S	28
5A	H319003C	McNeil Const. Co.	Tucson	0203-10	4000	28
5B	H319003C	McNeil Const. Co.	Tucson	0203-15	4000	28
6	H313401C	McNeil Const. Co.	Tucson	9710-3	4000	28

1.2 Randomly Selected Test Cases (Various supplier, plant, and mix specification) (Series 2)

The data in this test case were randomly selected. Five different suppliers (Chandler Ready Mix, Rinker, Arizona Materials, Hanson Aggregates of AZ, and TPAC) are selected with two plants each, and three mix specifications each as shown in Table 2.

Table 2: Series 2 Data Set

No	Supplier	Plant	Mix specification	Required strength (psi)	Age (days)
A11	Chandler Ready Mix	03	130624	3000	28
A12	Chandler Ready Mix	03	972502	2900	28
A13	Chandler Ready Mix	03	4425	2500	28
A21	Chandler Ready Mix	01	140204	4000	28
A22	Chandler Ready Mix	01	160604	6000	28
A23	Chandler Ready Mix	01	130224	3000	28
B11	Rinker	11241	14030	3500	28
B12	Rinker	11241	1333066	4000	28
B13	Rinker	11241	14504	4500	28
B21	Rinker	33341	14016	3000	28
B22	Rinker	33341	1333004	3500	28
B23	Rinker	33341	1345459	3000	28
C11	Arizona Materials	Val Vista	15030	4500	28
C12	Arizona Materials	Val Vista	13008	2500	28
C13	Arizona Materials	Val Vista	14030A	4000	28
C21	Arizona Materials	Queen Creek	13008	3000	28
C22	Arizona Materials	Queen Creek	14030	3000	28
C23	Arizona Materials	Queen Creek	13530	3000	28
D11	Hanson Agg. of AZ	Valley Plant	C35501	3500	28
D12	Hanson Agg. of AZ	Valley Plant	C40501	4000	28
D13	Hanson Agg. of AZ	Valley Plant	C35501A	3500	28
D21	Hanson Agg. of AZ	40	D402521	4000	28
D22	Hanson Agg. of AZ	40	1205104	4000	28
D23	Hanson Agg. of AZ	40	840913	4000	28
E11	TPAC	Phoenix	447	5000	28
E12	TPAC	Phoenix	444	5500	28
E13	TPAC	Phoenix	448M	5500	28
E21	TPAC	Tucson	2245	4500	28
E22	TPAC	Tucson	2248	5000	28
E23	TPAC	Tucson	2250	6000	28

1.3 Members of the ADOT/ARPA committee Supplied Test Cases (Series 3)

The industrial members of the task group identified several test cases which had resulted in compressive strength disputes. Six bridge projects were recommended for exploration. These test cases are listed as shown in Table 3.

Table 3: Series 3 Data Set

Case Number	Bridge Name	Required strength (Psi)
1	Wilson Wash	4500
2	Sandy Blevens	4500
3	Quail Springs	4500
4	Poison	4500
5	Deveore	4500
6	Apprentice	4500

2. Exploratory Data Analysis

Statistical process control is widely used in various manufacturing sectors. The first step in the evaluation of the data is to conduct an exploratory data analysis. In this procedure, the number of samples, distribution of the samples, and basic statistical techniques are utilized to evaluate if the data meets certain criteria for follow up steps. In the exploratory data analysis section, the adequacy of the data was tested by scatter plot, histogram, and probability plots. These plots verify the validity of assumptions. The assumption in applying the control chart is that the data is normally distributed. In this case a normal distribution was assumed, due to a sufficient number of data points representing the symmetrical nature of a bell shaped curve with equal distribution about the mean. The Anderson-Darling (AD) test, which can be applied to any assumed distribution, confirmed a normal distribution. Additionally the AD test also acknowledged that the test samples came from a much larger population of normally distributed data. If there is sufficient sample size to form a hypothesis, then the analysis on the data yields a very good estimation of the entire population. If there is not a sufficiently large sample size, then the margin of error is rather large. Most probability plots satisfied this assumption. The test data which did not meet the normal distribution criteria was not used in the analysis. The cases were rejected primarily because there were few sample points (six or seven strength values) in these cases, the reliability of the analysis is quite low, so larger data sets, which could provide a better representation of statistical process, were chosen. The basic control chart is also applied to the concrete strength data. The X-bars are presented for two methods including current ADOT and modified American Concrete Institute (ACI) methods. ADOT employs the design strength (F'_c) as the lower limit. The X-bar and S charts are also employed by using a modified ACI method which requires specified strength (F'_{cr}) as the mean of the chart. The X-bar chart plots the subgroup means, whereas the S chart relates to the subgroup standard deviation, according to Montgomery.[6] The X-bar control chart presents the mean. S charting measures the process variability and helps monitor the stability of process. The data is shown in chronological order, so the trends or shifts in the process can be detected.[7]

2.1. Exploratory Data Analysis of Series 1

Figure 4 represents the Normal Probability plot for Series 1 data sets (see Appendix A). Here N represents the number of samples tested and StDev represents the standard deviation with a 95% Confidence Indicator (CI) with respect to the mean, The AD test is a statistical procedure applied to evaluate if the samples come from a particular distribution, as explained by the National Institute of Standards and Technology[8] and Hayes et al,[9] A small AD value indicates that an assumed distribution (for example a normal distribution) fits the data. Projects 5 (H416001C_ Campbell Redi-mix_ Lake Havasu_2500S_2500B) and Project 8 (H319003C_ McNeil Const. Co._ Tucson_0203-15_4000) do not follow the normality assumption because Anderson-Darling statistics are quite large in comparison to the other projects (AD = 1.238 and 1.165).

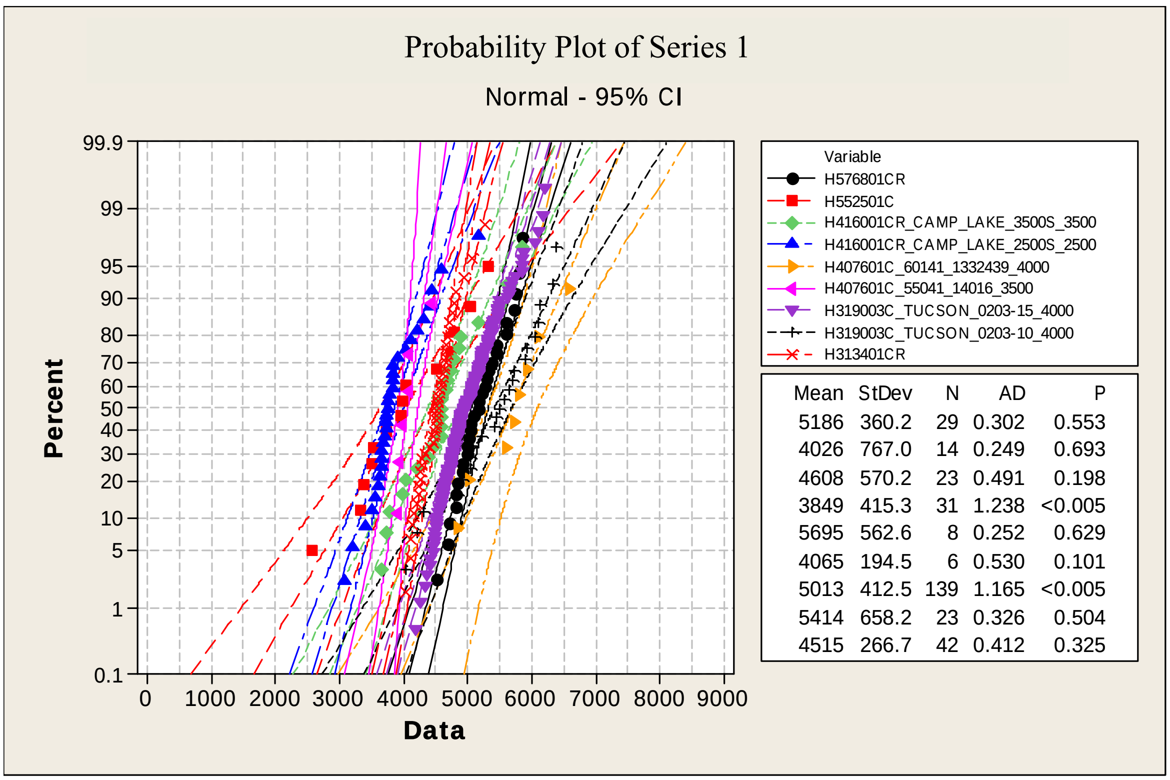


Figure 4. Probability plot for Series 1

The next step is to assume that the data are normally distributed, and one can conduct a hypothesis test and find the probability (or P-value). The P value is calculated based on the results by assuming the null hypothesis is true. The significance level (or the alpha (α) level) is the particular probability level that the evidence is either an irrational estimate or the decisive factor used for rejecting the null hypothesis, as explained by Hayes et al.[10] The P-value can be interpreted as the probability of a false rejection of the null hypothesis or the chance of making a Type I error (the error of rejecting a null hypothesis when the null hypothesis is actually true). For example, the significant level of 0.05 corresponds to a 5% chance that the normality assumption was rejected due to the sample specimen belonging to a normally distributed set of data. When comparing the probability to the significance level, if the P-value is less than or equal to the alpha level, one may conclude that the null hypothesis is 'statistically significant' and rejected, according to Lane.[11] In general, the popular levels of significance level are 0.05 and 0.01. The lower the significance level, the more the data significantly deviate from the null hypothesis.[11]

Based on the above, it is clearly observed that Projects 5 and 8 might not fit the normal distribution very well since P-values are quite small (< 0.005). For discussion purposes of this report, the rest of the data set is assumed to be valid test data collected from normally distributed populations. A summary of all the X-bar and S-Charts for these samples are listed in Appendix B (Figures B1 – B9).

An alternative method to present data is to show X-bar and S charts. The X-bar charts are plotted in two sets, first by considering the lower limit as specified minimum strength (F'_c) which is the current approach of ADOT, and second by a method similar to ACI-214 in which the mean (center line) is the required jobsite strength (F'_{cr}) with lower and upper limits. The second criterion of ACI-214 is used in which:

$F'_{cr} = F'_c + \frac{s.z}{\sqrt{n}}$, s is the standard deviation of the data set, z is associated with the normality of the data set (here z=1.28 for 10%) and n=3. The formula of the lower and upper control limit (LCL and UCL) is $CL \pm \frac{k\sigma}{\sqrt{n}}$ where

CL = the center line (F'_{cr})
n = 3= the size of the subgroup
k = the number of standard deviations from the center line. In this situation, k = 3.
σ = the standard deviation that is calculated by the pooled standard deviation.

It is written as $\hat{\sigma} = \frac{\bar{S}}{c_4} = \frac{(\frac{\sum_{i=1}^{n} S_i}{n})}{c_4}$ where c_4 is the value from the table. The summary table of the factors for constructing variable control charts is shown in Table 4.

Table 4: Factors used for Constructing Variable Control Charts

Sample size	Factor for Central Line	Factor for Control Limits of the S chart	
	c_4	B_3	B_4
2	0.7979	0	3.267
3	0.8862	0	2.568
4	0.9213	0	2.266
5	0.9400	0	2.089

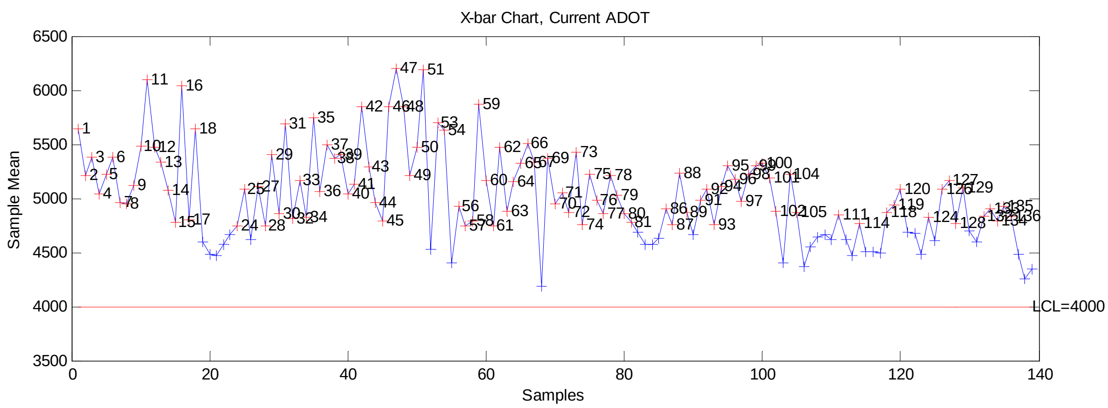
From Montgomery. *Introduction to Statistical Quality Control.* 4th ed. 2001. [6]

For instance, the standard deviation of project 8 (Figure 5) is 658.2, but the sigma is calculated by $\hat{\sigma} = \frac{\bar{S}}{c_4} = \frac{207}{0.8862} = 233.58$ since the sample size = 3. Here,

$$F'_{cr} = 4000 + \frac{658 \times 1.28}{\sqrt{3}} = 4486 \quad \text{psi}$$

Then: $LCL = \mu - \frac{k\sigma}{\sqrt{n}} = 4486 - \frac{(3)(233.58)}{\sqrt{3}} = 4081.43$

$$UCL = \mu + \frac{k\sigma}{\sqrt{n}} = 4486 + \frac{(3)(233.58)}{\sqrt{3}} = 4890.57$$



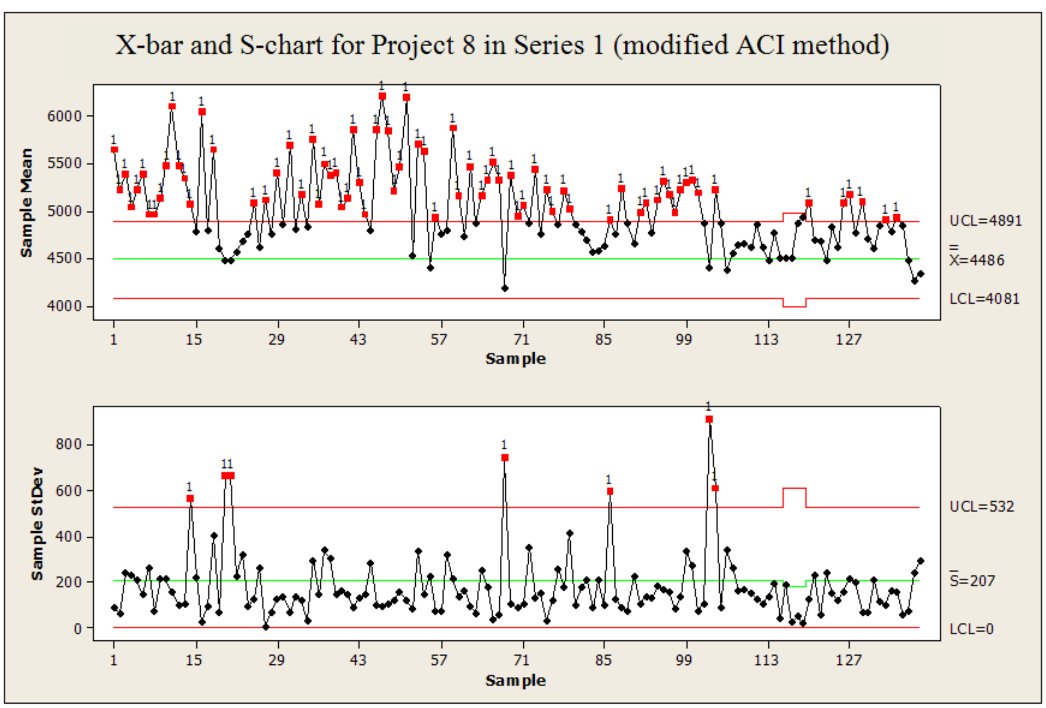


Figure 5. X-bar and S Chart for Project 8 in Series1

The S chart demonstrates the instability and variability in several projects (Project 1, 5, 6, 7, and 8). Figure 5 presents the S chart which is a running sequence of the average strength values as a function of project time. The center line is the average of all subgroup standard deviations. It is defined as $CL = \overline{S}$. Then CL = 207. The lower and upper control limits can be written as $B_3\overline{S}$ and $B_4\overline{S}$ respectively, where B_3 and B_4 are values from a table above which depends on the subgroup size. Then $LCL = B_3\overline{S} = (0)(207) = 0$ and $UCL = B_4\overline{S} = (2.568)(207) = 531.576$.

It should be mentioned that the real lower limit for concrete strength is the specified design strength (F'_c) and the values for different samples can vary about the required strength (F'_{cr}). However, in this analysis, the obtained lower limit (e.g. 4081 psi) would be slightly higher than the F'_c (e.g. 4000 psi).

The S chart detects the shifts that are above and below the target. Since there are several points greater than the upper control limit, this indicates that the process is out-of-control as shown above. Nevertheless, it is acceptable for the compressive strength data to be above the specified strength, so this report focuses on the out-of-control signal, particularly the lower specification. This means that this process can be considered as the good process since there are no points that fall beyond the lower control limits. The presence of an out-of-control signal shows the assignable causes (effects that can be corrected, adjusted, or removed, i.e, process control, extra cement factor, etc.) in the process, so the process should be investigated to remove the variation and increase its capability.

2.2. Exploratory Data Analysis of Series 2

This test case was selected based on a random selection of various suppliers, plants, and mix specifications (Series 2). There are some cases in this series where the data set is too small (less than 5 data points). Since such a data set was not appropriate to analyze, several projects were discarded such as A12, A22, A23, B23, D11, and D22. Figure A2, A3, A4, A5, and A6 represent the Normal Probability plot for Series 2 Project A, B, C, D, and E data sets respectively (see Appendix A). Using the Anderson-Darling statistic (AD), Project A21, B11, B12, D21, D23, E11, and E12 do not follow the normality assumption because the Anderson-Darling statistics are quite large in comparison to the other projects (AD = 1.054, 0.747, 0.625, 0.866, 0.622, 0.854, and 0.742). The large Anderson-Darling values indicate that the distribution does not fit the normality assumption. In addition, the P-values (0.008, 0.043, 0.053, 0.022, 0.088, 0.024, and 0.037 respectively) are smaller than the chosen α-level (0.05 and 0.10), so Project A21, B11, B12, D21, D23, E11 and E12 might not follow the normal distribution very well either. For the purposes of discussion in this report, other projects are assumed to be collected from normally distributed populations. A summary of both the X-bar and S-Charts for these samples are listed in Appendix C (Figures C1 – C24). The S control chart presents the variability by detecting an out-of-control signal in some cases including B22, C11, C13, D12, D13, D23, and E23. Most cases however, had higher strength than the defined upper limit and are considered over-designed.

2.3 Exploratory Data Analysis of Series 3

This test case (Series 3) was supplied by the members of the ADOT/ARPA committee. Figure A7 represents the Normal Probability plot for Series 3 data sets (see Appendix A). In this set of data, project D22 was discarded since the number of observations was quite small. All the Anderson-Darling values (AD) are relatively small (AD = 0.567, 0.537, 0.232, 0.445, 0.210, 0.171), therefore, all bridge projects are assumed to follow a normal distribution. In addition, the p-values (0.117, 0.147, 0.757, 0.194, 0.833, and 0.907 respectively) are greater than the commonly chosen α-level (0.05 and 0.10). All bridge projects seem to be normally distributed. For the purposes of discussion in this report, most data sets within this series are assumed to be collected from normally distributed populations. A summary of all the X-bar and S-Charts for these samples is listed in Appendix D (Figures D1 – D6). In this series, all the bridge projects had rejected lots with strength lower than design strength (F'_c). They also had some strengths higher than the upper limit.

3. Pay Factor Determination

Once the normality assumptions were properly tested, all projects were examined for various penalty/bonus criteria by using four different approaches. These alternatives were identified as: FHWA, Currently enforced ADOT guidelines (ADOT), recently proposed ADOT guidelines (new ADOT), and Caltrans.

It should be mentioned that in the current ADOT method, only a lower limit (F'_c) is considered as the criterion for the pay factor and the data history and statistical analysis is not employed to determine the level of penalty. However, following a similar method to ACI-214 (such as the FHWA method) would enhance the overall quality control of concrete production in which lower and upper limits are defined and a lot is of good quality if it is between the two limits and of poor quality otherwise. The summary of this analysis is presented in the following table in which the out of control data are shown in all series. "L" means lower strength and "H" means higher strength compared to the mean strength (F'_c in ADOT and F'_{cr} in ACI). Details for all four methods are shown in Table 5.

Table 5: Out-of-Control Data in all Series

		Number of out of control data			Percentage of Out of Control data		
Series	**Code**	**ADOT:L**	**ACI:L**	**ACI:H**	**ADOT:L, %**	**ACI:L, %**	**ACI:H, %**
3	1	0	0	13	0.0	0.0	44.8
	2	1	3	8	7.1	21.4	57.1
	3	0	0	4	0.0	0.0	66.7
	4	0	0	8	0.0	0.0	100.0
	5	0	0	31	0.0	0.0	100.0
	6	0	0	17	0.0	0.0	73.9
	7	0	0	20	0.0	0.0	87.0
	8	0	0	74	0.0	0.0	53.2
	9	0	0	30	0.0	0.0	71.4
2	A11	0	0	7	0.0	0.0	100.0
	A13	0	0	11	0.0	0.0	100.0
	A21	0	0	47	0.0	0.0	94.0
	B11	0	0	19	0.0	0.0	100.0
	B12	0	0	3	0.0	0.0	50.0
	B13	0	0	21	0.0	0.0	100.0
	B21	0	0	8	0.0	0.0	100.0
	B22	1	4	8	5.6	22.2	44.4
	C11	1	1	45	1.4	1.4	62.5
	C12	0	0	5	0.0	0.0	100.0
	C13	5	5	6	17.9	17.9	21.4
	C21	0	0	16	0.0	0.0	100.0
	C22	0	0	20	0.0	0.0	100.0
	C23	0	0	5	0.0	0.0	100.0
	D12	1	1	1	16.7	16.7	16.7
	D13	0	1	18	0.0	5.0	90.0
	D21	0	0	22	0.0	0.0	91.7
	D23	0	4	9	0.0	23.5	52.9
	E11	0	0	28	0.0	0.0	100.0
	E12	0	0	11	0.0	0.0	100.0
	E13	0	0	21	0.0	0.0	100.0
	E21	0	0	23	0.0	0.0	88.5
	E22	0	0	55	0.0	0.0	94.8
	E23	1	1	6	9.1	9.1	54.5
3	Wilson Wash	7	8	4	50.0	57.1	28.6
	Sandy Bleven	2	2	7	10.5	10.5	36.8
	Quail Springs	3	3	1	20.0	20.0	6.7
	Poison	1	2	5	14.3	28.6	71.4
	Deveore	2	3	1	11.8	17.6	5.9
	Apprentice	1	3	5	9.1	27.3	45.5

3.1 FHWA-PWL Method

The Pay factor is calculated by using the PWL method. PWL (percent conforming or percent within limit) is the percentage of the lot that is in the specification: between the upper specification limit and lower specification limit. The PWL is calculated based on normality assumption. A lot is defined as a finite sample size. Within each lot, several sub-lots are defined. Samples are collected at the sublot level. Within each lot the mean and standard deviation are calculated. These values are used by means of statistical process control procedures to compute the quality measures. Upper and lower specification limits are either specified or calculated based on a number of standard deviations away from the mean. Instead of using the Z-value, the quality index, Q, is used to estimate the PWL. The Q-value is given by Burati, et al.[5] as:

$$Q_L = \frac{(\bar{x} - LSL)}{s}$$ where LSL = lower specification limit

$$Q_U = \frac{(USL - \bar{x})}{s}$$ where USL = upper specification limit

The Q-value is used to determine the estimated PWL for the lot as shown in the table by Specification Conformity Analysis.[12] Each Q_U and Q_L value will transform to P_U and P_L and then used to calculate the PWL. The total estimated percentage of the lot within the U and L is $PWL = P_U + P_L - 100$. The lot strength PWL is related to the pay factor. Figure 6 represents the relationship between the Q-value and the PWL when n (sample size) is varied from 3 to 10.

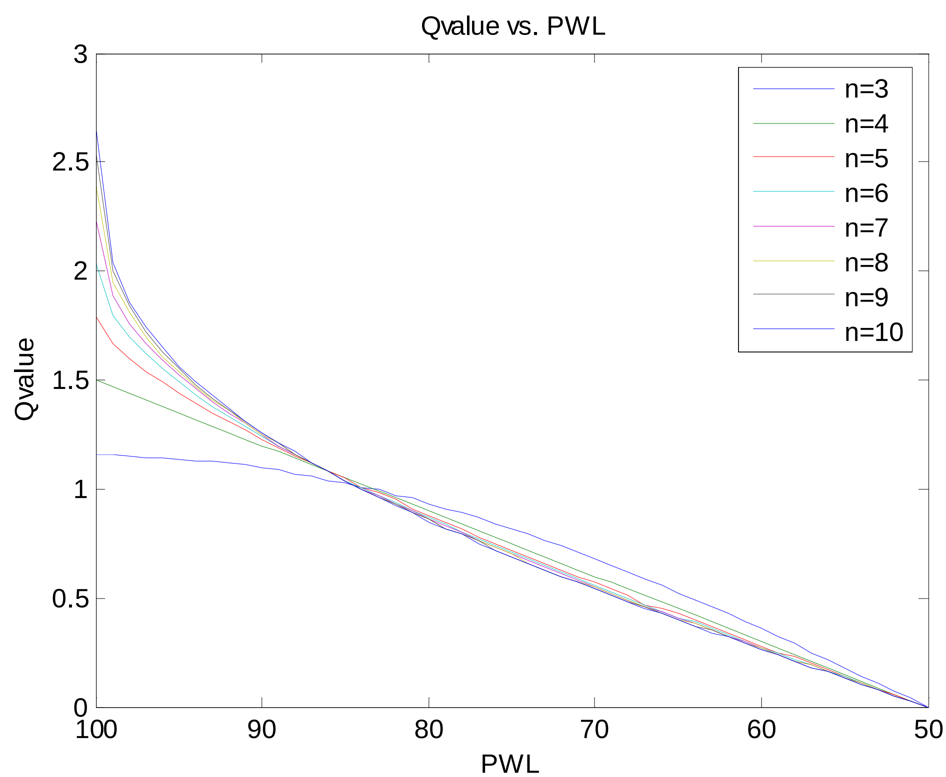


Figure 6 Plot of the Relationship between the Q-value and the PWL

Subsequent to estimation of PWL, the next step is finding the pay factor for each sublot. The pay factor is estimated by two ways: the Acceptable Quality Level and the OC Curve.

- *Pay Factor determination using acceptable quality level.*

There are two important definitions by the FHWA.[5] First, the Acceptable Quality Level (AQL) is the minimum percentage of the quality work that is considered acceptable for payment. Second, the Rejectable Quality Level (RQL) is the maximum percentage of the quality work that is considered unacceptable. There are 2 categories: I and II. Category I is based on an AQL of 95 percent whereas Category II is based on AQL of 90 percent. The contractor's risk is 5 percent in both cases. The seller's risk (or contractor's risk) is the chance of rejecting material that is at the AQL level. This is also called Type II Error (or β) by Montgomery.[6] The Government Agency's risk is defined as the probability of accepting material if it is at the RQL level. It may be called the 'buyer's risk' by Mahboub and Hancher [13] or Type I Error (or α) by Montgomery.[6] Figure 7 shows the defining table of Type I and Type II errors.

		Result of Decision	
		Accept the lot	Reject the lot
Quality of lot	Good lot (AQL)		Producer's Risk (Type I error)
	Bad lot (RQL)	Consumer's Risk (Type II error)	

Figure 7 The Defining table of Type I and Type II errors from Mahboub and Hancher.[13]

In this report, we applied Category II to the data set. The pay factor depends on sample size and the calculated PWL by Mahboub and Hancher [13] (See Appendix E). Figure 8 represents the determining pay factor by using Category II and varying number of sample size.

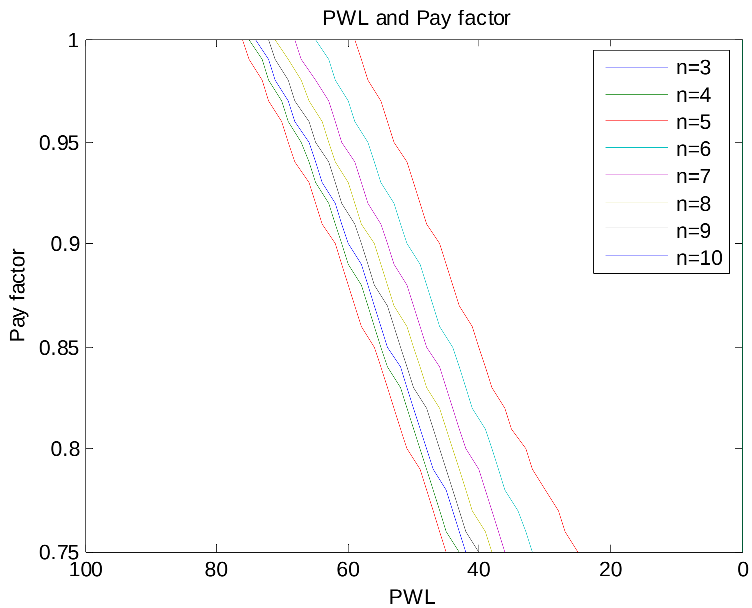


Figure 8 Plot of Relationship between PWL and Pay Factor by Category II

- *OC curve*

The OC curve plots the probability of acceptance against the true value or percent of defectives. The probability of acceptance is the parameter on the vertical axis whereas the percent defective is on the horizontal axis, according to Mahboub and Hancher.[13] Figure 9 shows the OC curve for any plan.

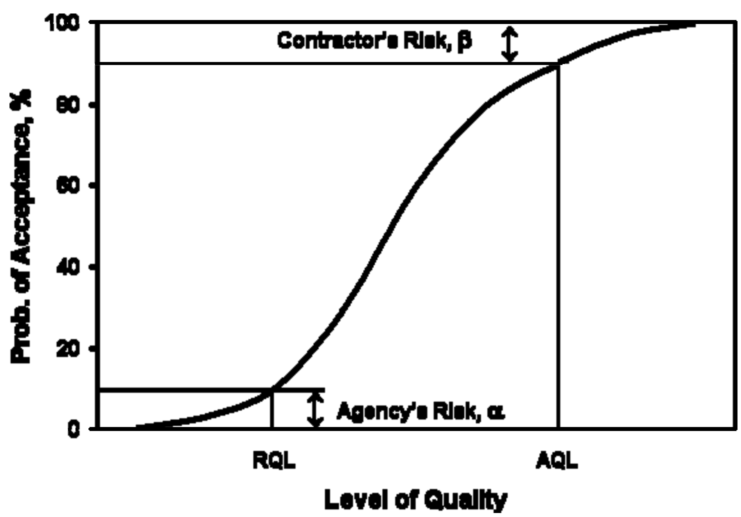


Figure 9. OC Curve from Mahboub and Hancher [13]

OC curves are tools widely accepted to manage risk analysis since they allow one to choose the number of samples to detect the particular probability, per Montgomery.[6] In general, the payment adjustment is related to α and β risks. An alternative method for acceptance is to consider the payment performance as mentioned in Mahboub and Hancher [13] and shown in Figure 10.

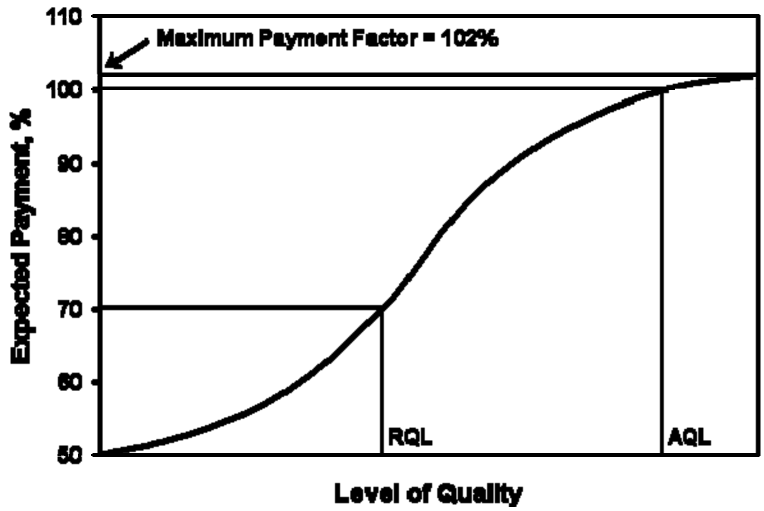


Figure 10. The Payment Curve from Mahboub and Hancher [13]

In the present method we chose the Kentucky OC curve, as in Mahboub and Hancher.[13] The table below and Figure 11 show the relationship between the PWL and the pay factor. It is clear that a higher PWL would result in better pay factors.

Table 6: Relationship Between PWL and Pay Factor

Lot Strength PWL (%)	Seller's Risk for rejecting the lot (%)	Pay factor*
100	0	102.5
95	5.3	100
90	15.2	97.5
85	27.1	95
80	40.5	92
75	51.1	90
70	62.0	87.5
65	70.5	85
60	78.2	82.5
55	83.5	80
50	88.5	77.5
45	92.6	75
40	94.9	72.5
35	97.1	70
30	98.3	67.5
25	99	65
20	99.1	62.5

* Assuming a sample lot PWL of a given lot is approximately equal to the population lot PWL

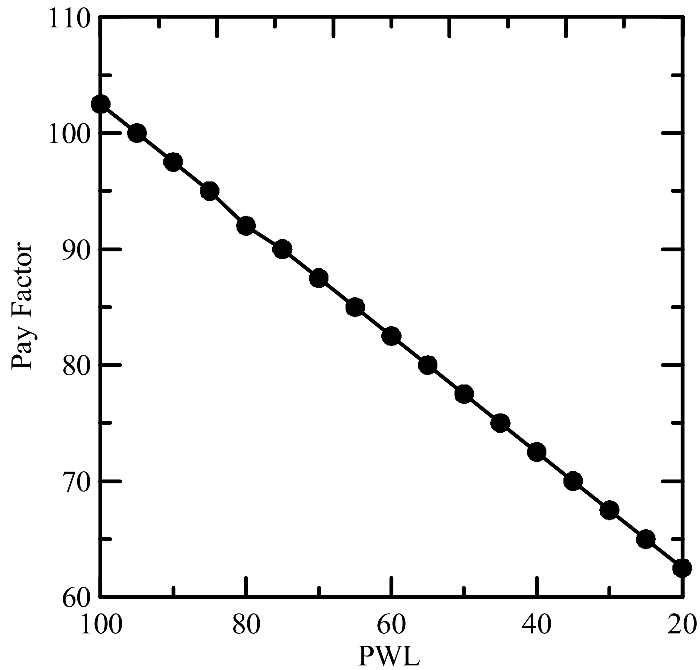


Figure 11. Plot of the Relationship between PWL and Pay Factor by Kentucky OC curve

3.2 Current ADOT Pay Factor Determination

The pay factor, according to the ADOT method, is calculated from the average of two compressive strength samples representing a finite volume of concrete defined as a lot. Normally the volume of concrete corresponds to approximately 100 cubic yards. The strength result is the percentage of compressive strength as a function of the required and/or specified strength. The present ADOT method does not penalize or reward the various ready mix suppliers in accordance to the statistics of the sampled data. The current technique is primarily focused on meeting the minimum specified level.

The ADOT method is neither based on statistical methodology nor does it take into account the variations that take place in normal operating conditions. Therefore, a sample may be slightly above the required level, and that sample will be considered acceptable although a large proportion of that population may actually fall below the specified strength level from a statistical point of view. In conclusion, when the mistaken sample was chosen, it cannot represent the true strength of cement. This misrepresented strength results in an invalid payment determination. The adjustment in contract for the ADOT method is shown as follows:

Table 7: Adjustment in Contract for ADOT Method

Strength result (% of F'_c)	Reduction in Contract Unit Price (%)
100 or More	0
98 - 99	5
96 - 97	10
95	15
Less than 95*	45
* If allowed to remain in place	

To check the sensitivity of the strength, the round-off numbers are applied to the boundary values. The table below shows the new adjustment in contract.

Table 8: Sensitivity of Adjustment in Contract for ADOT Method

Strength result (% of F'_c)	Reduction in Contract Unit Price (%)
99.5 or more	0
97.5 – 99.5	5
95.5 – 97.5	10
94.5 - 95.5	15
Less than 94.5*	45
* If allowed to remain in place	

3.3 Proposed ADOT Pay Factor Determination

This method is an improvement over the old ADOT method. It applies the same concept, but also depends on the level of required compressive strength. The adjustment in contract for strength is shown as follows:

Table 9: Adjustment in Contract for New ADOT Method

Adjustment in Contract Unit Price For Compressive Strength of Class S and Class B Concrete					
3000 and Below		3000 and 4000		4000 and Above	
Percent of Specified 28-Day Compressive Strength Attained, to the Nearest One Percent	Percent Reduction in Contract Unit Price (See Note 1)	Percent of Specified 28-Day Compressive Strength Attained, to the Nearest One Percent	Percent Reduction in Contract Unit Price (See Note 1)	Percent of Specified 28-Day Compressive Strength Attained, to the Nearest One Percent	Percent Reduction in Contract Unit Price (See Note 1)
100 or More	0	100 or More	0	100 or More	0
99	1	99	1	99	1
98	2	98	2	98	2
97	3	97	3	97	3
96	4	96	4	96	4
95	5	95	5	95	5
94	6	94	6	94	30
93	7	93	7	93	30
92	8	92	8	92	30
91	9	91	9	91	30
90	10	90	10	90	30
89	11	89	30	89	30
88	12	88	30	88	30
87	13	87	30	87	30
86	14	86	30	86	30
85	15	85	30	85	30
Less than 85	30 (See Note 2)	Less than 90	30 (See Note 2)	Less than 95	30 (See Note 2)
Note1: For items measured and paid for by the cubic yard, the reduction shall not exceed $150 per cubic yard Note2: If allowed to remain in place.					

It is possible to write the simple linear regression for calculating the new ADOT penalty by

$$P = \begin{cases} 100 & , x > 1 \\ x & , x \geq \beta \\ 70 & , x < \beta \end{cases}$$

where P = penalty, and $x = \dfrac{strength\ \ required}{specified\ \ strength}$

Table 10: The Value of β

Strength	β
3000 and Below	85
3000 to 4000	90
4000 and Above	95

Figure 12 below shows the plot of percent reduction comparing the table to computations from two different equations.

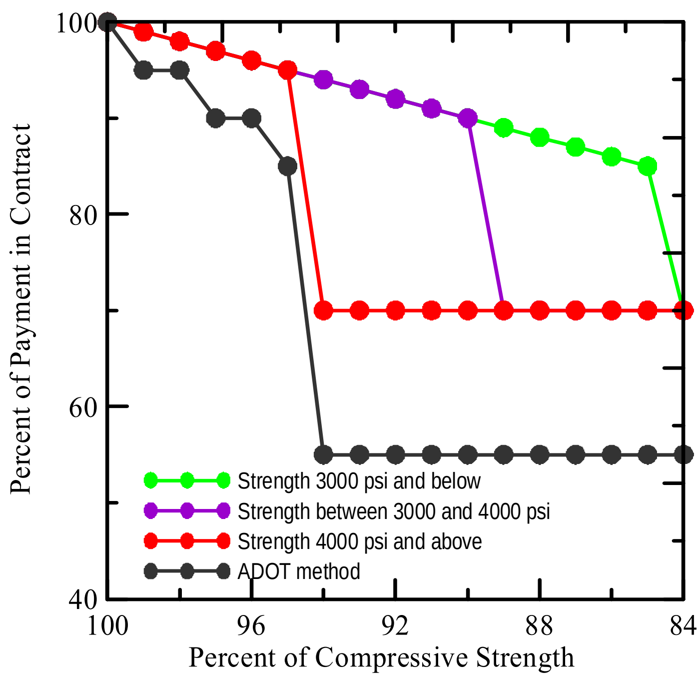


Figure 12. Comparison of the present ADOT Pay Factor equation (shown in black) and the proposed method which is dependant on the concrete strength class.

3.4 California Department of Transportation method

The California Department of Transportation (Caltrans) method is based on the average percent of strength of two cylinders by removing the improper one from the samples due to any evidence of inappropriate sampling, molding, or testing. The test cylinder will be molded, cured, and tested in conformance with the requirements of the California Test. The assumptions in the estimation for the Caltrans penalty are: Lot size = 100 cubic yards with 4 samples for each lot size. Unit cost = $150 per cubic yard. The penalty is calculated by the cost per cubic yard as shown in Table 11.

Table 11: Penalty Calculated by the Cost per Cubic Yard

Strength result (% of F'_c)	Penalty
95 - 100	$10.70/ cy
85 - 94	$15.29/ cy
< 85	Reject

Note: No single test if the sample is more than 327 cy

III. Discussion of Results

1. Comparing two different methods for the PWL based analysis of the FHWA method

The results are shown for three different scenarios (Series 1, 2, and 3). The acceptable quality level with Category II is more generous than the Kentucky OC curve. The starting point for 100% payment for the first method, the minimum required PWL = 65 while the required minimum PWL = 95 for the second method. An additional constraint is the value of the standard deviation. For the purpose of analysis, if the standard deviation is zero, then the appropriate value (to avoid a divide by zero error) of the standard deviation is assumed to be 0.000001. In addition, using the acceptable quality level with Category II does not provide the bonus or award. The positive penalty represents the bonus/award or the amount that the supplier can potentially accumulate due to consistently above-average strength values. In contrast, the negative penalty means the loss of payment since the strength of concrete is lower than the minimum required level. Zero penalties correspond to the full amount of payment.

To simplify the problem, some assumptions are applied to the penalty calculation for the rejected sublot: Lot size = 100 cubic yards and unit cost = $150 per cubic yard. Then the estimation of penalty for each unit in a rejected sublot is around $15,000. For the calculation of penalty or bonus, the lower limit is set to be the design strength (F'_c) and the upper limit is set to an arbitrary value such as 10,000 psi to make sure it would be higher than all the design strengths. The penalties calculated from the FHWA method are presented in the following tables for Series 1, 2, and 3 separately.

Table 12: Series 1.
The FHWA Penalty for both Kentucky OC Curve and Category II Pay Factor Methods.

Project	TRACs number	Supplier	Required strength	FHWA with Kentucky OC, $	FHWA with Pay factor category II, $
1	H576801	Rinker	4500	10,875	0
2	H552501	Sunshine Concrete	3000	1,610.6	0
3	H407601	Rinker	3500	2,250	0
4		Rinker material	4000	3,000	0
5	H416001C	Cambell Redi-mix	2500B	11,625	0
6			3500S	7,529	0
7	H319003C	McNeil Const. Co.	4000	5,398.9	0
8	H319003C	McNeil Const.	4000	5,212	0
9	H313401C	McNeil Const.	4000	13,226	0

Note: If any lot is rejected, the total penalty is computed as the cost of the lot.

Table 13: Series 2.
The Penalty from both the Kentucky OC and the Category II Methods

No	Supplier	Required strength	FHWA with Kentucky OC,$	FHWA with Pay factor category II,$
A11	Chandler Ready Mix	3000	2,625	0
A13		2500	4,125	0
A21		4000	-4,522.7	0
B11	Rinker	3500	7,125	0
B12		4000	2,250	0
B13		4500	7,875	0
B21		3000	3,000	0
B22		3500	-4,628.4	0
C11	Arizona Materials	4500	23,900	0
C12		2500	1,875	0
C13		4000	-123,230	-120,000
C21		3000	6,000	0
C22		3000	7,500	0
C23		3000	1,875	0
D12	Hanson Aggregates of AZ	4000	-4,183.7	0
D13		3500	6,402.4	0
D21		4000	9,000	0
D23		4000	313.8	0
E11	TPAC	5000	12,375	0
E12		5500	4,125	0
E13		5500	7,875	0
E21		4500	9,750	0
E22		5000	21,750	0
E23		6000	-228	0

Note: If any lot is rejected, the total penalty is computed as the cost of the lot.

The sensitivity of the specification to the penalty is investigated in the next step. In addition, the table above clearly shows that if there was a PWL-based method in place, then many of these problematic cases could have been identified during the construction phase. One observation is that the huge penalties in project E come from many rejected sublots. When the FHWA method is applied by converting the Q-value to the PWL, either q_l or q_u become 100 and 0. Finally, PWL is 0 and this lot size will be rejected.

To clearly understand the behavior of the PWL, the category II method was tested by varying the specification limits. Focusing on project E, the table below compares the FHWA with LSL = required strength and USL = 10,000 psi, with LSL and USL within ±2 sigma and ±6 sigma respectively, based on overall data. The results are different for these three sets of analyses. Some cases indicate the rejected sublot whereas the other criteria do not show the rejected sublot. This means that setting the USL and LSL too tight results in rejecting the sublot. The alternative to solving this problem is using the LSL as the required strength and setting the USL at a high value such as 10,000 psi or more.

Table 14: Pay Factor in the FHWA Method calculated using different LSL and USL

No	Supplier	Plant	Required strength	FHWA penalty with LSL = required strength and USL = 10,000	FHWA penalty with LSL and USL= CL ±6s overall σ	FHWA penalty with LSL and USL= CL ±2s overall σ
E11	TPAC	PHX	5000	0	0	-495,000
E12			5500	0	0	-165,000
E13			5500	0	-60,000	-315,000
E21		TUCSON	4500	0	0	-390,000
E22			5000	0	0	-870,000
E23			6000	0	0	-65,106

Note: If any lot is rejected, the total penalty is computed as the cost of the lot.

Table 15: Series 3. The Results for both Methods.

	Supplier	Required strength, psi	FHWA with Kentucky OC	FHWA with Pay factor category II
1	Wilson Wash	4500	-77,420	-62,521
2	Sandy Blevens	4500	-8,573.4	-1,743.9
3	Quail Springs	4500	-14,823	-3,020.9
4	Poison	4500	-6,151.2	0
5	Deveore	4500	-4,891.2	0
6	Apprentice	4500	-1,545.9	0

Note 1: If any lot is rejected, the total penalty is computed as the cost of the lot.

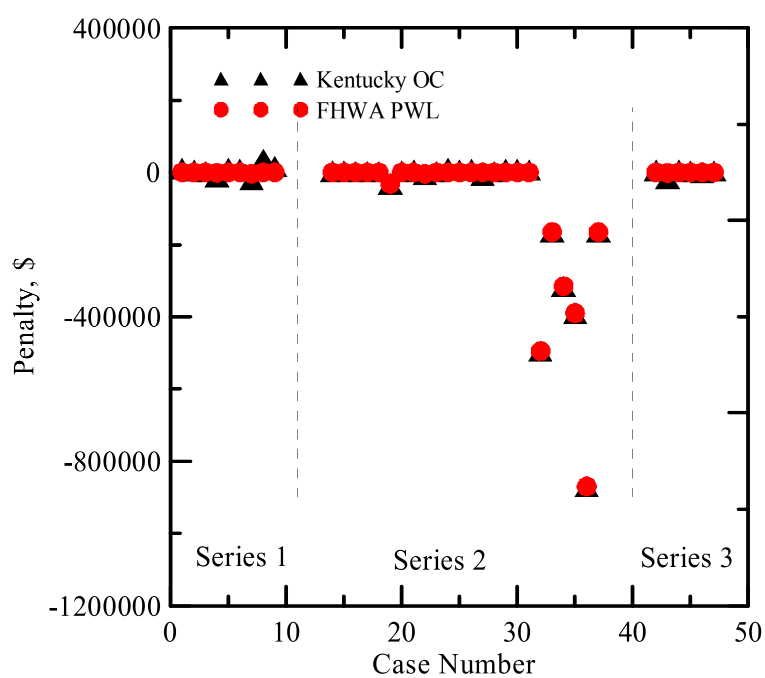


Figure 13 Comparison of two methods (FHWA PWL and Kentucky DOT) penalties for all series.

Figure 13 implies that the FHWA PWL method calculated by the Kentucky OC curve is more supplier friendly as compared to FHWA Category II. These two methods show the different direction in some cases. Finally, Table 13 in Series 2 illustrates that many problematic cases could be identified when the PWL based method is applied.

2. Sensitivity analysis of the PWL and the Q-value for FHWA method

To find the PWL, the Q-value is calculated and estimated from the table by a Specification Conformity Analysis. Subsequently, the P_U and P_L values are computed based on the value of Q and will lead to the estimation of the PWL. The Q-value is variable and sensitive to the PWL depending on the sample size (n = 3 to 10). The tolerance value (±0.25 and ±0.50) is respectively added to the Q-value and to the PWL table. Figure 14 represents the relationship between the Q-value and the PWL. Note that when the Q-value is sufficiently low, one cannot reduce it further such that negative values are obtained. In order to circumvent the problem, both the P_U and P_L values correspond to 100 minus the table value for P_U and P_L.

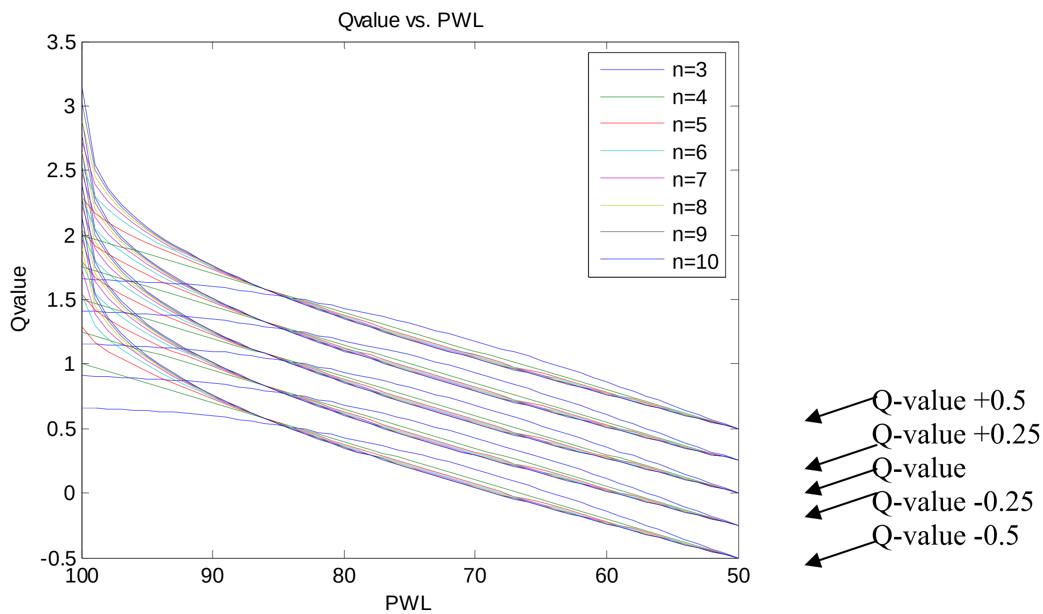


Figure 14 Plot of Relationship between Q-value and PWL

For the FHWA method, each lot is assumed to have four sublots or four sample sizes (measured in cubic yards). To understand this behavior clearly, the sample size of four is explored by adding the small tolerance value (+0.05, +0.10, +0.15, and +0.2) to the Q-value. The result is shown in Figure 15 and Figure 16. It is noted that in Table 16, the values of the lower limit and upper limit are set to be 2000 and 6000 psi respectively. If other limits (such as F'_c for the lower limit) were used, we could have seen different results. The details of the case numbers are presented in Appendix F.

Table 16: Pay Factors in FHWA Category II Method calculated using different Q's

Case Number	Pay Factor with Category II ($)				
	Q+0	Q+0.05	Q+0.1	Q+0.15	Q+0.2
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	-726	-1463	-2289	-2863	-3789
5	0	0	0	0	0
6	0	0	0	0	0
7	-3275	-4337	-4875	-6468	-61231
8	0	0	0	0	0
9	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
19	-315000	-315000	-315000	-315000	-315000
20	0	0	0	0	0
21	0	0	0	0	0
22	-3381	-4520	-6304	-7697	-9562
23	0	0	0	0	0
24	0	0	0	0	0
25	0	0	0	0	0
26	0	0	0	0	0
27	0	0	0	0	-404
28	0	0	0	0	0
29	0	0	0	0	0
30	0	0	0	0	0
31	0	0	0	0	0
32	-495000	-495000	-495000	-495000	-495000
33	-165000	-165000	-165000	-165000	-165000
34	-315000	-315000	-315000	-315000	-315000
35	-390000	-390000	-390000	-390000	-390000
36	-870000	-870000	-870000	-870000	-870000
37	-165000	-165000	-165000	-165000	-165000
42	0	0	0	0	0
43	-1505	-2405	-2905	-4382	-5873
44	0	0	0	0	0
45	0	0	0	0	0
46	0	0	0	0	0
47	0	0	0	0	0

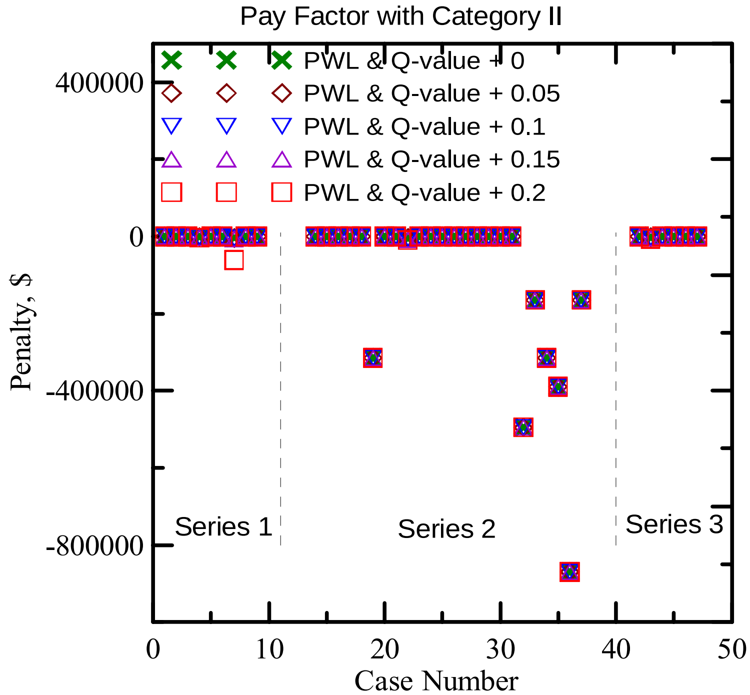


Figure 15 Plot of Pay Factor (Penalty) between Q-value and the PWL by Category II

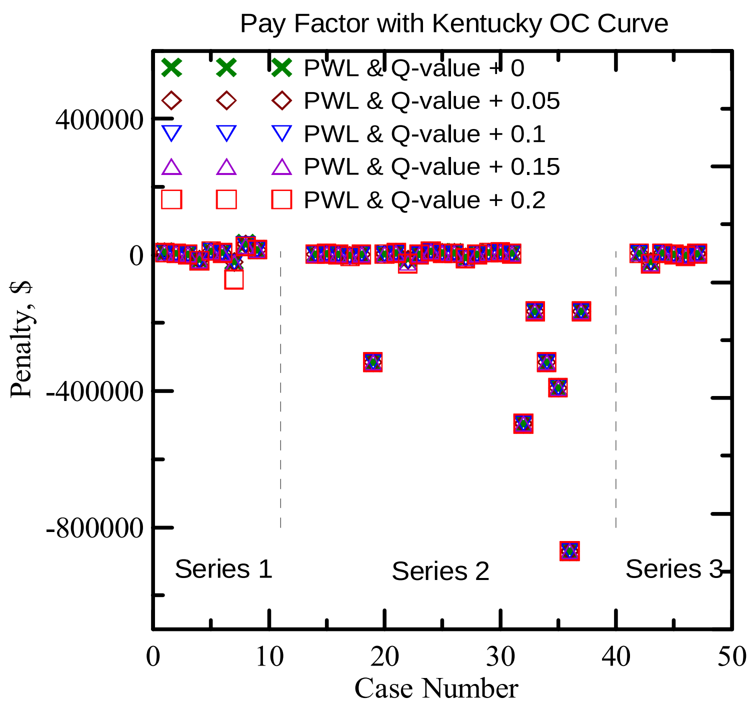


Figure 16 Plot of Pay Factor (Penalty) between Q-value and PWL by the Kentucky OC Curve

Table 17: Pay Factors in the FHWA Kentucky OC Method calculated by using different Q's

Case Number	Pay Factor with Kentucky OC Curve				
	Q+0	Q+0.05	Q+0.1	Q+0.15	Q+0.2
1	8775	8410	8004	7576	7070
2	5233	5168	5102	5037	4913
3	2250	2250	2250	2250	2250
4	-12450	-13422	-14484	-15537	-16607
5	11625	11625	11625	11625	11625
6	7599	7378	7128	6878	6589
7	-18797	-20275	-21764	-23486	-71368
8	34000	32215	30251	27979	25557
9	15750	15750	15750	15750	15750
14	2625	2625	2625	2625	2625
15	4125	4125	4125	4125	4125
16	2250	2250	2250	2250	2250
17	-249	-1009	-1811	-2752	-3686
18	2250	2250	2250	2250	2250
19	-315000	-315000	-315000	-315000	-315000
20	3000	3000	3000	3000	3000
21	6750	6746	6681	6590	6492
22	-10320	-13628	-17160	-20892	-24951
23	1875	1875	1875	1875	1875
24	10500	10500	10500	10500	10500
25	6000	6000	6000	5970	5905
26	6402	6107	5732	5321	4884
27	-6929	-7429	-7929	-8429	-9029
28	2250	2250	2250	2250	2250
29	7500	7500	7440	7375	7310
30	8844	8730	8549	8286	8005
31	5362	5143	4893	4643	4356
32	-495000	-495000	-495000	-495000	-495000
33	-165000	-165000	-165000	-165000	-165000
34	-315000	-315000	-315000	-315000	-315000
35	-390000	-390000	-390000	-390000	-390000
36	-870000	-870000	-870000	-870000	-870000
37	-165000	-165000	-165000	-165000	-165000
42	5250	5250	5250	5250	5250
43	-18532	-20208	-21789	-23706	-25465
44	5625	5625	5625	5625	5625
45	2423	2358	2251	2101	1933
46	-530	-1007	-1568	-2202	-2908
47	4125	4125	4125	4125	4125

3. Comparing Current and New ADOT methods

Table 18: Series 1. Comparison of Pay Factors for Current and New ADOT Methods

TRAC No	TRACs number	Supplier	Total Cost, $	Penalty of New Method	% Penalty of the Total Cost	Penalty of Current Method	% Penalty of the Total Cost
1	H576801	Rinker	435,000	0	0.0	0	0.0
2	H552501	Sunshine concrete	210,000	-2250	1.1	-6750	3.2
3	H407601	Rinker	90,000	0	0.0	0	0.0
4		Rinker material	120,000	0	0.0	0	0.0
5	H416001C	Cambell Redi-mix	465,000	0	0.0	0	0.0
6			345,000	0	0.0	0	0.0
7	H319003C	McNeil Const. Co.	345,000	0	0.0	0	0.0
8			2,085,000	0	0.0	0	0.0
9	H313401C	McNneil Const. Co.	630,000	0	0.0	0	0.0

Table 19: Series 2. Comparison of Pay Factors for Current and New ADOT methods

Project No	Name	Supplier	Total Cost	Penalty of New ADOT Method	% Penalty of the Total Cost	Penalty of Current ADOT Method	% penalty of the total cost
1	A11	Chandler Ready Mix	10,5000	0	0.0	0	0.0
2	A13		165,000	0	0.0	0	0.0
3	A21		750,000	0	0.0	0	0.0
4	B11	Rinker	285,000	0	0.0	0	0.0
5	B12		90,000	0	0.0	0	0.0
6	B13		315,000	0	0.0	0	0.0
7	B21		120,000	0	0.0	0	0.0
8	B22		270,000	-1500	0.6	-6750	2.5
9	C11	Arizona Materials	1,080,000	-600	0.1	-1500	0.1
10	C12		75,000	0	0.0	0	0.0
11	C13		420,000	-4100	1.0	-21750	5.2
12	C21		240,000	0	0.0	0	0.0
13	C22		300,000	0	0.0	0	0.0
14	C23		7,5000	0	0.0	0	0.0
15	D12	Hanson Aggregates of AZ	90,000	-150	0.2	-750	0.8
16	D13		300,000	0	0.0	0	0.0
17	D21		360,000	0	0.0	0	0.0
18	D23		255,000	0	0.0	0	0.0
19	E11	TPAC	495,000	0	0.0	0	0.0
20	E12		165,000	0	0.0	0	0.0
21	E13		315,000	0	0.0	0	0.0
22	E21		390,000	0	0.0	0	0.0
23	E22		870,000	0	0.0	0	0.0
24	E23		165,000	-450	0.3	-1500	0.9

Table 20: Series 3. Comparison of Pay Factors for Current and New ADOT Methods

Bridge Project	Supplier	Total Cost	Penalty of New Method	% Penalty of the Total Cost	Penalty of Current Method	% penalty of the total cost
1	Wilson Wash	210,000	-10950	5.2	-18750	8.9
2	Sandy Blevens	285,000	-4500	1.6	-6750	2.4
3	Quail Springs	225,000	-5250	2.3	-21750	9.7
4	Poison	105,000	-4500	4.3	-6750	6.4
5	Deveore	255,000	-1200	0.5	-16500	6.5
6	Apprentice	165,000	-750	0.5	-15000	9.1

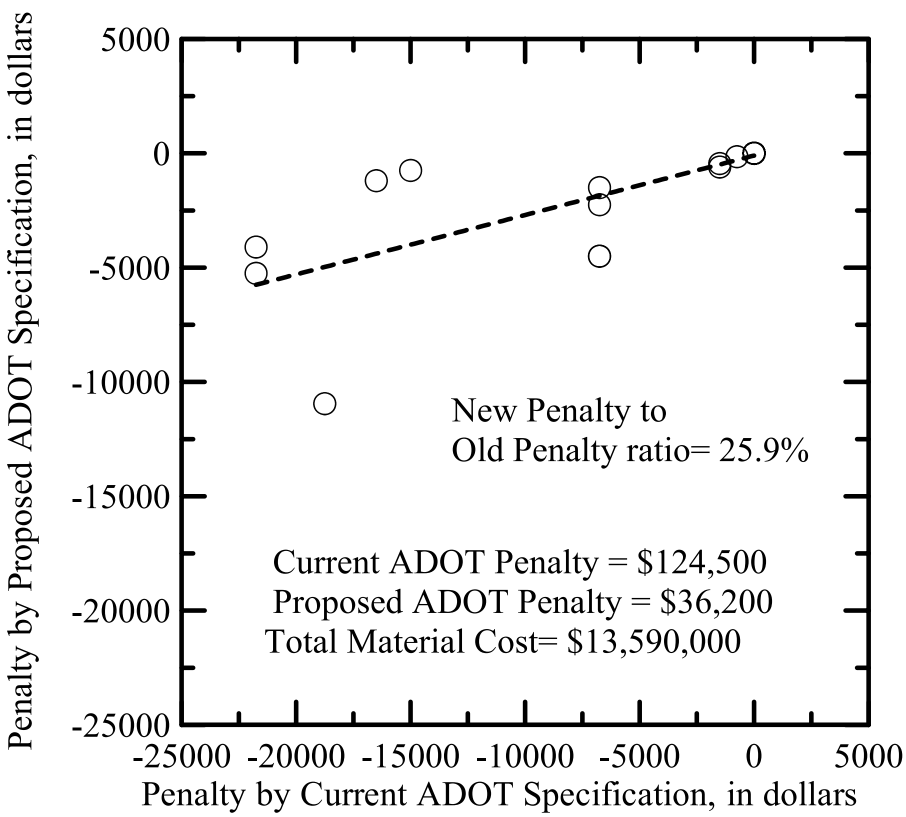


Figure17 Penalty from both ADOT methods

The penalty of the two ADOT methods from all series is plotted in Figure17. A straight line relationship with a 45 degree angle and a zero intercept represents the same amount of penalty of both ADOT methods. A slope steeper than 1:1 value means that the penalty from the proposed ADOT method is higher than the current ADOT method. On the other hand, a slope flatter than 1:1 implies that the proposed ADOT penalty is less than the current ADOT penalty, which is the case here.

4. Exploring the Comparison of Four Different Methods

Applying these four methods, the penalty is calculated based on the following data: lot size = 100 cubic yards and unit cost = $150 per cubic yards. The sample is assumed to be four (each lot has four samples). Both sides of specification limits are selected. The upper specification is 6000 and the lower specification is 2000. The results are shown in Table 21.

Table 21: Series 1. Comparison of Pay Factors for the different Methods

Project	TRACS number	Supplier	Required strength	FHWA with Pay Factor Category II	Current ADOT	New ADOT	CA
1	H576801	Rinker	4500	0	0	0	0
2	H552501	Sunshine Concrete	3000	0	-6750	-2250	-6116
3	H407601	Rinker	3500	0	0	0	0
4		Rinker Material	4000	0	0	0	0
5	H416001C	Cambell Redi-mix	2500B	0	0	0	0
6			3500S	0	0	0	0
7	H319003C	McNeil Const. Co.	4000	0	0	0	0
8			4000	0	0	0	0
9	H313401C	McNeil Const. Co.	4000	0	0	0	0

Note: If any lot is rejected, the total penalty is computed as the cost of the lot.

Table 22: Series 2. Comparison of Pay Factors for different Methods

No	Supplier	Require strength	FHWA with Pay factor category II	Current ADOT	New ADOT	CA
A11	Chandler Ready Mix	3000	0	0	0	0
A13		2500	0	0	0	0
A21		4000	0	0	0	0
B11	Rinker	3500	0	0	0	0
B12		4000	0	0	0	0
B13		4500	0	0	0	0
B21		3000	0	0	0	0
B22		3500	0	-6750	-1500	-6116
C11	Arizona Materials	4500	0	-1500	-600	-4280
C12		2500	0	0	0	0
C13		4000	-120000	-21750	-4100	-20792
C21		3000	0	0	0	0
C22		3000	0	0	0	0
C23		3000	0	0	0	0
D12	Hanson Aggregates of AZ	4000	0	-750	-150	-4280
D13		3500	0	0	0	0
D21		4000	0	0	0	0
D23		4000	0	0	0	0
E11	TPAC	5000	0	0	0	0
E12		5500	0	0	0	0
E13		5500	0	0	0	0
E21		4500	0	0	0	0
E22		5000	0	0	0	0
E23		6000	0	-1500	-450	-4280

Note: If any lot is rejected, the total penalty is computed as the cost of the lot.

Table 23: Series 3. Comparison of Pay Factors for different Methods

	Supplier	Require strength	FHWA with Pay factor category II	Current ADOT	New ADOT	CA
1	Wilson Wash	4500	-62521	-18750	-10950	-29352
2	Sandy Blevens	4500	-1743.9	-6750	-4500	-6116
3	Quail Springs	4500	-3020.9	-21750	-5250	-10396
4	Poison	4500	0	-6750	-4500	-6116
5	Deveore	4500	0	-16500	-1200	-8560
6	Apprentice	4500	0	-15000	-750	-4280

Note: If any lot is rejected, the total penalty is computed as the cost of the lot.

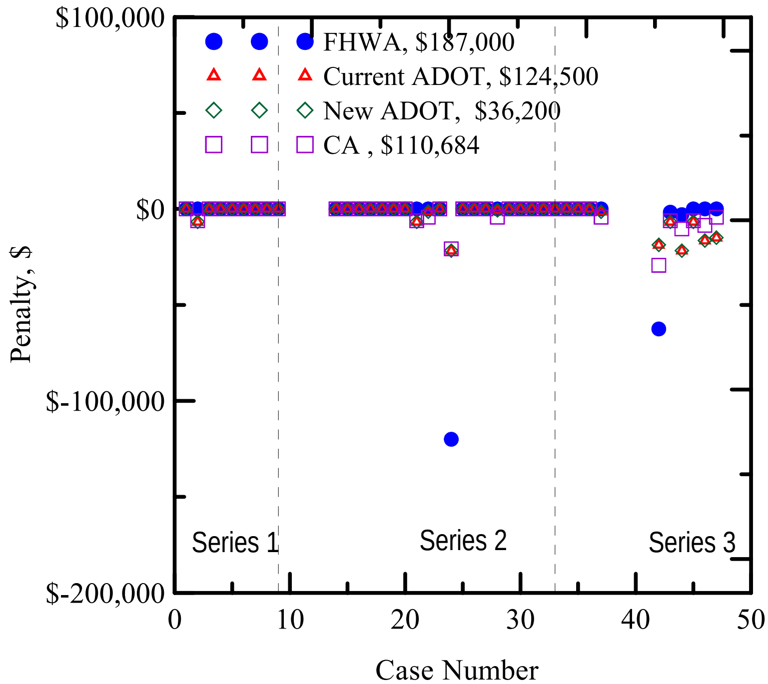


Figure 18 Plot Comparing four methods for all series

Figure18 presents that the FHWA penalty method is signifigant in Series 2. This can be attributed to the chosen specification limits (USL = 10,000 psi and LSL = F'_c). Other methods look similar and show the same direction. Considering the project cost, the percentages of the total penalty for all four methods are low compared to the total material cost of each series. It can be observed that the penalty given by FHWA is higher than the other methods; however, the new ADOT method gives the lowest penalties. The values in Table 24 show the summation of all the data in each series.

Table 24: All Series. Comparison of Pay Factors for different Methods

Case	Total Cost of All the Lots in the Series, $	Total Penalty from FHWA, $	Total Penalty from FHWA, %	Total Penalty from New ADOT, $	Total Penalty from New ADOT, %	Total Penalty from Current ADOT, $	Total Penalty from Current ADOT, %	Total Penalty from CA, $	Total Penalt y from CA, %
Series 1	4,725,000	0	0	-2,250	0.05	-6,750	0.14	-6,116	0.13
Series 2	7,620,000	-120,000	1.57	-6,800	0.09	-32,250	0.42	-39,748	0.52
Series 3	1,245,000	-67,285	5.40	-27,150	2.18	-85,500	6.87	-64,820	5.21
Total	13,590,000	-187,285	1.38	-36,200	0.27	-124,500	0.92	-110,684	0.81

IV. Conclusions

- A majority of the samples evaluated meet or exceed the strength requirements specified for the ADOT jobs. The overall process is satisfied, except for Series 3.

- There are excessive variations in the trends of the data which do not correlate with the specified strength of the concrete and the areas of its applications. There are potential opportunities to reduce the average and standard deviations of the strength data. Reduction of the mean strength values delivered at the expense of better quality control will translate into significant raw materials savings.

- The FHWA-PWL penalty is based on many factors such as the Q-value table and the specification's upper and lower limit. These factors lead to the rejection of a sublot. This means that the FHWA approach should be employed carefully because of the sensitivity of the method.

- In cases where an entire sublot is rejected, certain assumptions were applied to the penalty calculation. For example, lot size = 100 cubic yards and unit cost = $150 per cubic yard. Then the estimation of penalty for each rejected sublot is around $15,000. Such calculations may affect the comparison of the various methodologies used.

- For the TRACs number samples (Series 1), the FHWA-PWL method with Pay Factor Category II resulted in two potential penalties, whereas there was only one potential penalty for the other methods. Nevertheless, the total penalties for all four methods are quite low when the total costs are considered ($0, $6,750, $2,250 and $6116 for FHWA with Pay Factor Category II, current ADOT, new ADOT, and CA methods, respectively).

- In the case of the randomly selected samples (Series 2), the FHWA method with Pay Factor Category II gave a 1.57% penalty of the total costs, the current ADOT and CA methods gave an average of 0.45% penalty, while the new ADOT method gave the lowest penalty which was 0.09% of the total costs.

- In the six bridge cases (Series 3), all cases had lots rejected by the current ADOT, new ADOT, and CA methods, although the FHWA method with Pay Factor Category II showed only three cases that were penalized. The penalties given by FHWA, current ADOT, and CA methods were similar and averaged 6% of the total costs. The penalty from the new ADOT method was the lowest and resulted in a 2.2% penalty.

- The estimation of pay factor by two different methods shows that they are quite similar. The PWL method which was computed by the Kentucky OC curve was generally friendlier to the supplier compared to the Category II method. In addition, the Kentucky OC curve provided an award or bonus to the supplier whereas there was no extra payment by using Category II. On the other hand, the required PWL strength for the Category II method is 65%, but 95% to get the full payment by the Kentucky OC curve.

- The average cost comparisons between the current and proposed ADOT equations indicate that the approximate penalties in the new ADOT method are in the range of 26% of the present penalty levels.

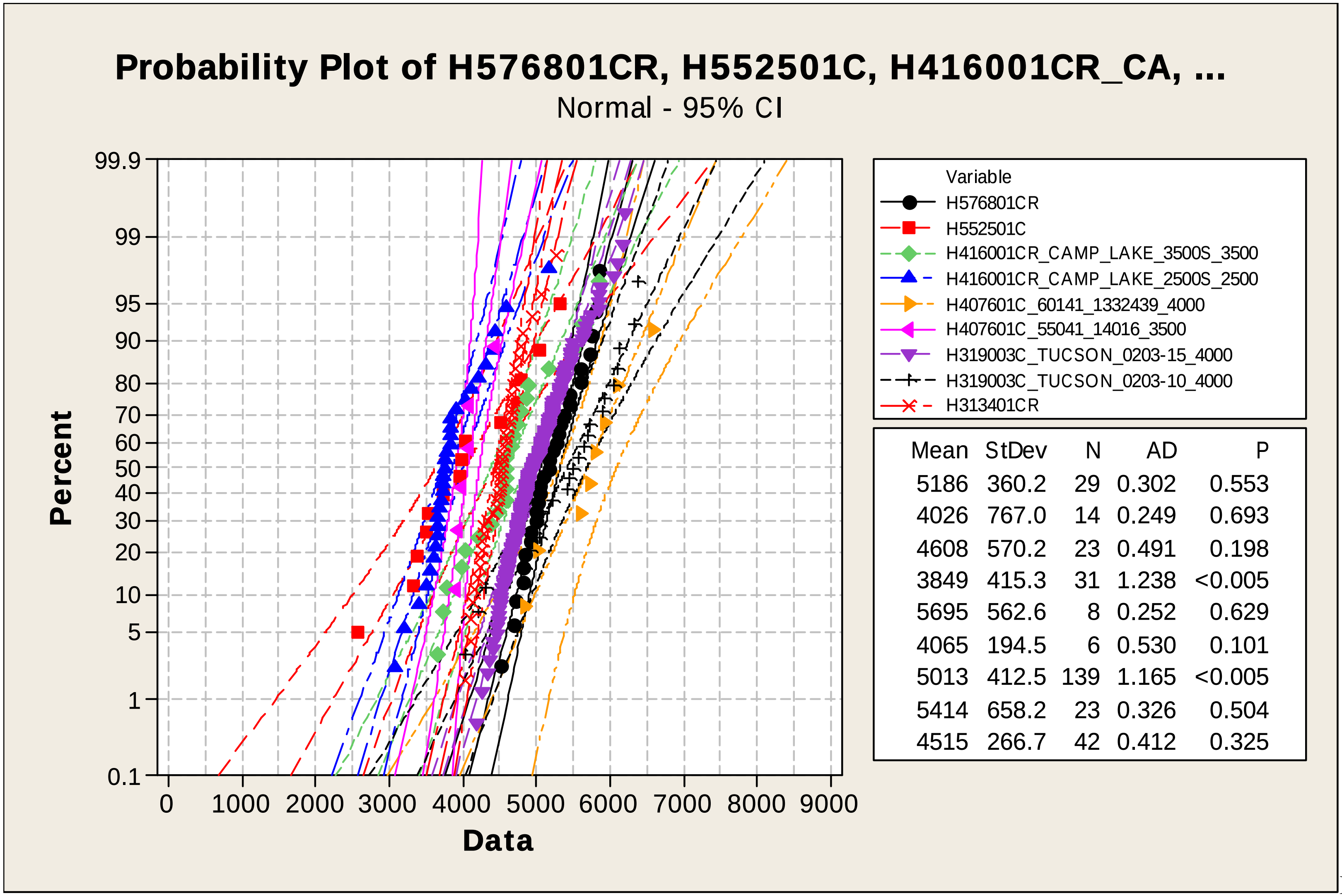
- Comparing the current and proposed ADOT methods, the penalties were assessed in all six bridge cases supplied by the ADOT/ARPA committee. The average level of penalty was in the range of 6.9%. This level of penalty could be reduced to 2.2% upon adoption of the new ADOT cost factor policy.

- The total amount of penalties in comparison to the cost of the projects is insignificant. Out of total materials cost of $13,590,000 for the projects studied, the total penalties are $124,000 (0.91% of total) and $36,200 (0.26% of total) depending on the use of present or proposed ADOT formulas, respectively.

- The FHWA method presents a higher penalty than the other methods (1.38% of the total cost of the projects) whereas the CA method shows a lower penalty (0.81%). The huge penalty is related to the rejection of several sublots. The penalties are less than 1% for current ADOT, proposed ADOT, and CA methods.

- The proposed ADOT method seems to be friendly to the supplier and provide a stable penalty. The 0.27% penalty is slightly lower than the current ADOT method (0.92%). Applying these methods with quality control criteria would help in enhancing concrete on jobsites with less out-of-control strength and thus obtaining required strength and quality with less materials consumption.

APPENDIX A (Probability plots) (Note that the labeling for different series in the following pages are in Appendix F)



F

Figure A1 Probability Plot for Series 1

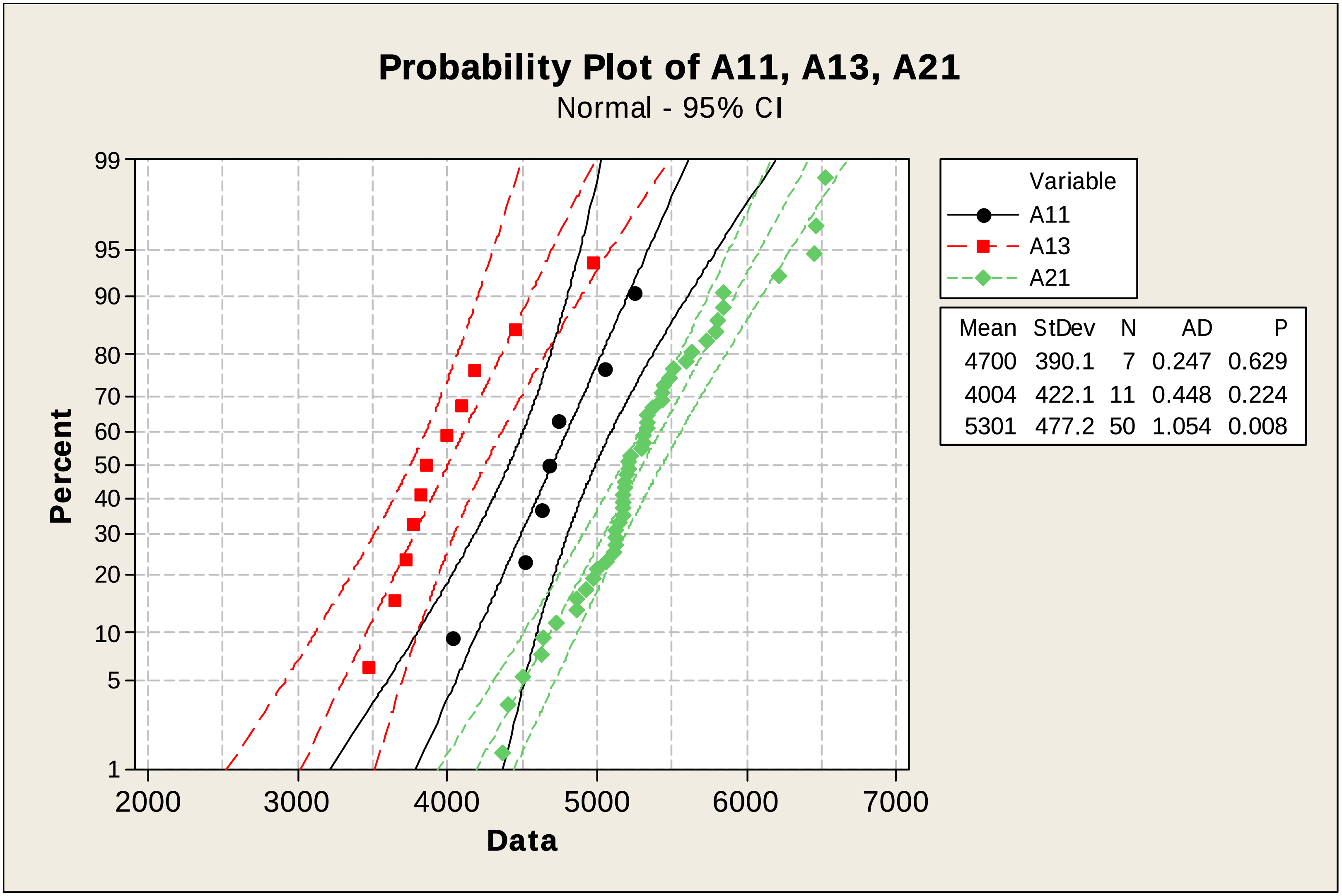


Figure A2 Probability plot for Project A: A11, A13 and A21

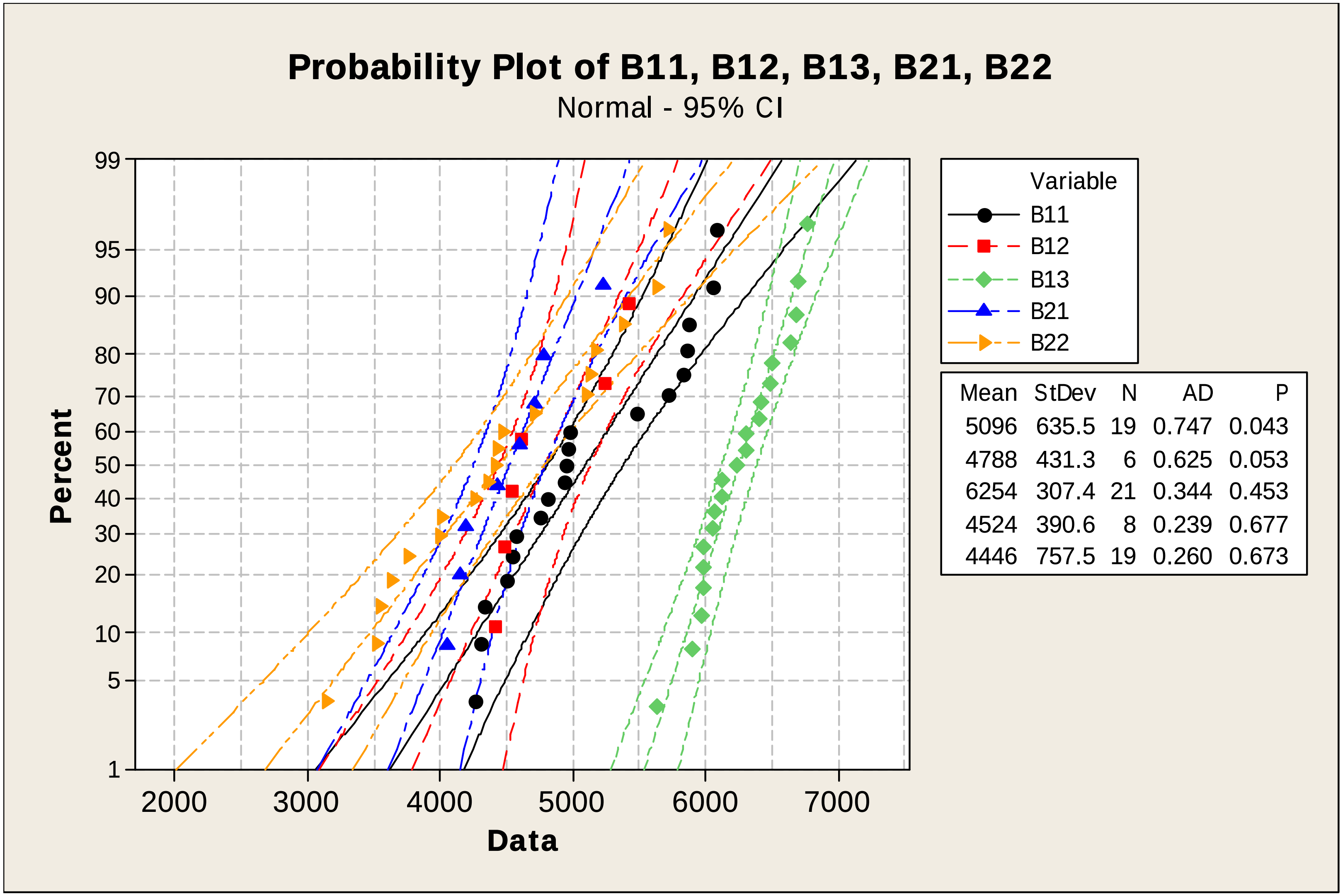


Figure A3 Probability plot of Project B: B11, B12, B13, B21 and B22

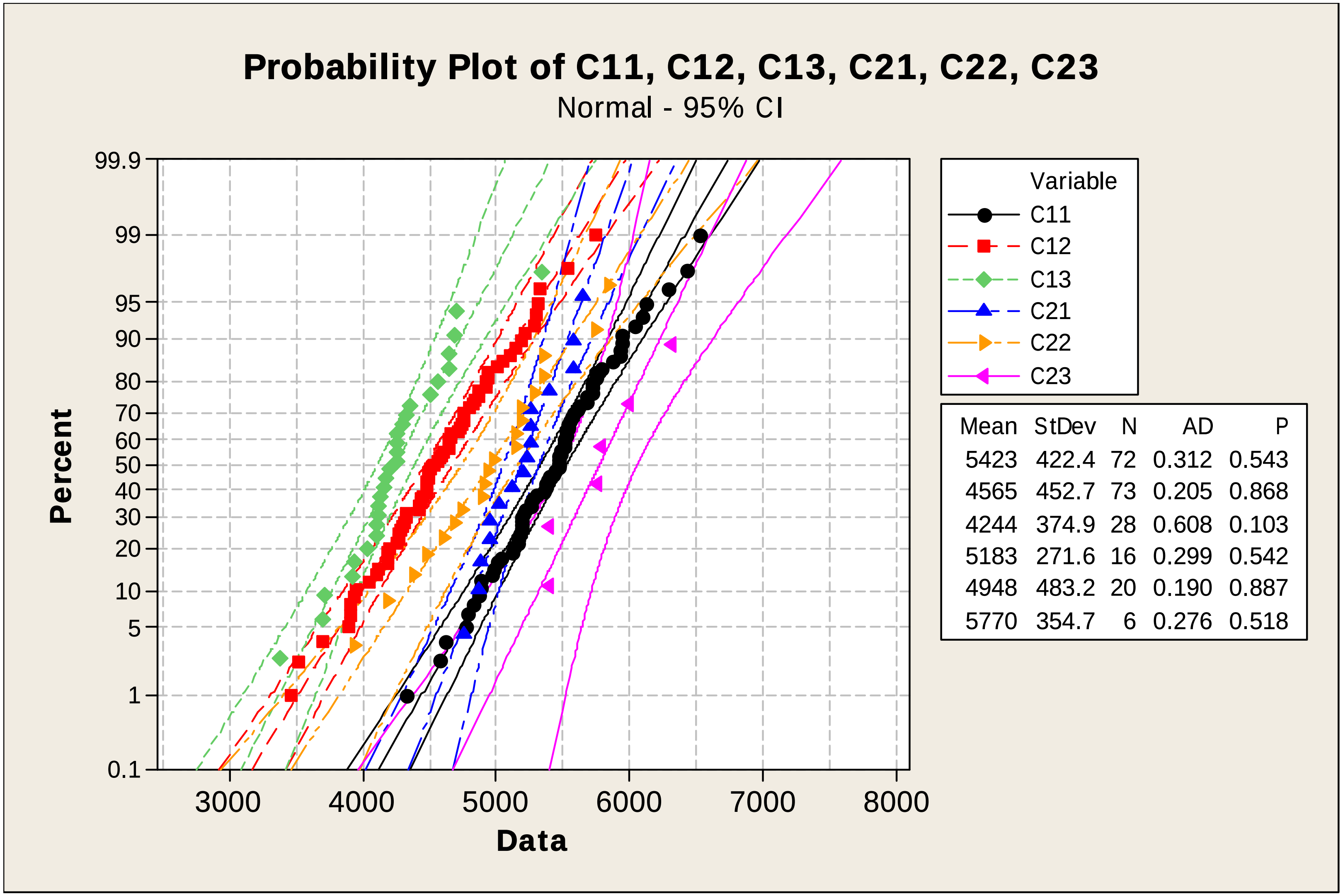


Figure A4 Probability plot of Project C: C11, C12, C13, C21, C22 and C23

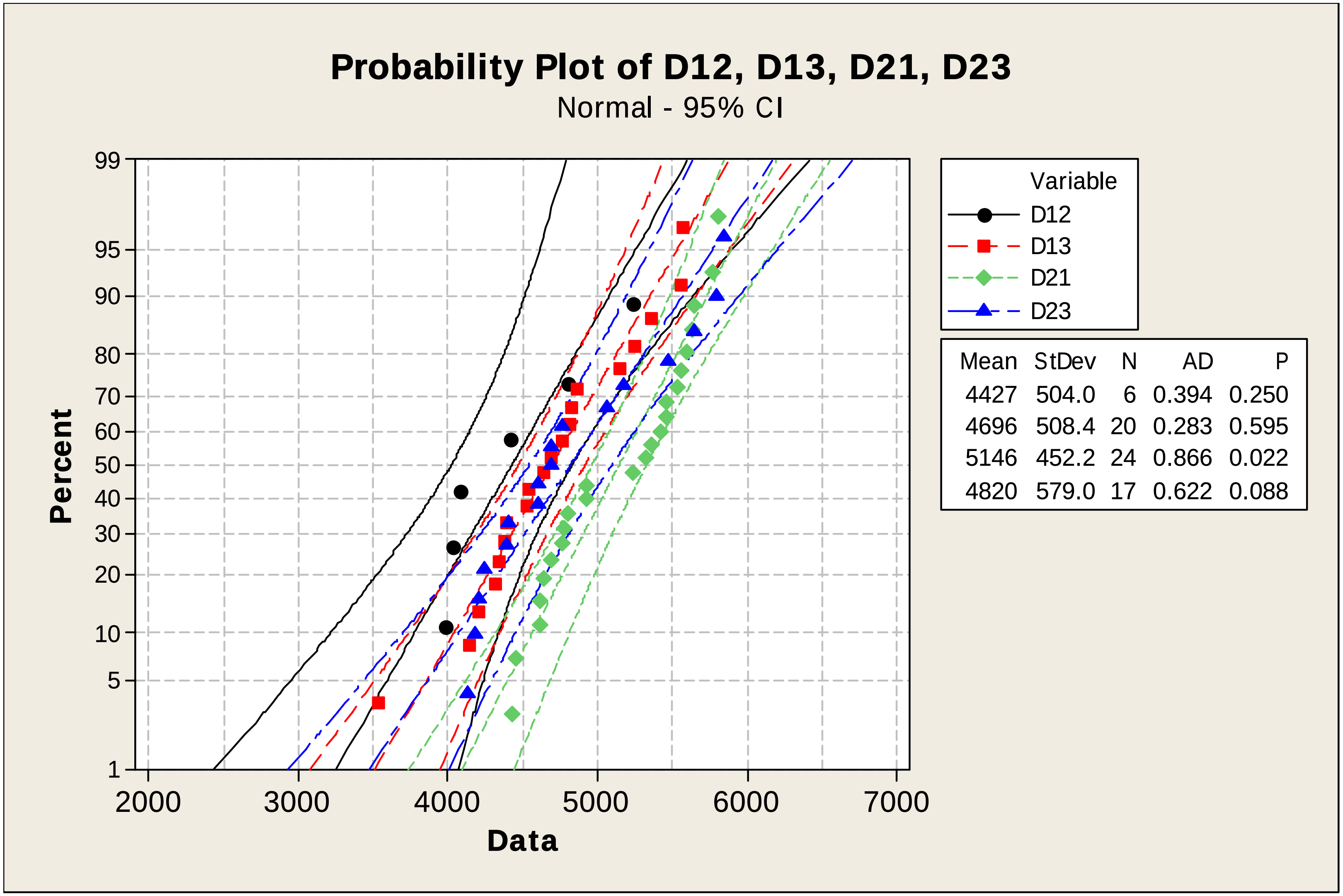


Figure A5 Probability plot of Project D: D12, D13, D21 and D23

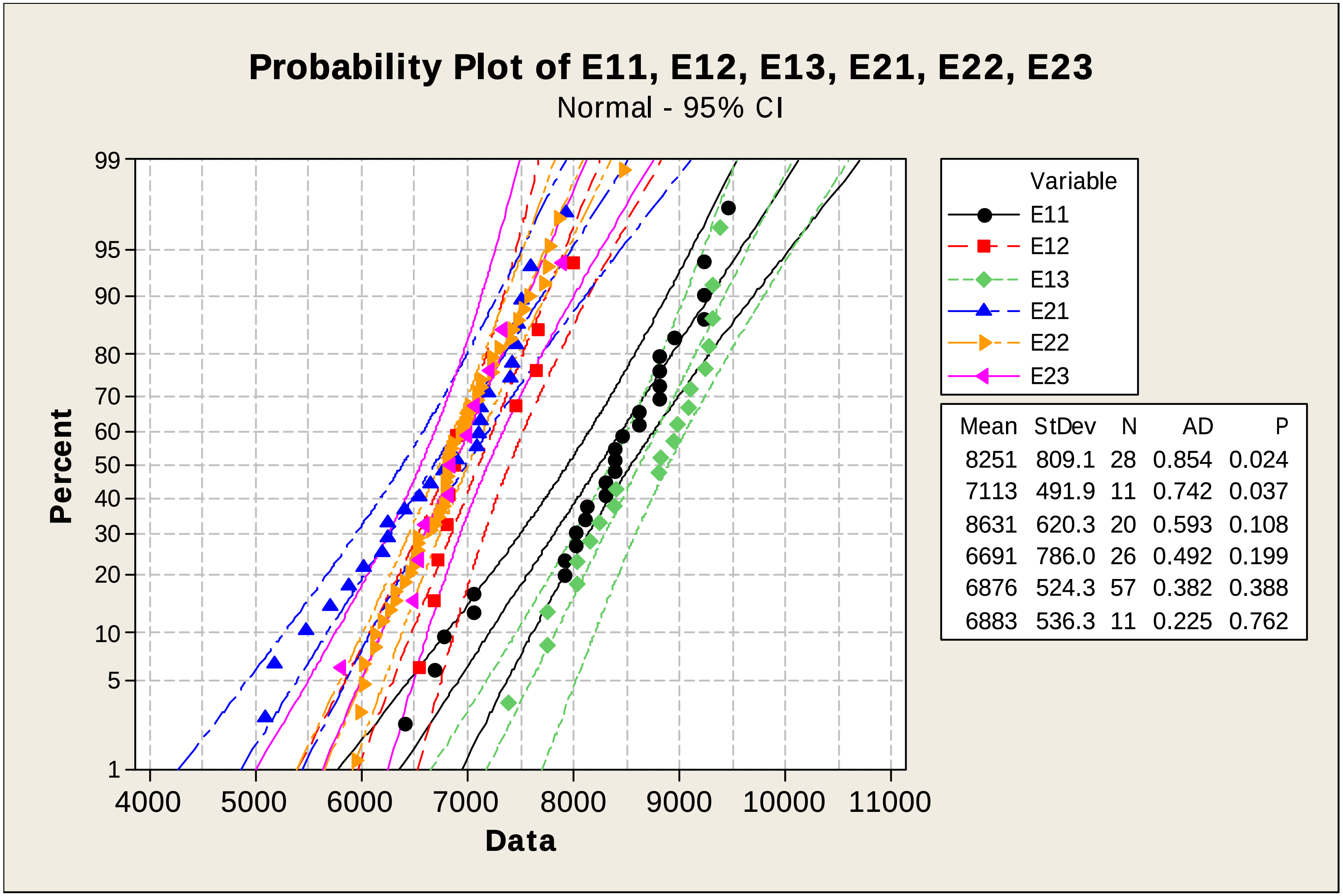


Figure A6 Probability plot of Project E: E11, E12, E13, E21, E22 and E23

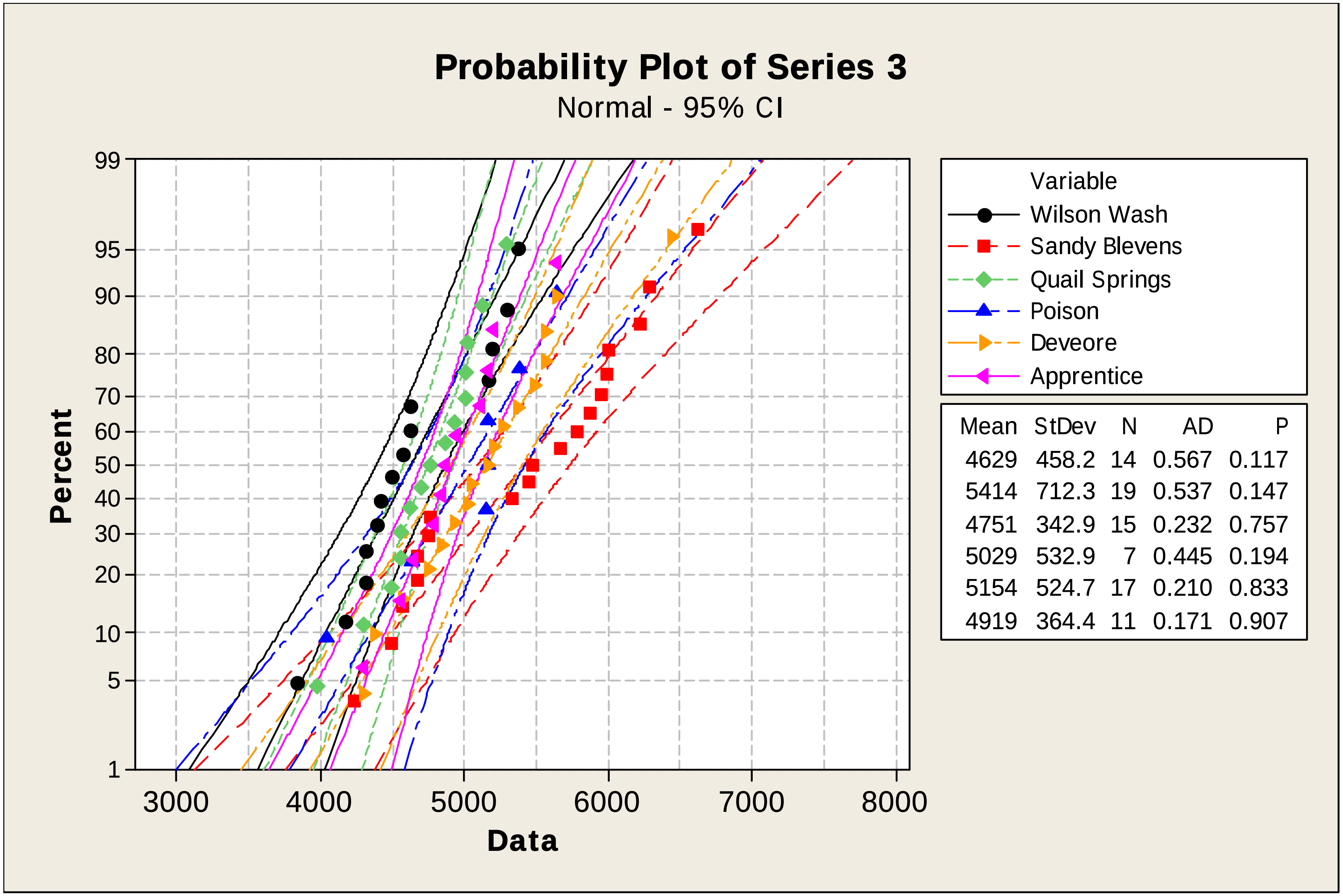
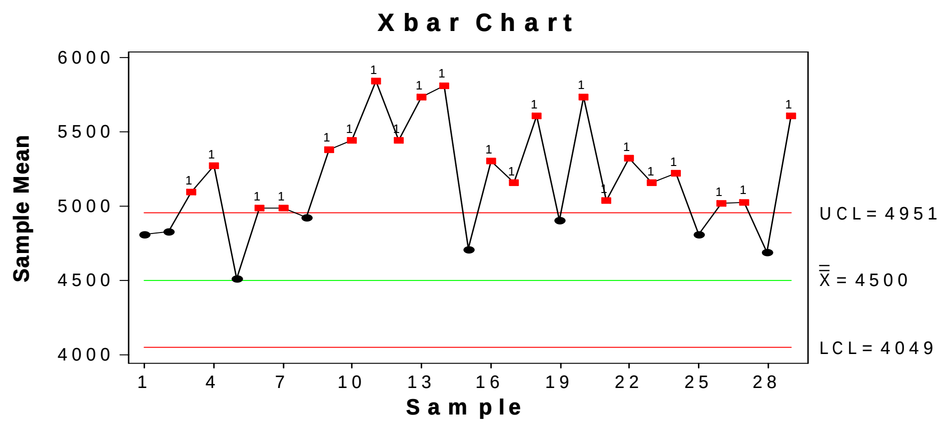


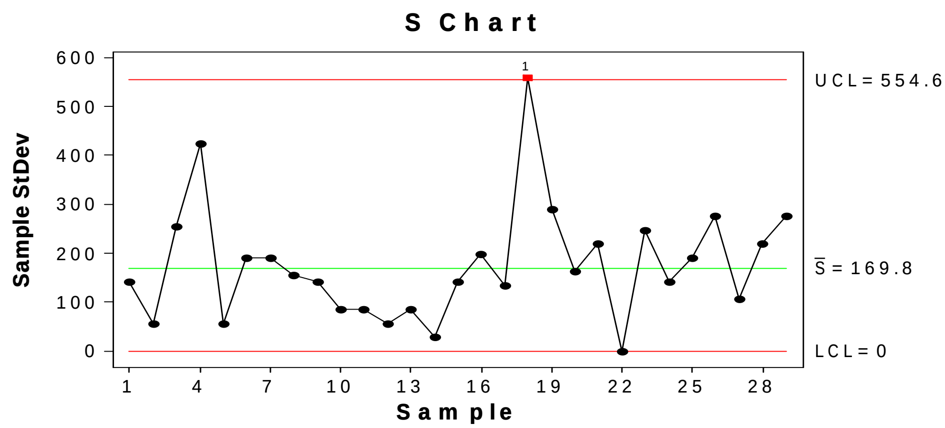
Figure A7 Probability plot for Series 3

APPENDIX B (X bar-S charts for Series 1)

Note: in the following pages, the top graph shows the X bar chart, which includes the current ADOT criterion setting F'_c as the lower limit (LCL) equal to the X bar. The bottom graph shows the S charts for modified ACI-214 second criterion assuming $F'_{cr} = F'_c + \frac{s.z}{\sqrt{n}}$ is the mean ($\overline{X}$).

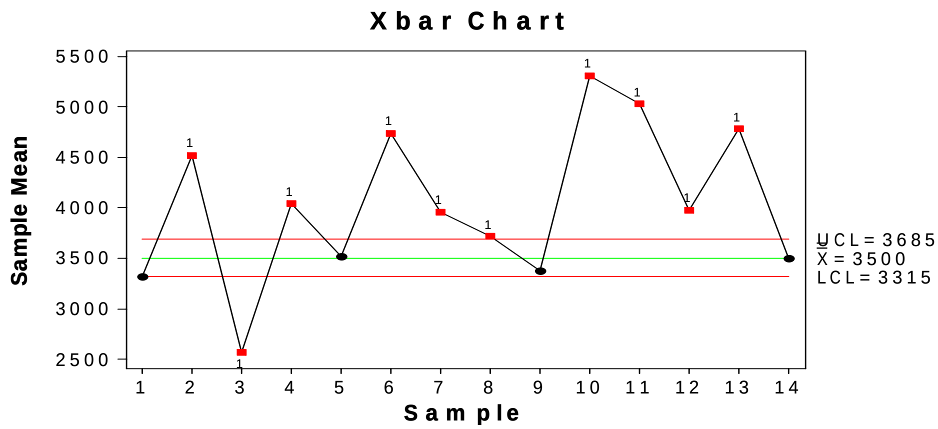
Figure B1. TRACs number: H576801C

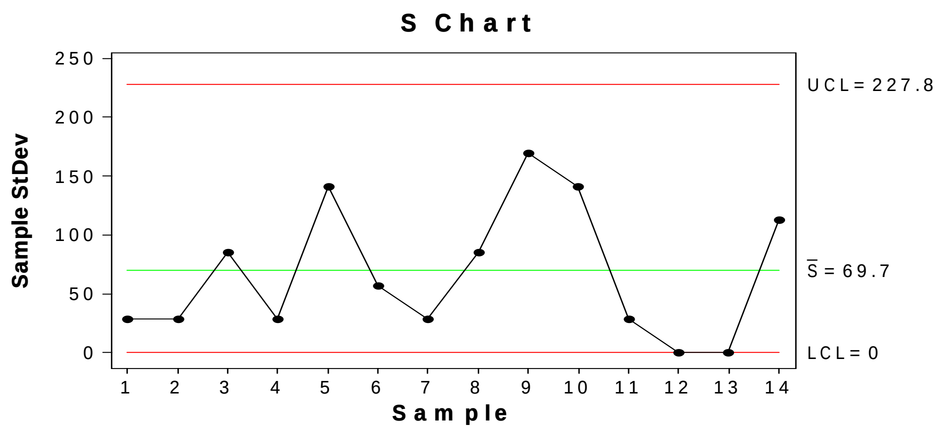




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

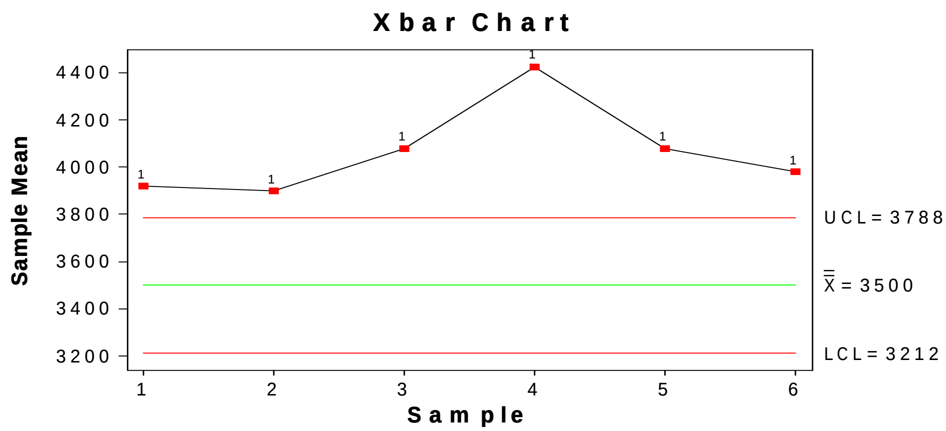
Figure B2. TRACs number: H552501C

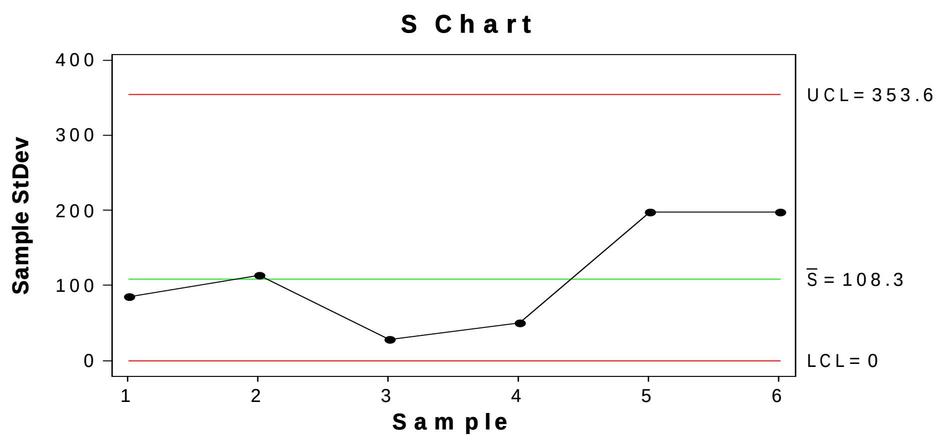




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

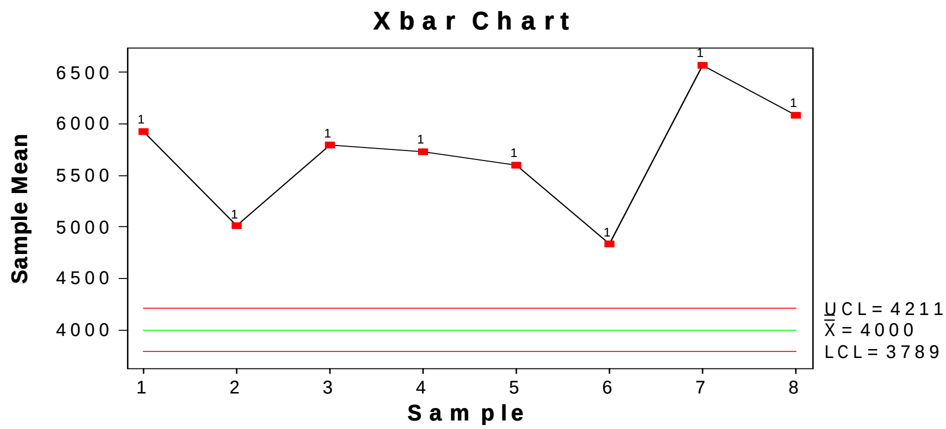
Figure B3. TRACs number: H407601C from plant 55041 and mix specification 14016

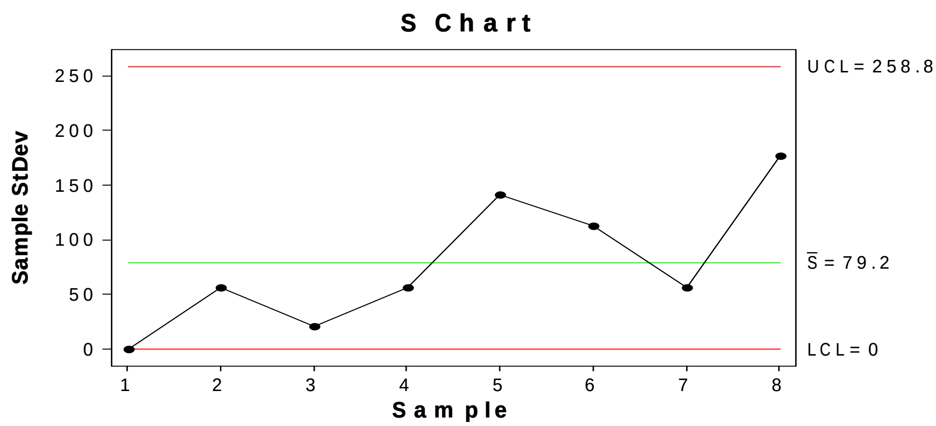




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

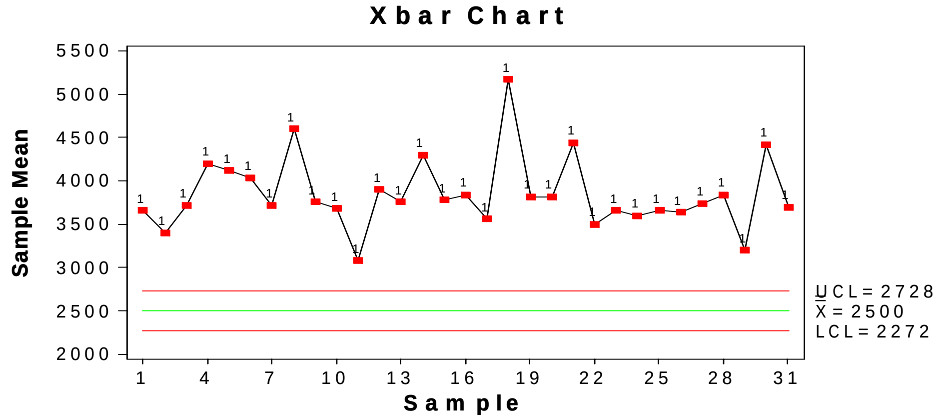
Figure B4. TRACs number: H407601C from plant 60141and mix specification 1332439.

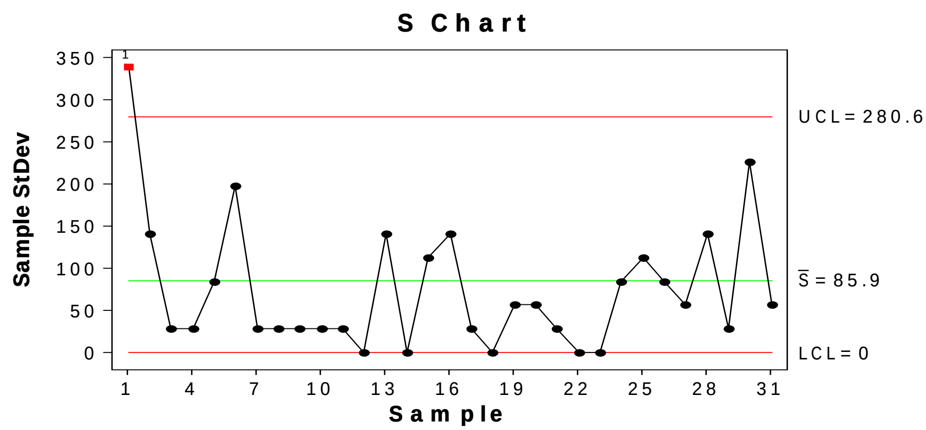




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

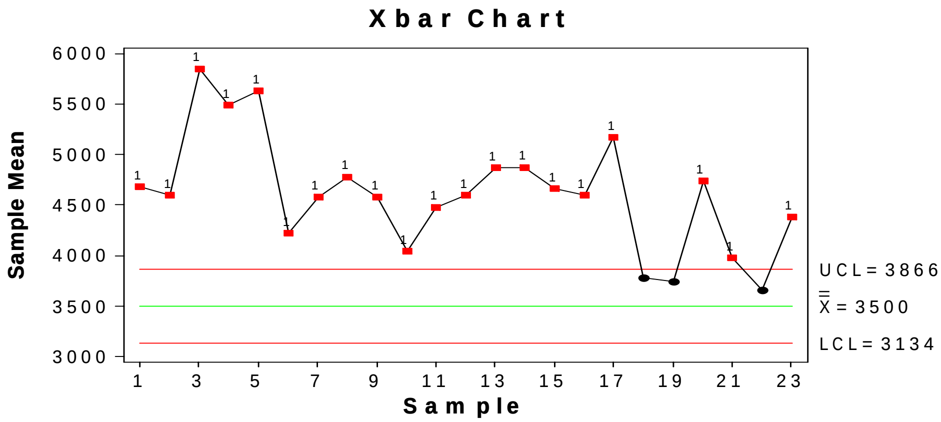
Figure B5. TRACs number: H416001C from the Lake Havasu plant and mix specification 2500S

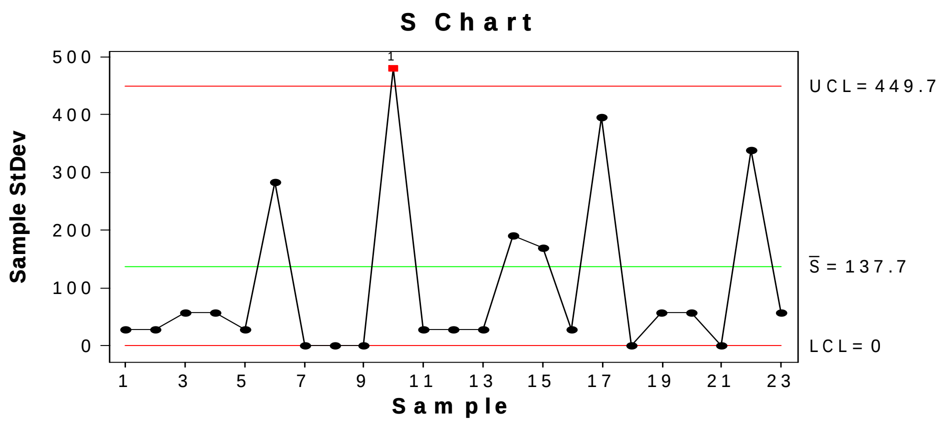




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

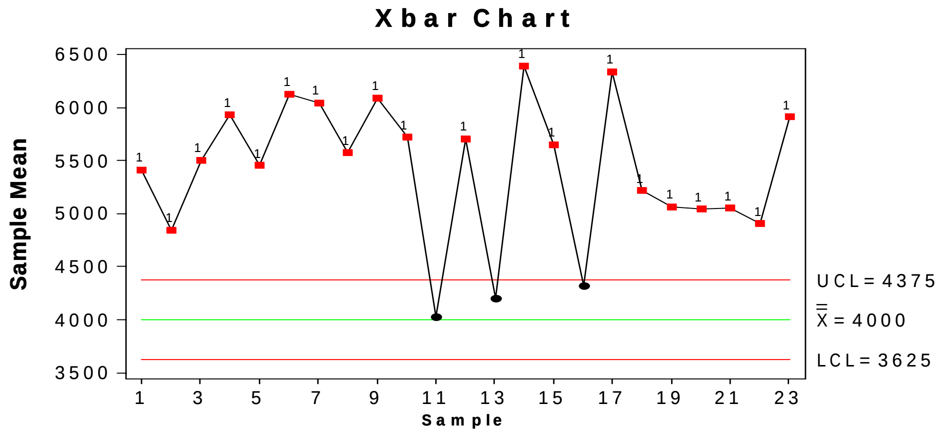
Figure B6. TRACs number: H416001C from the Lake Havasu plant and mix specification 3500S

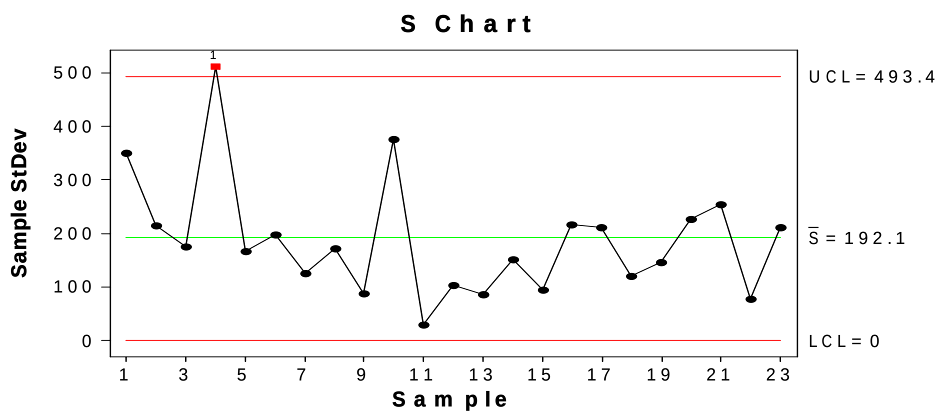




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

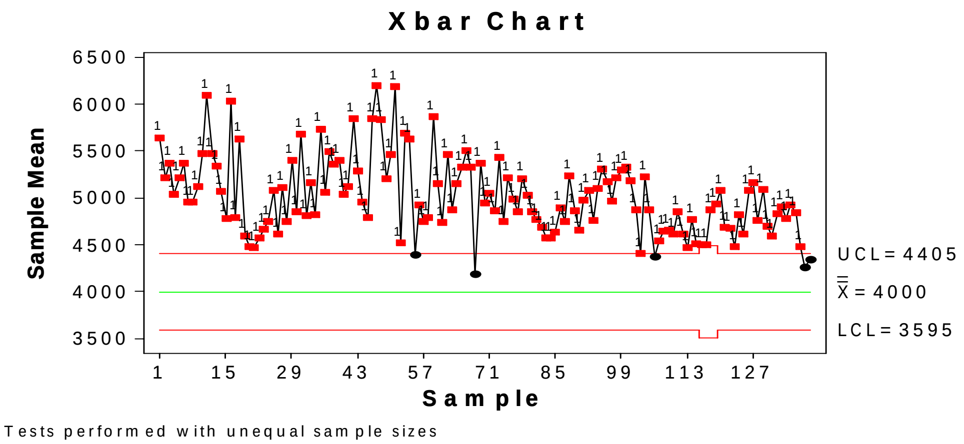
Figure B7. TRACs number: H319003C from the Tucson plant and mix specification0203-10

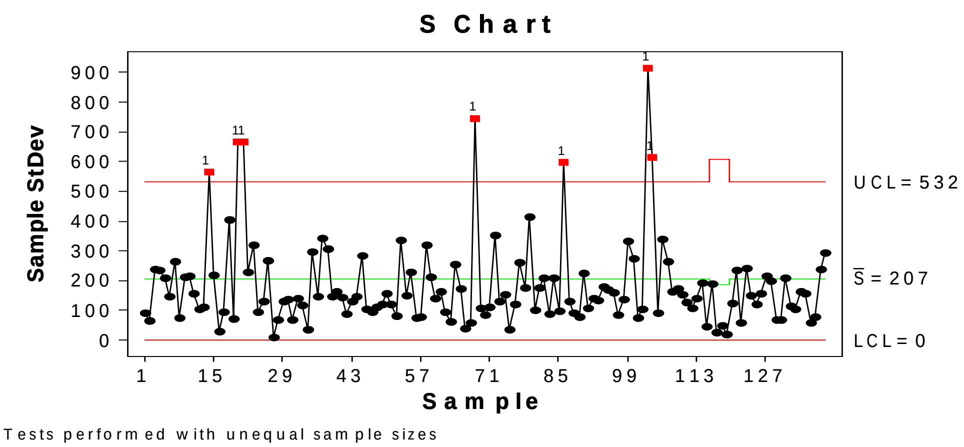




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

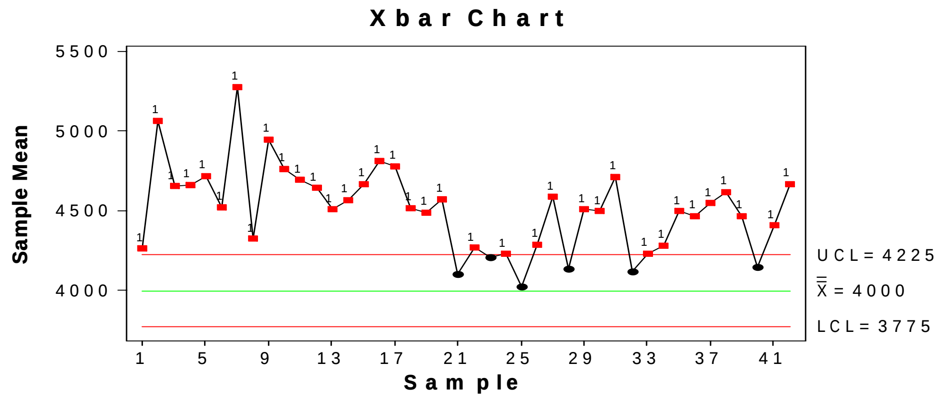
Figure B8. TRACs number: H319003C from the Tucson plant and mix specification0203-15

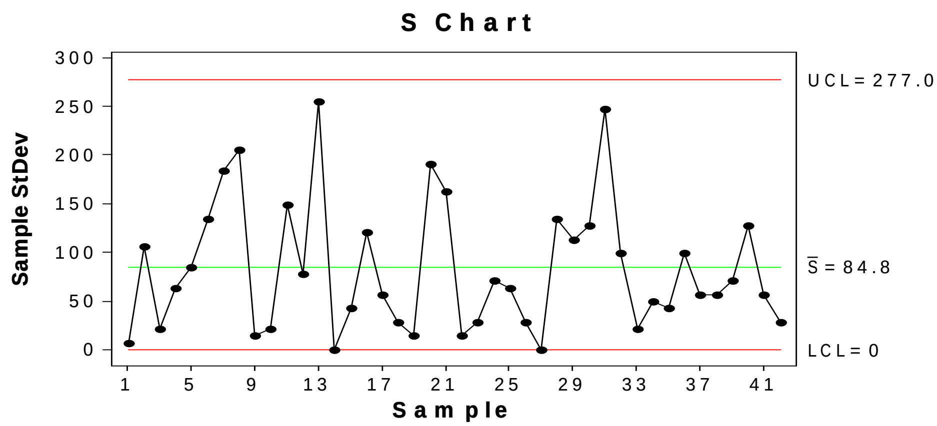




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

Figure B9. TRACs number: H313401C

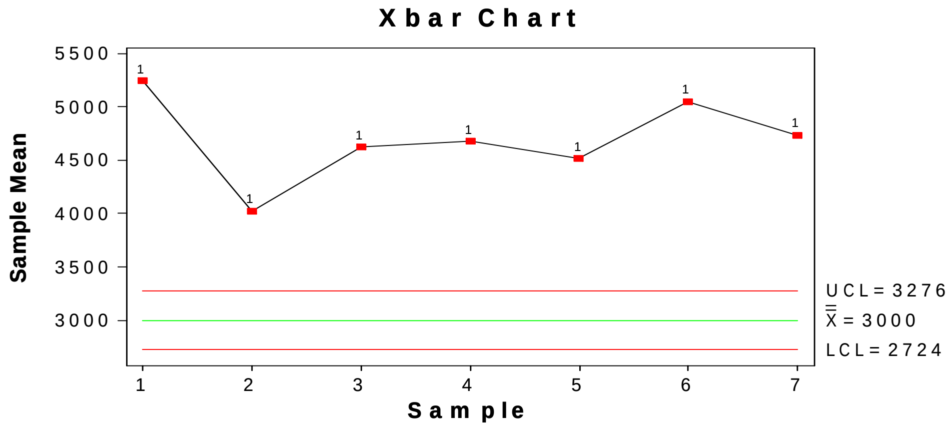


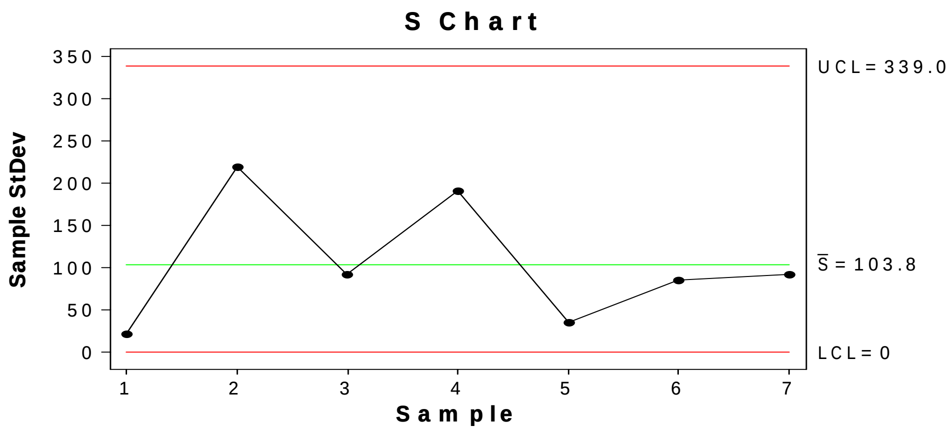


Sample mean and standard deviations represent statistical measures of compressive strength in psi.

APPENDIX C (X bar-S charts for Series 2)

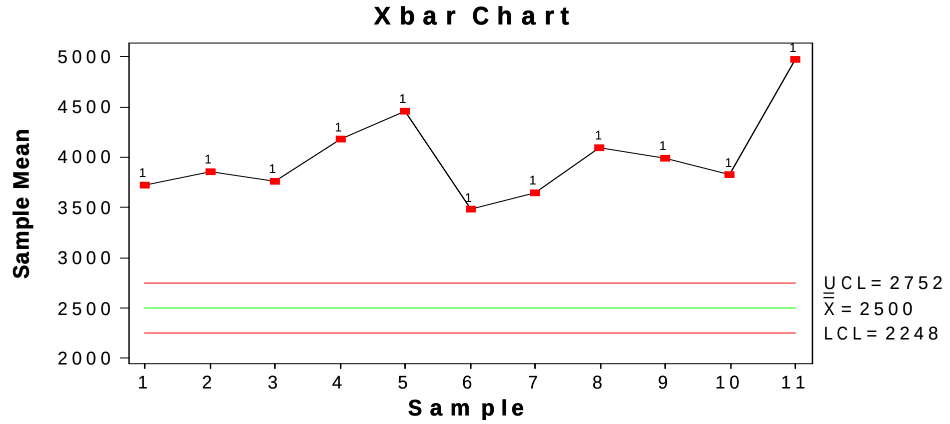
Figure C1. Project A11

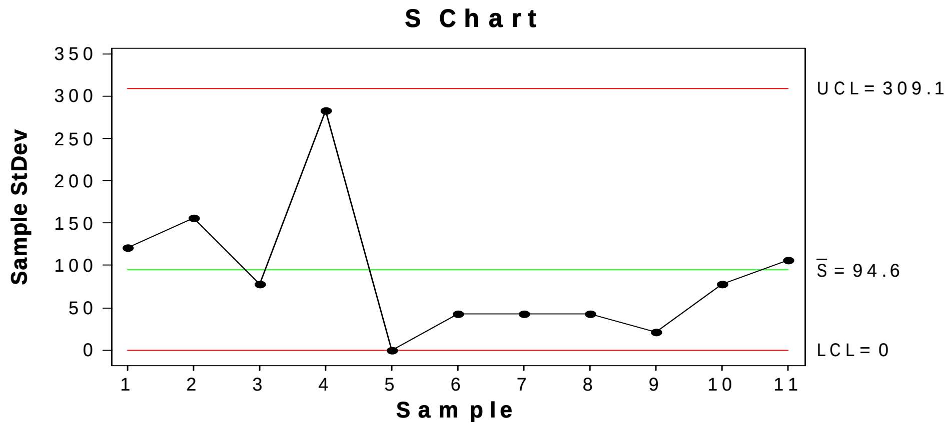




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

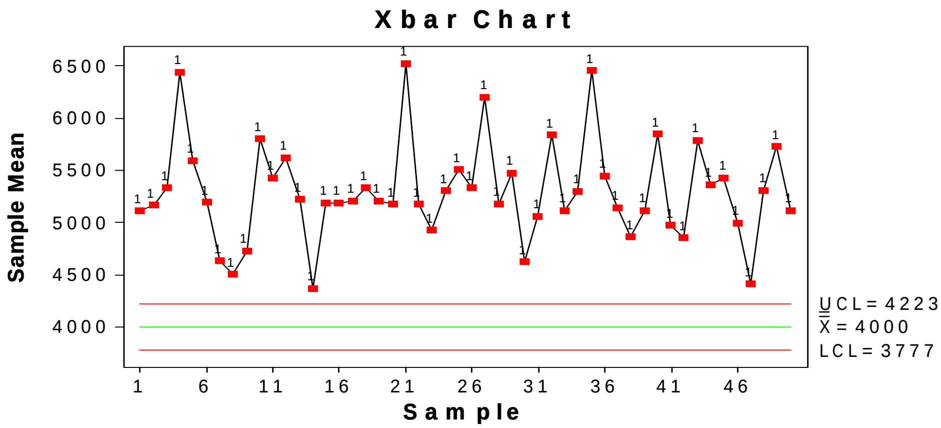
Figure C2. Project A13

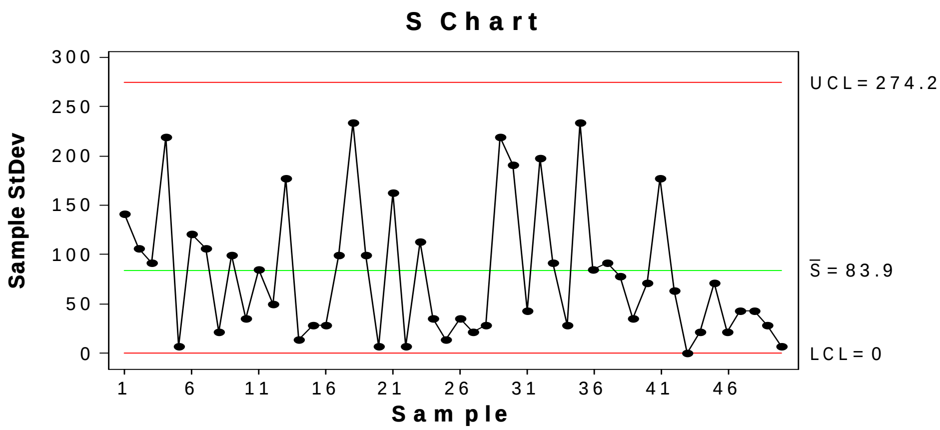




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

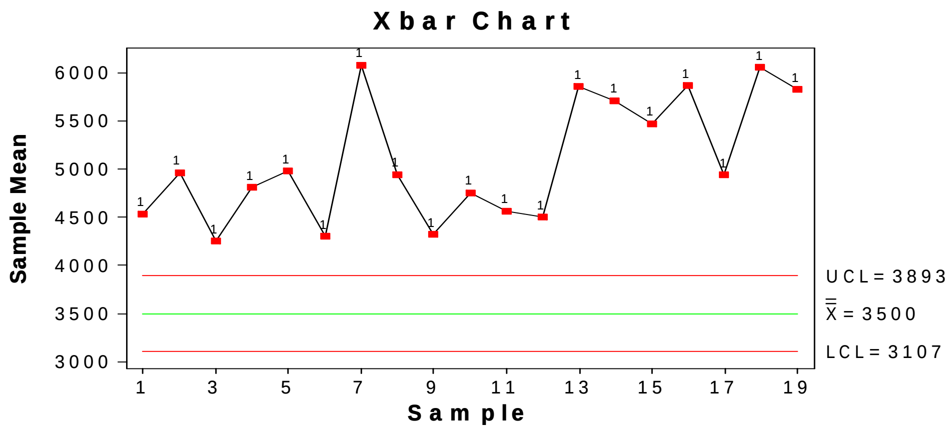
Figure C3. Project A21

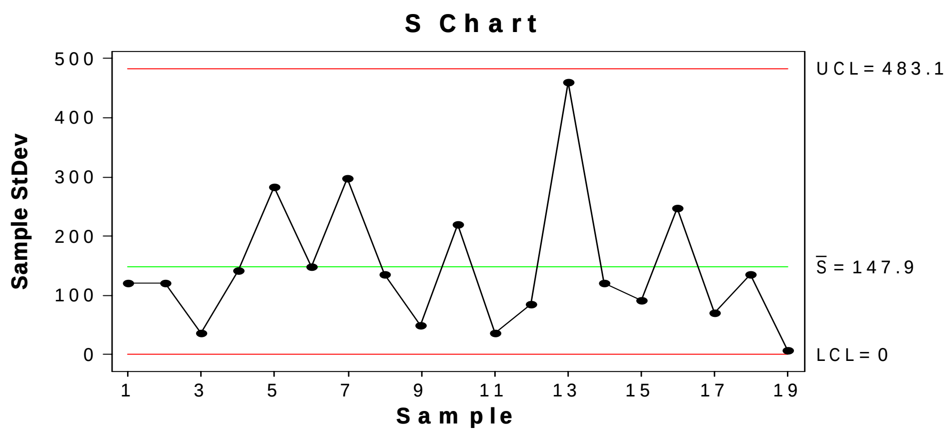




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

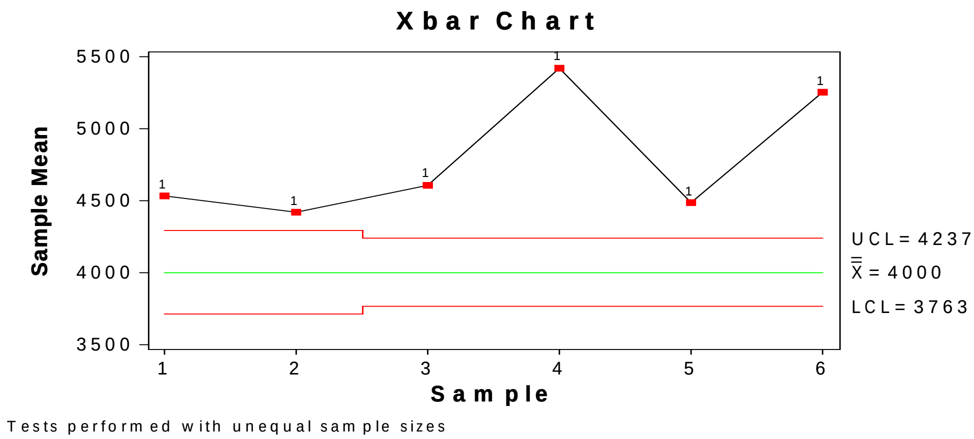
Figure C4. Project B11

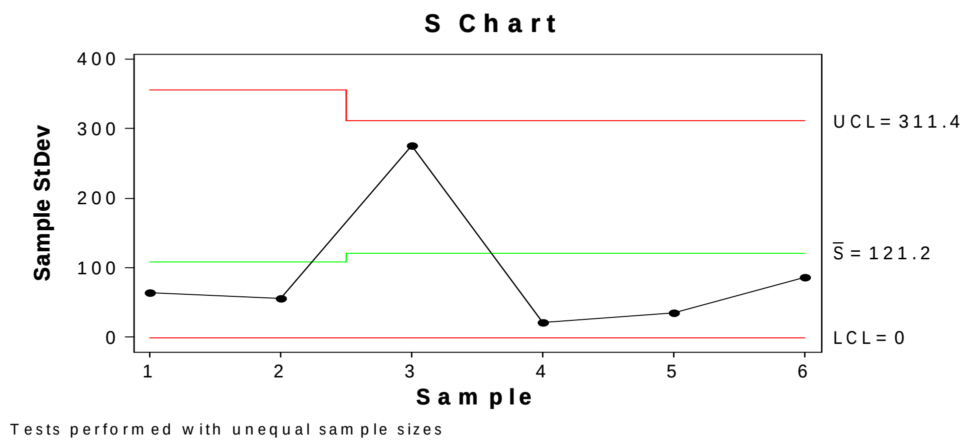




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

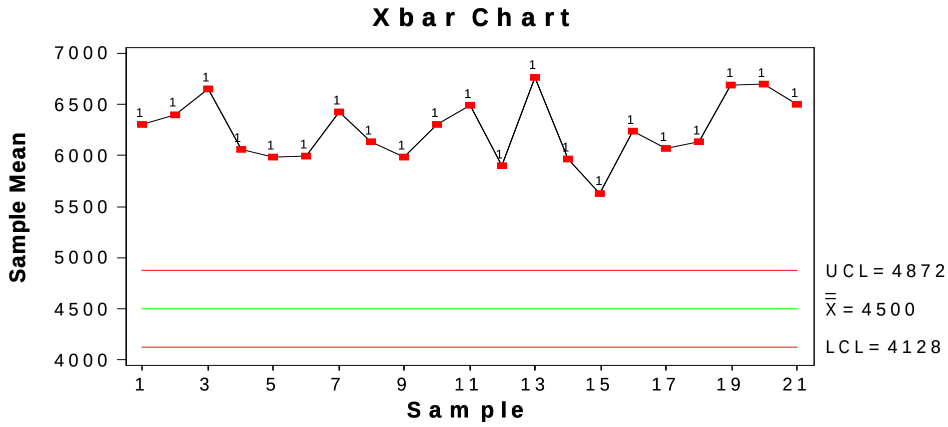
Figure C5. Project B12

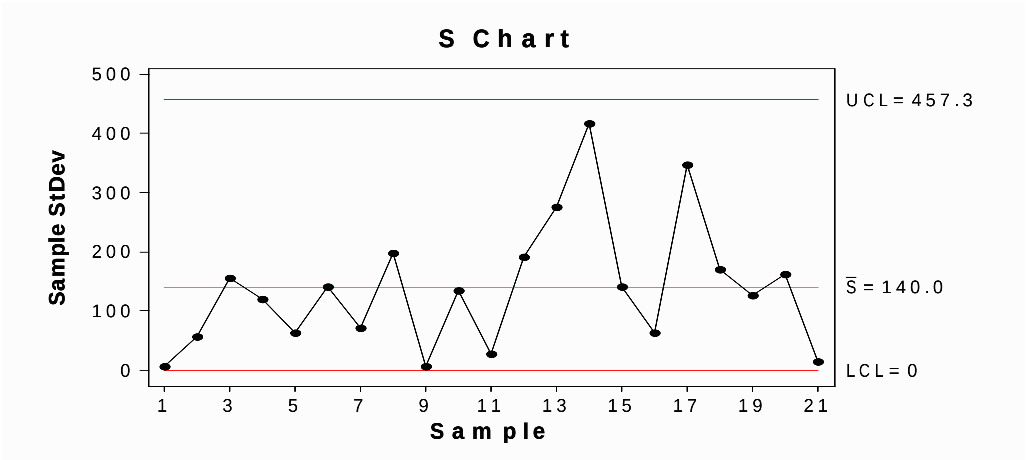




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

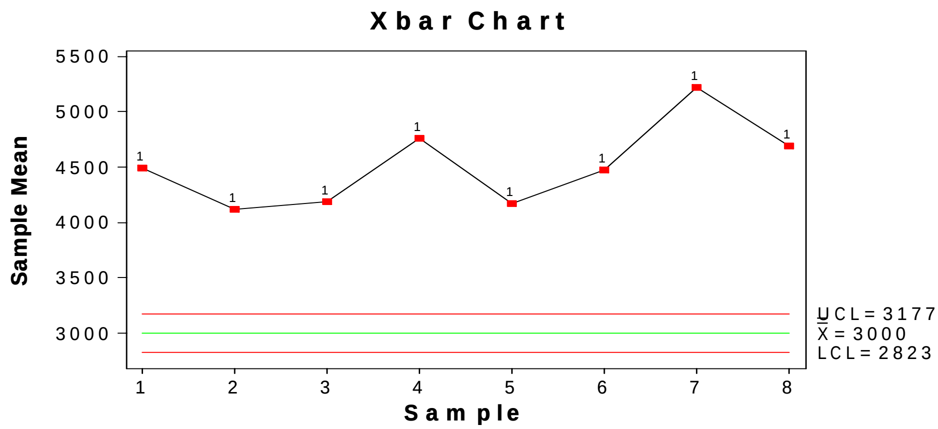
Figure C6. Project B13

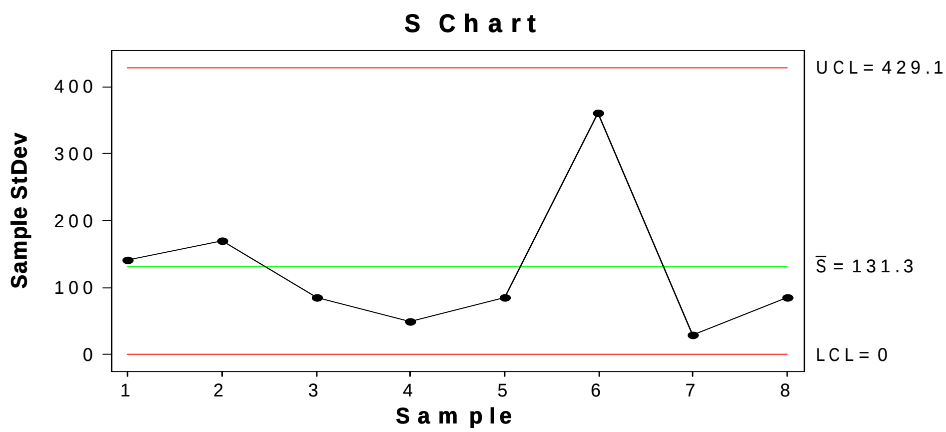




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

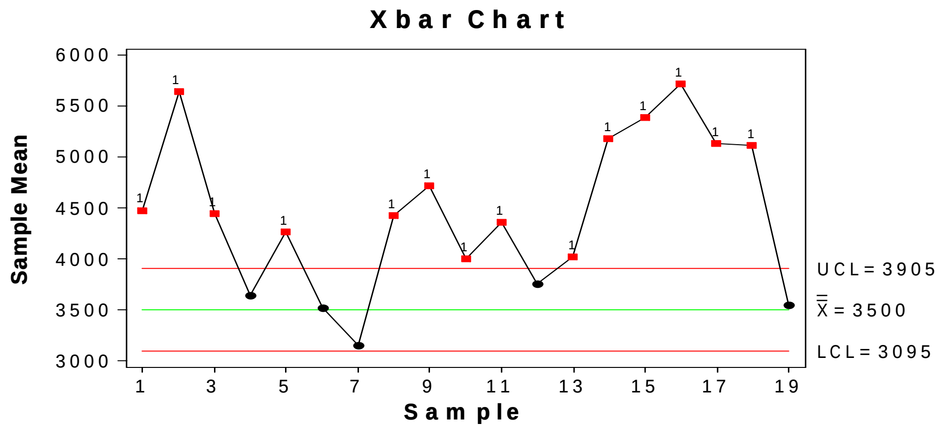
Figure C7. Project B21

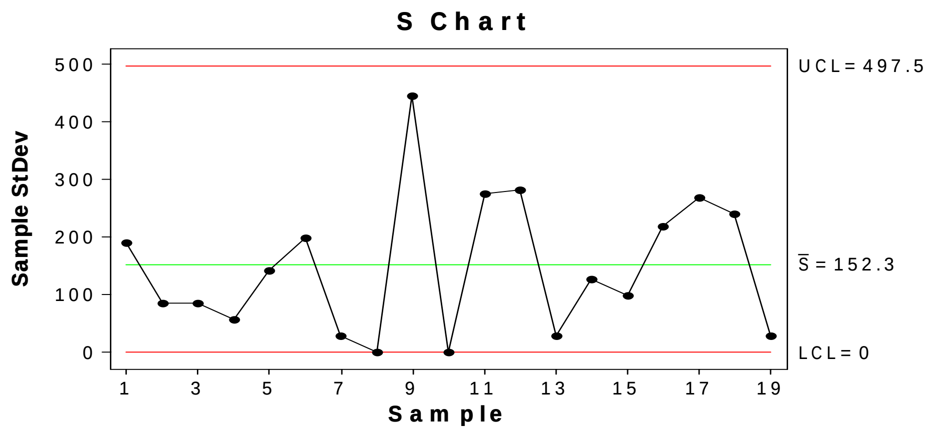




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

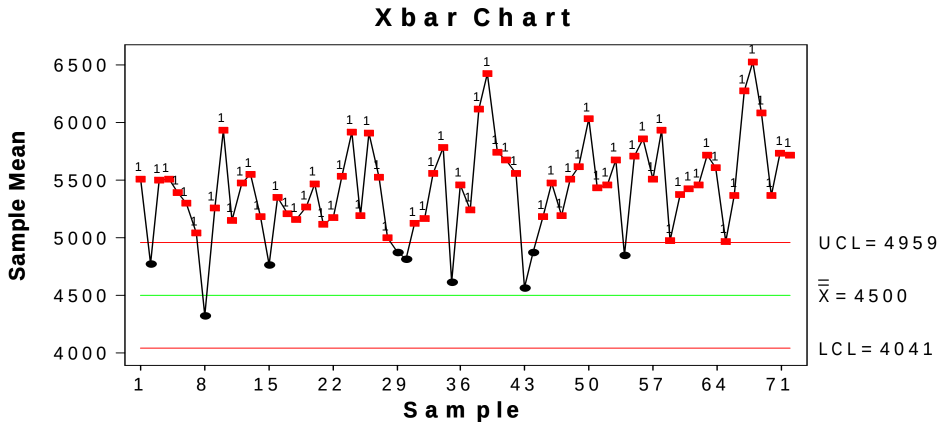
Figure C8. Project B22

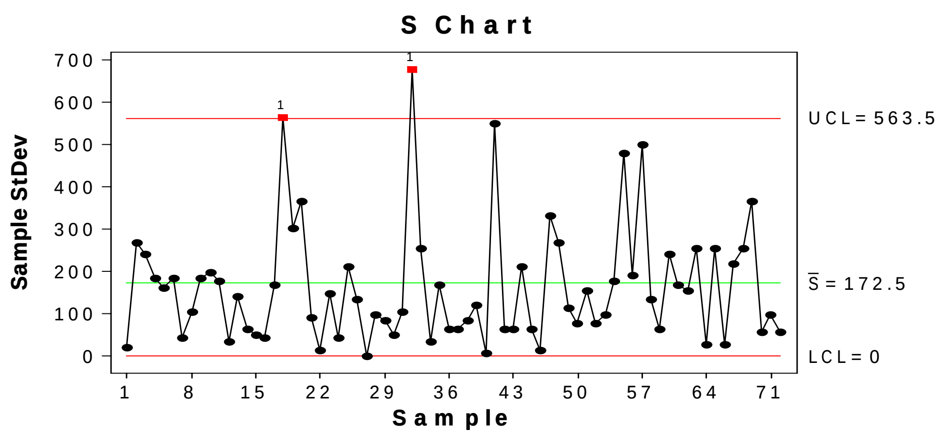




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

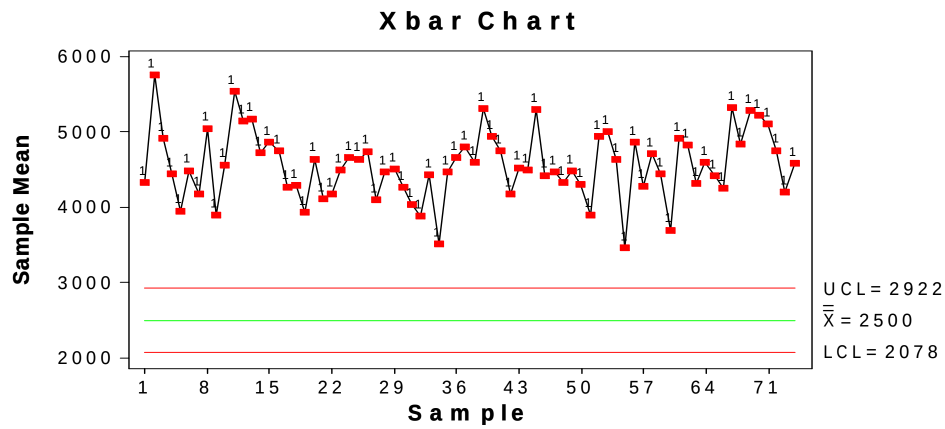
Figure C9. Project C11

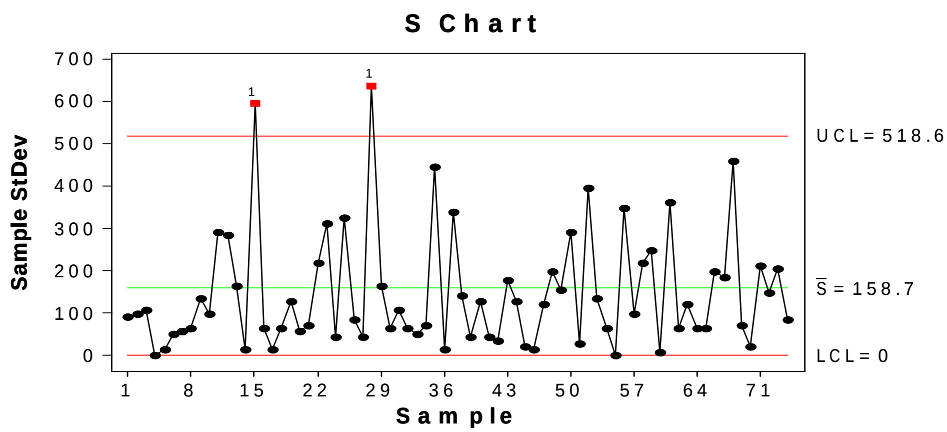




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

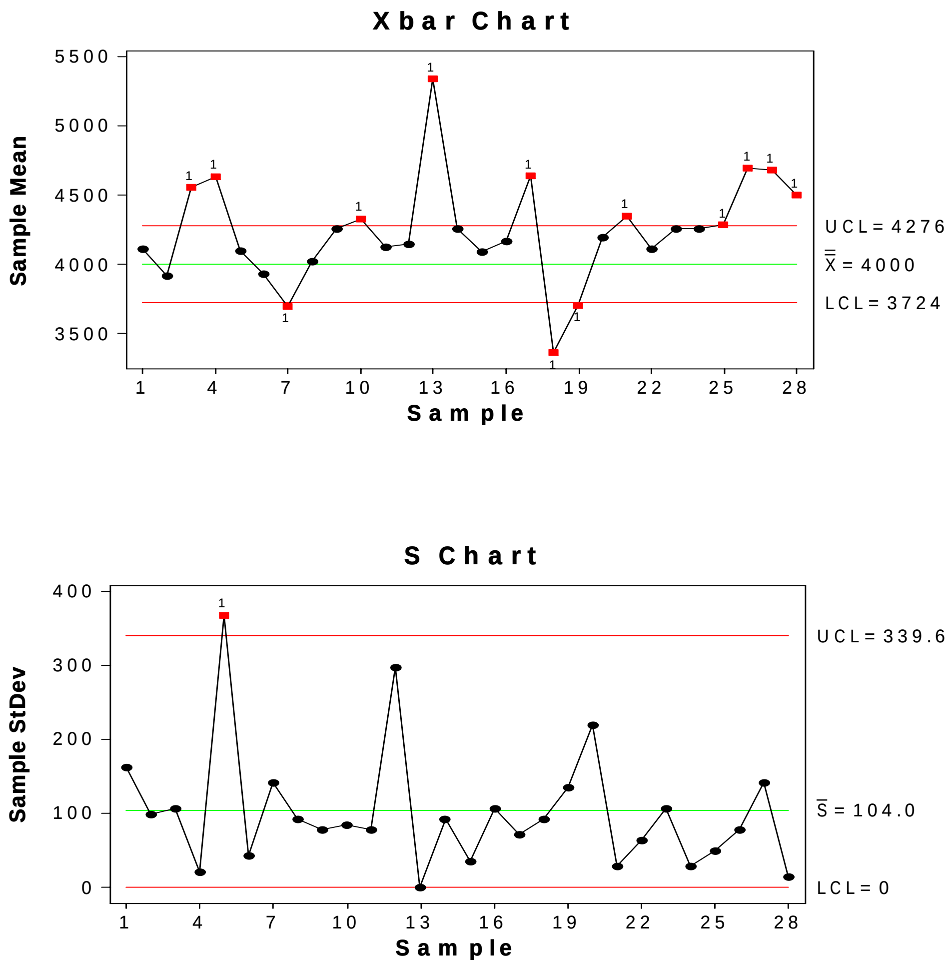
Figure C10. Project C12





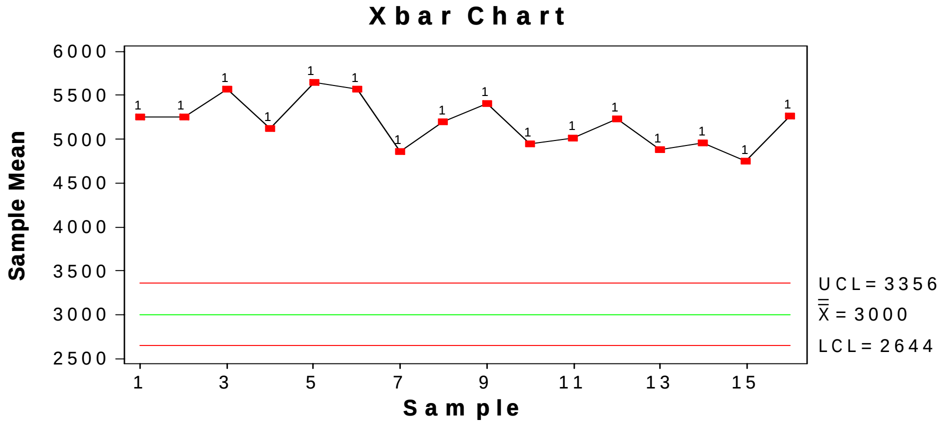
Sample mean and standard deviations represent statistical measures of compressive strength in psi.

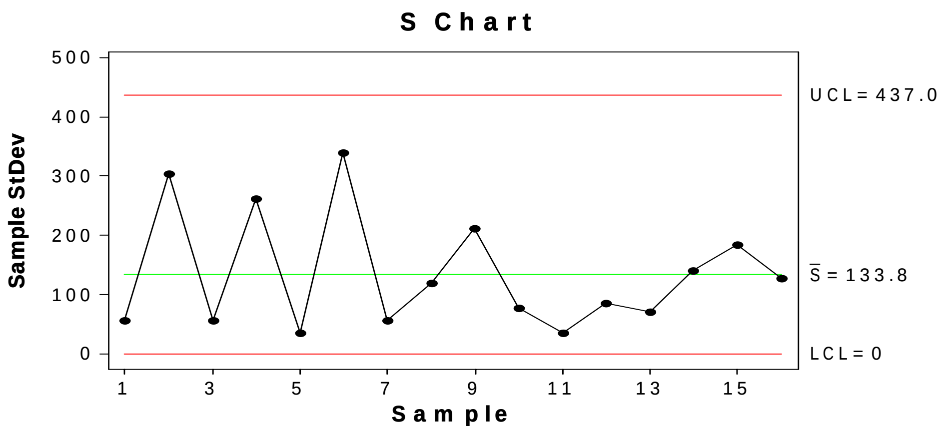
Figure C11. Project C13



Sample mean and standard deviations represent statistical measures of compressive strength in psi.

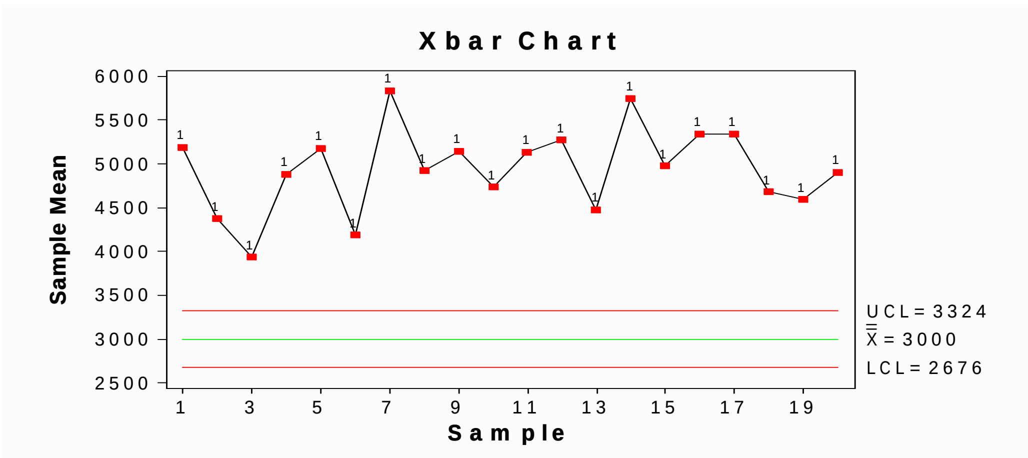
Figure C12. Project C21

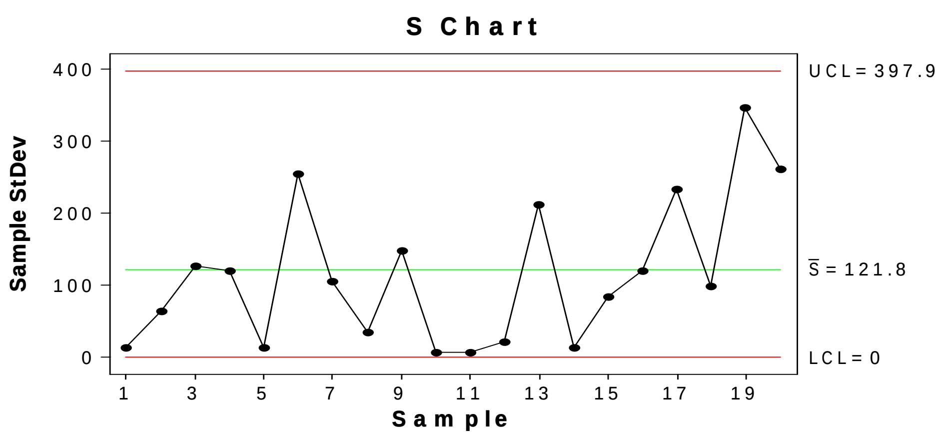




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

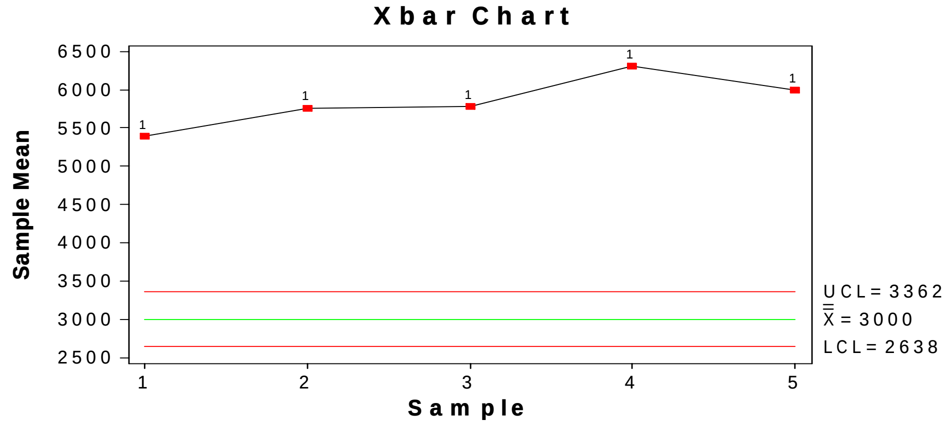
Figure C13. Project C22

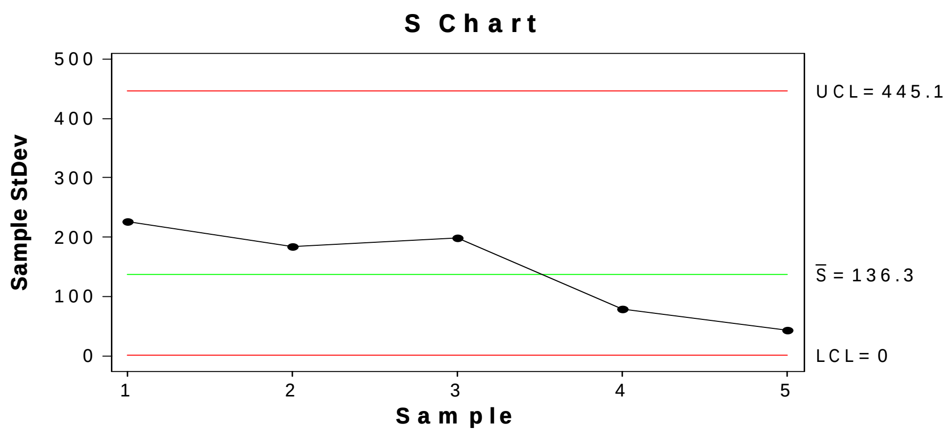




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

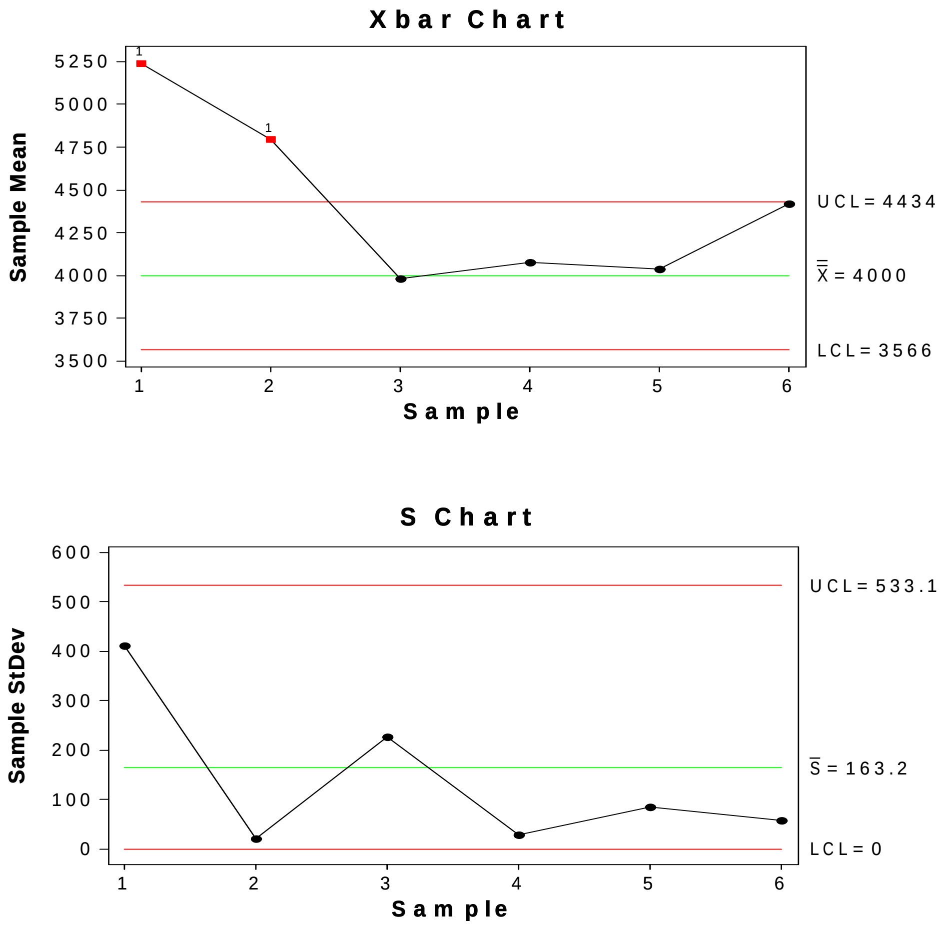
Figure C14. Project C23





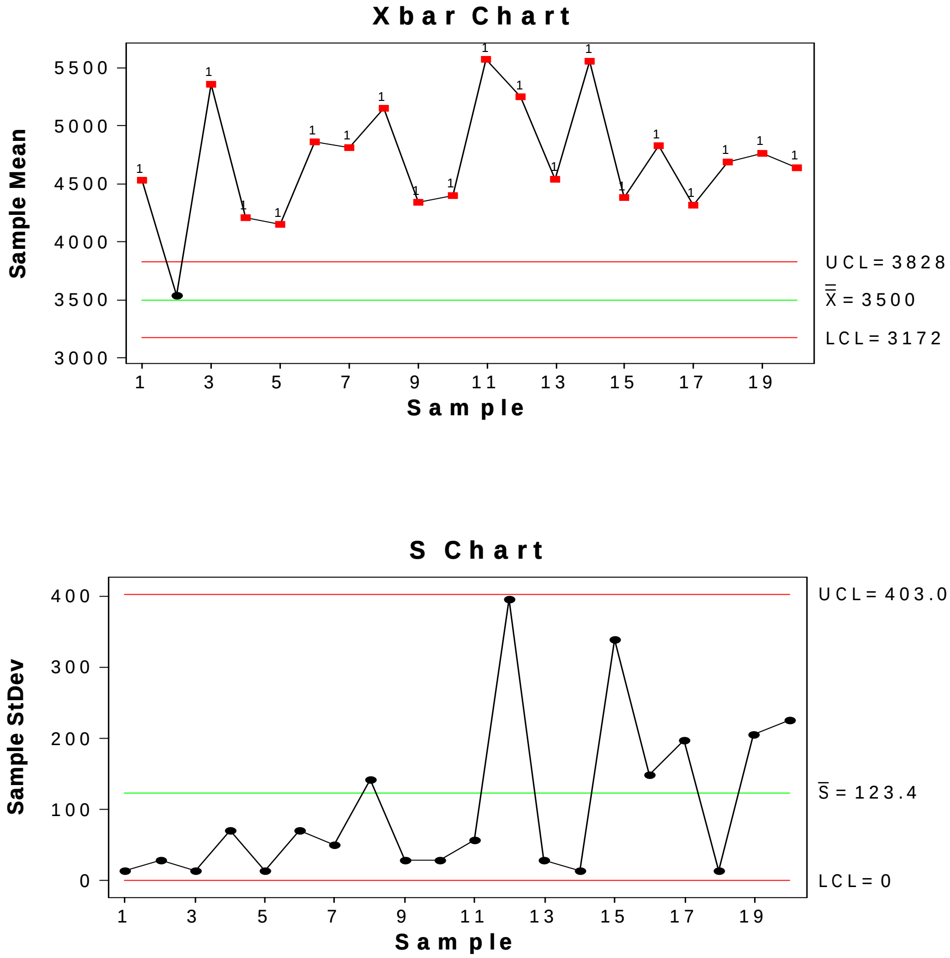
Sample mean and standard deviations represent statistical measures of compressive strength in psi.

Figure C15. Project D12



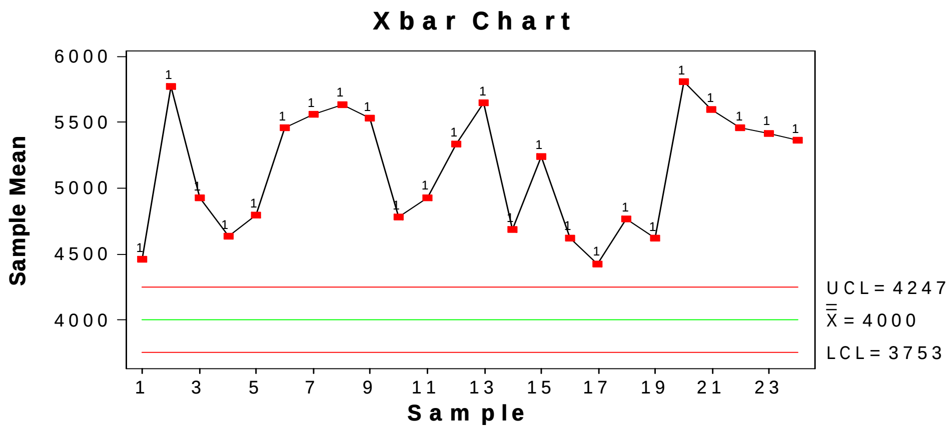
Sample mean and standard deviations represent statistical measures of compressive strength in psi.

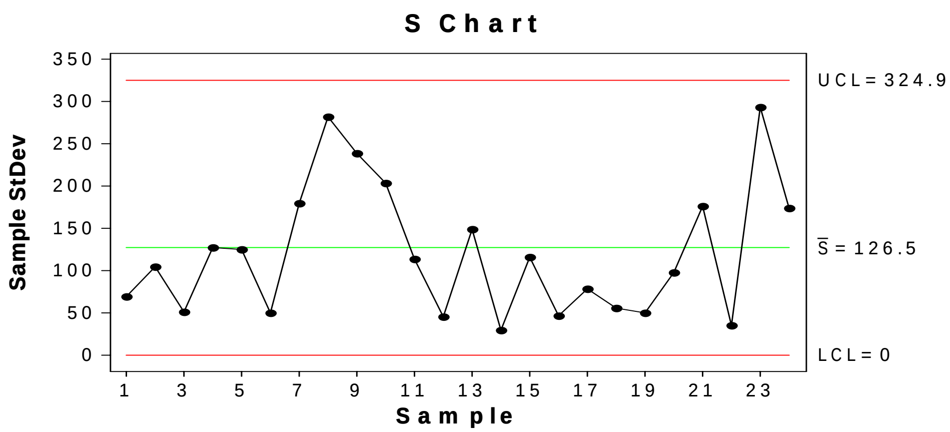
Figure C16. Project D13



Sample mean and standard deviations represent statistical measures of compressive strength in psi.

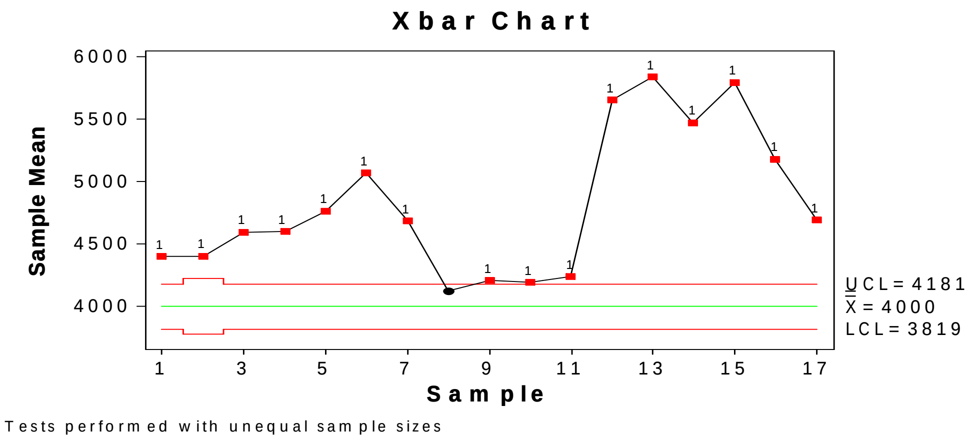
Figure C17. Project D21

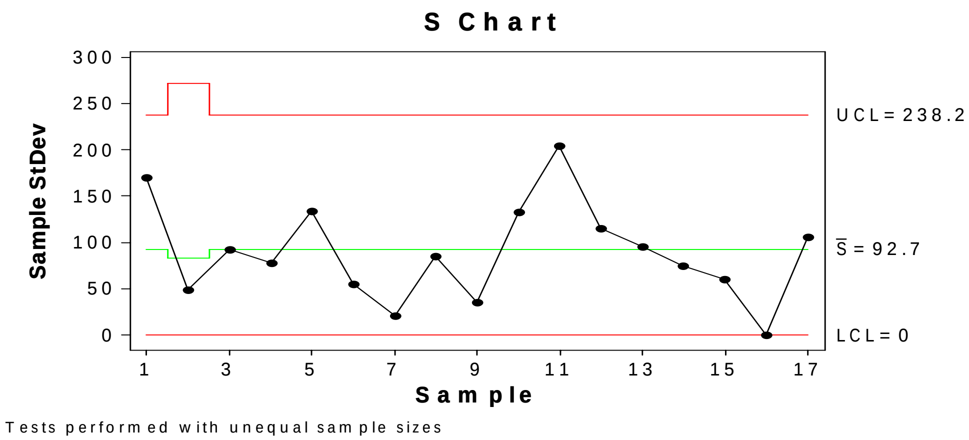




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

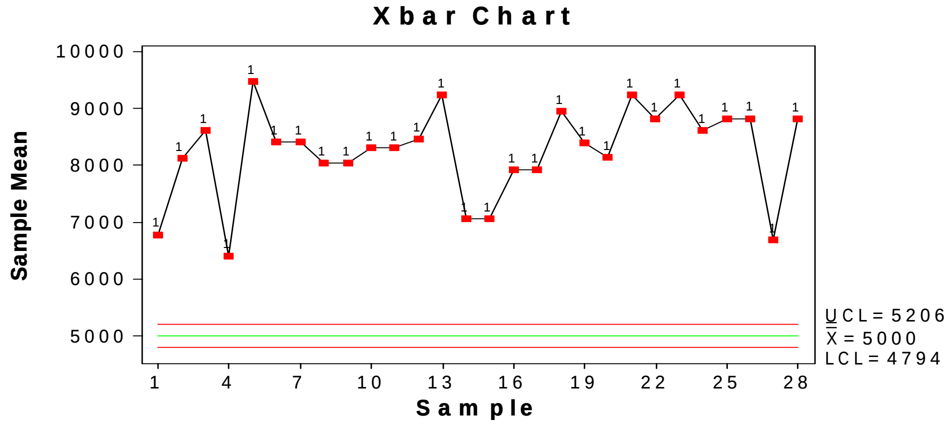
Figure C18. Project D23

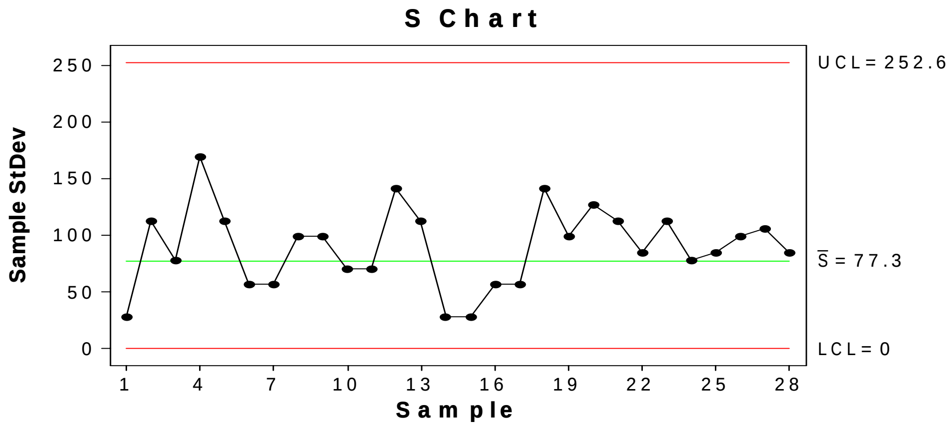




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

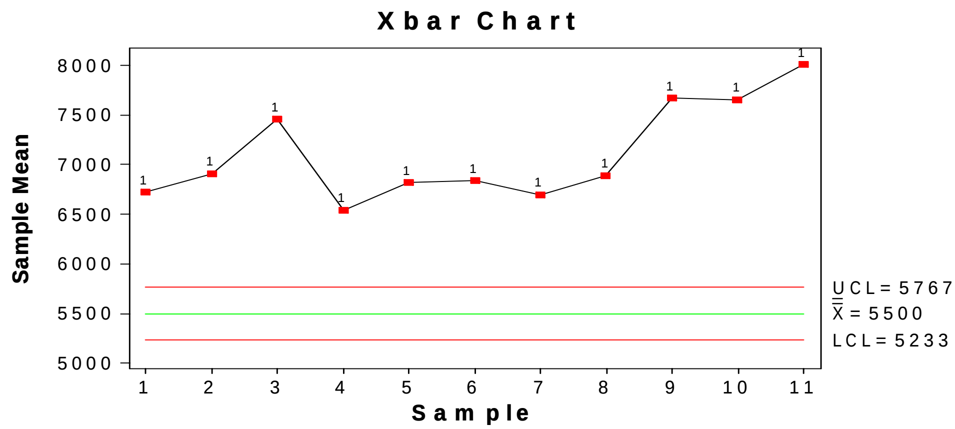
Figure C19. Project E11

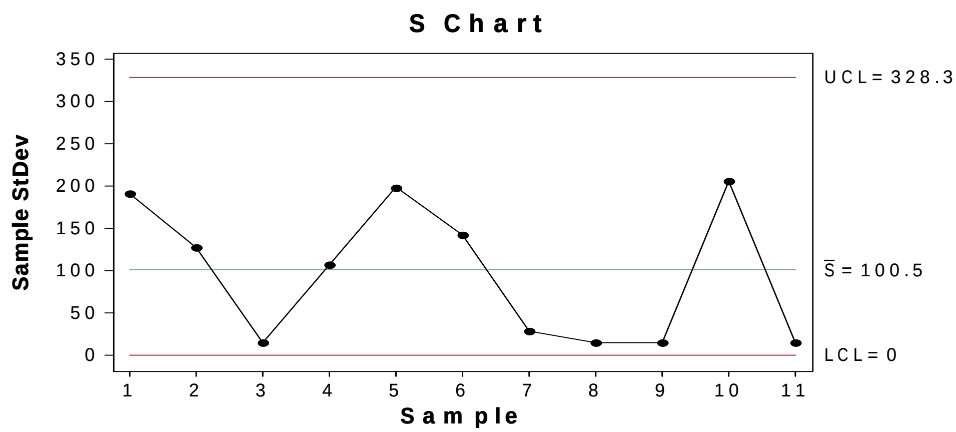




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

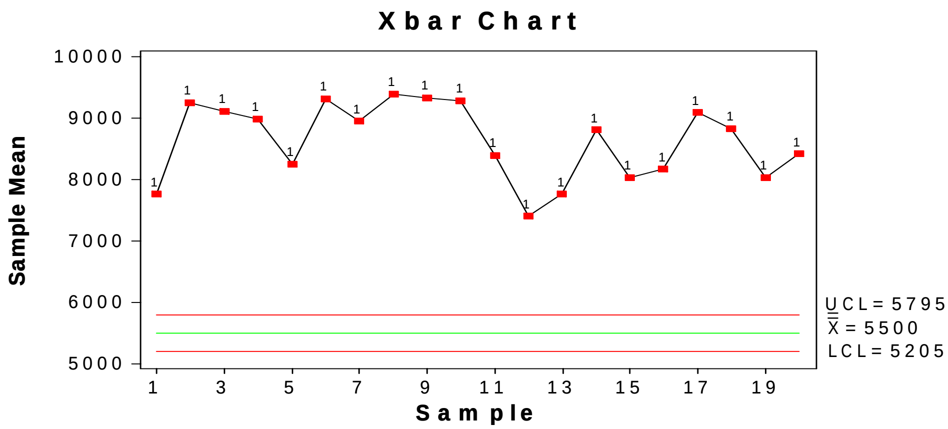
Figure C20. Project E12

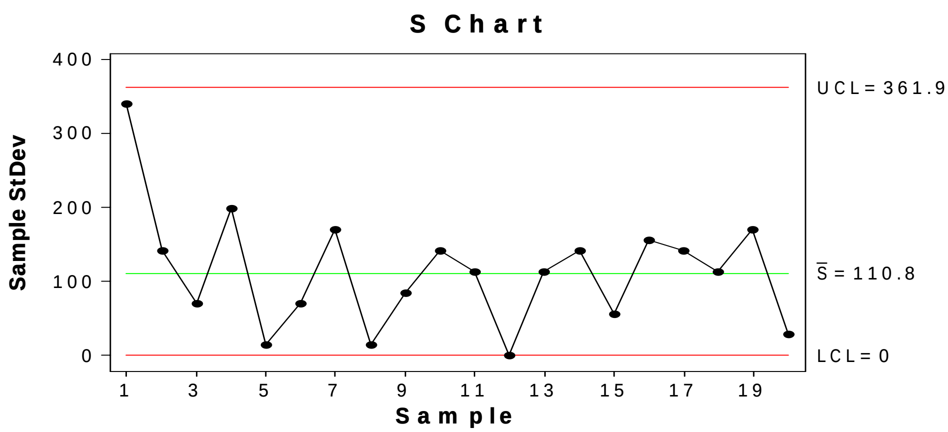




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

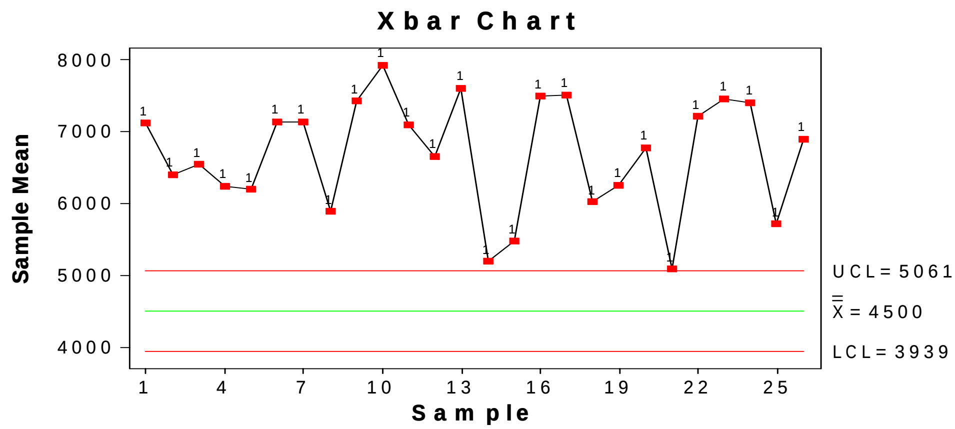
Figure C21. Project E13

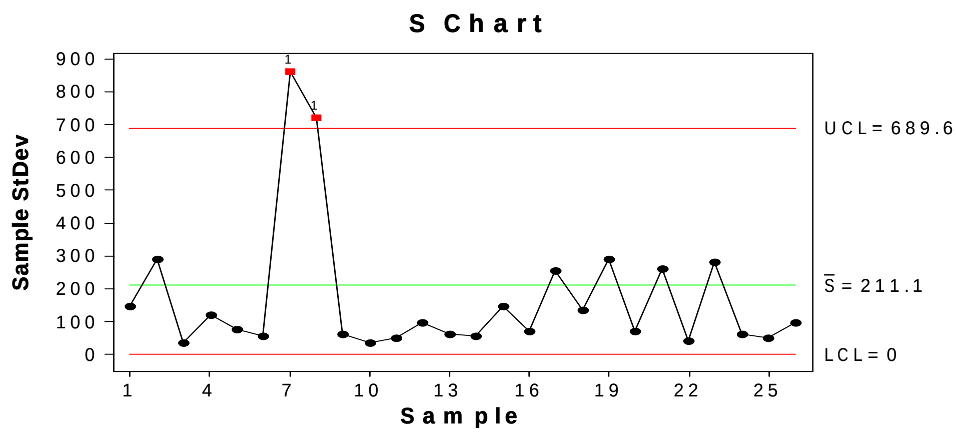




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

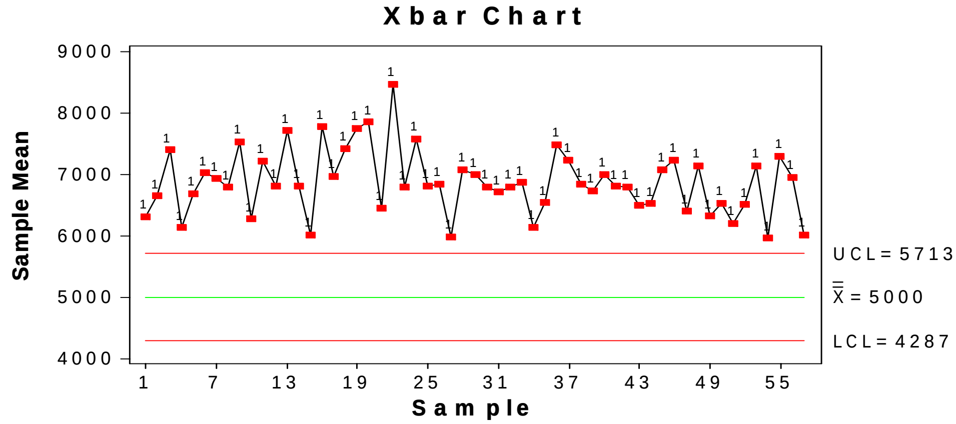
Figure C22. Project E21

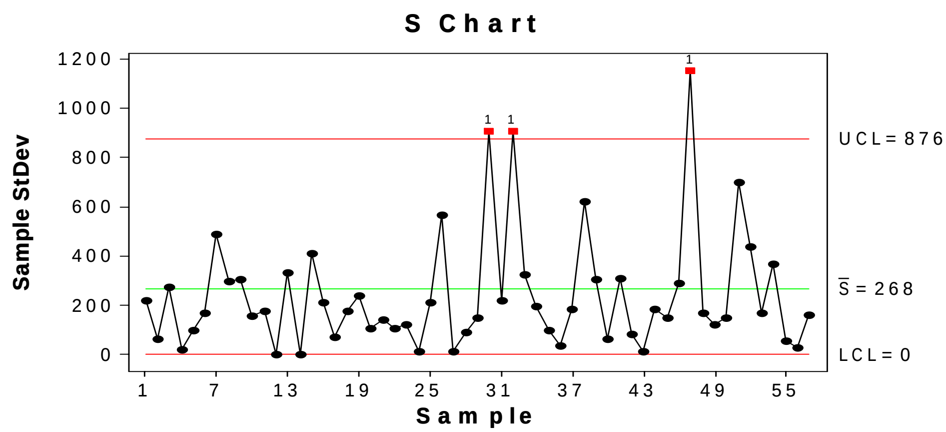




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

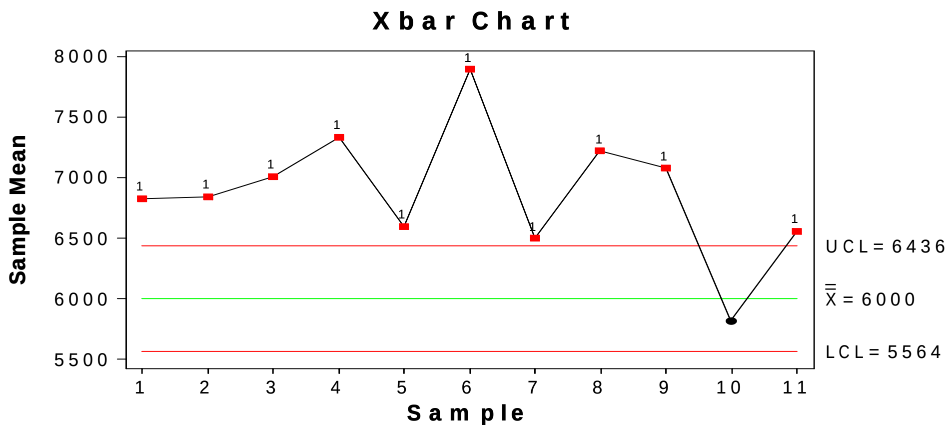
Figure C23. Project E22

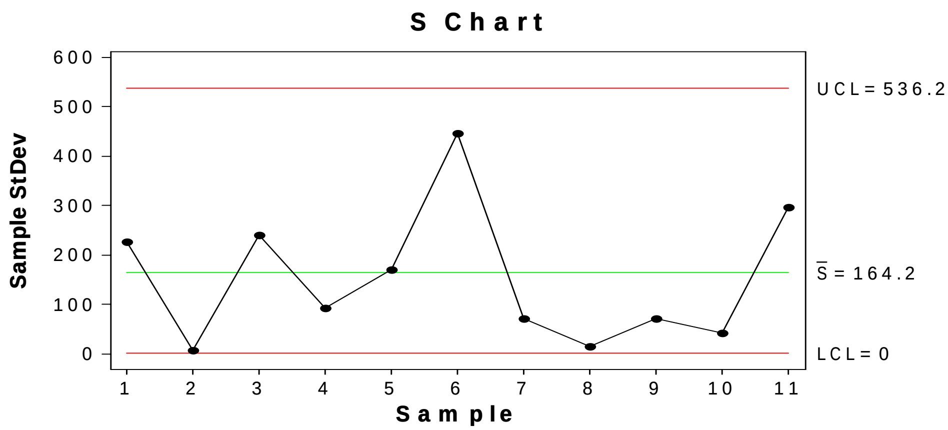




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

Figure C24. Project E23

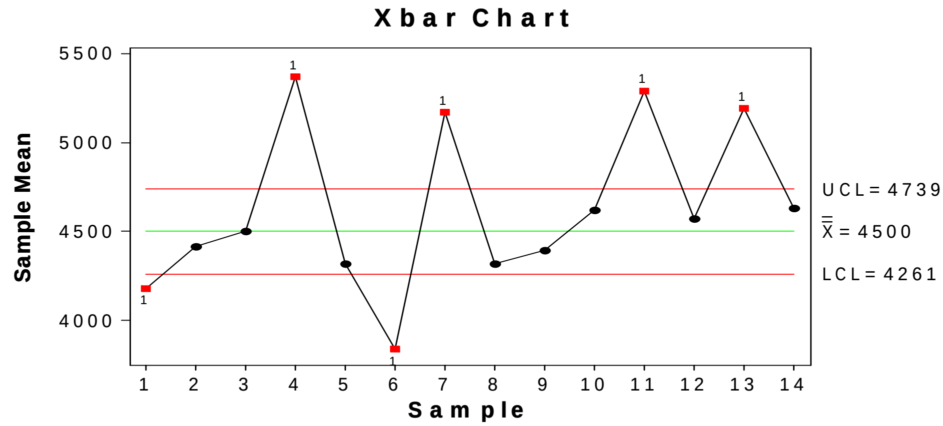


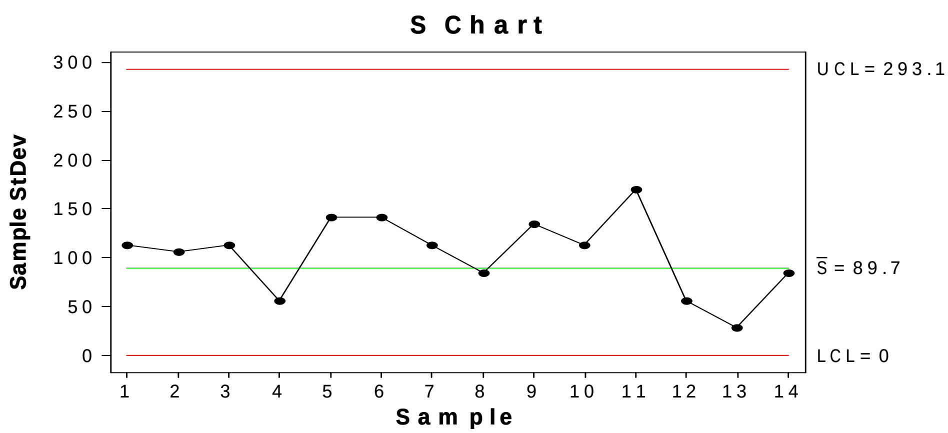


Sample mean and standard deviations represent statistical measures of compressive strength in psi.

APPENDIX D (X bar-S charts for Series 3)

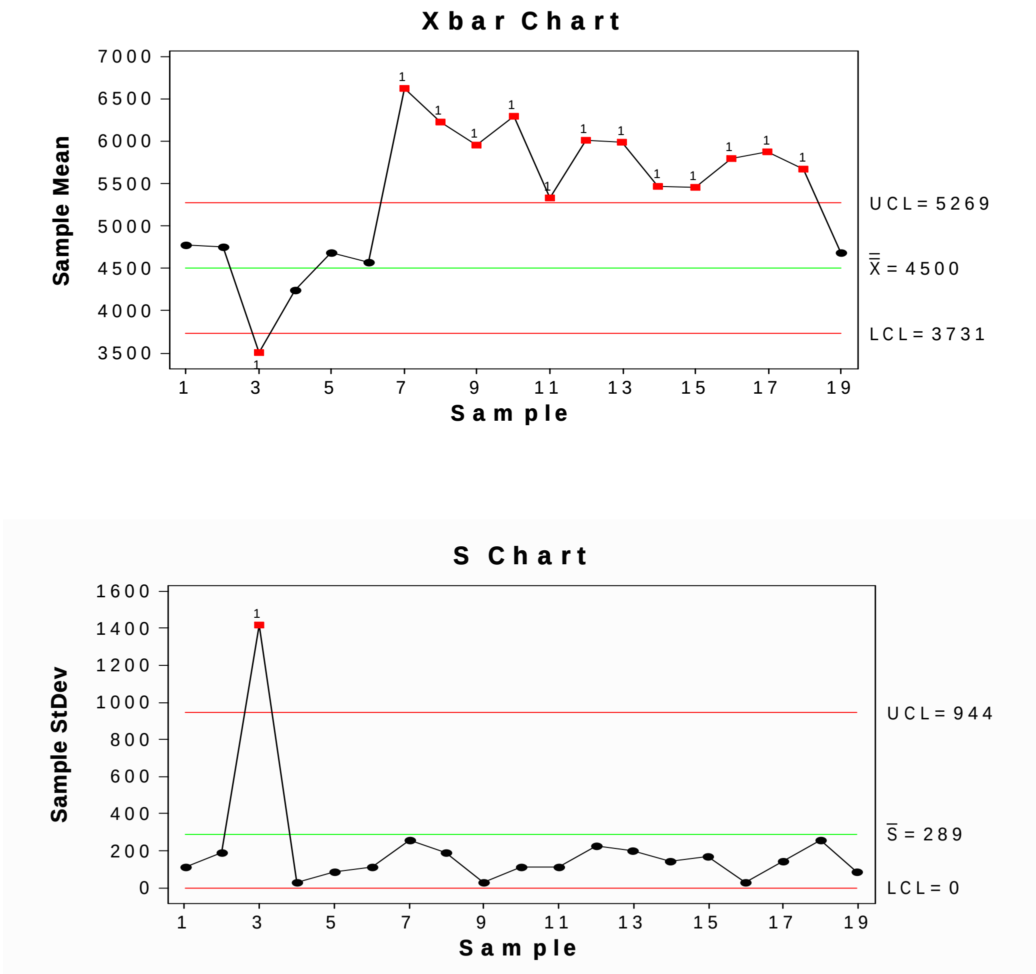
Figure D1. Wilson Wash.





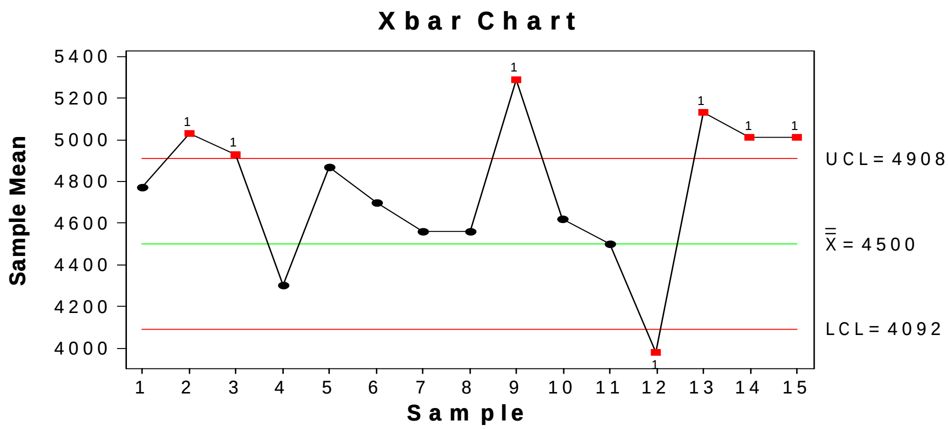
Sample mean and standard deviations represent statistical measures of compressive strength in psi.

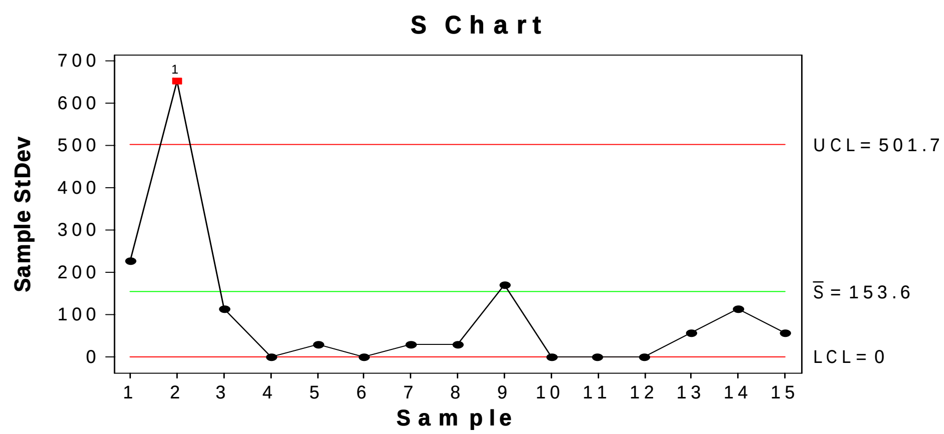
Figure D2. Sandy Blevens



Sample mean and standard deviations represent statistical measures of compressive strength in psi.

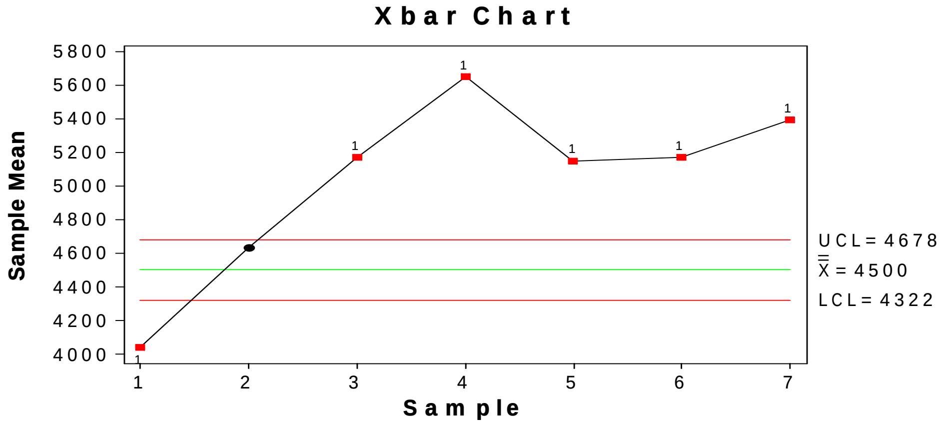
Figure D3. Quail Springs

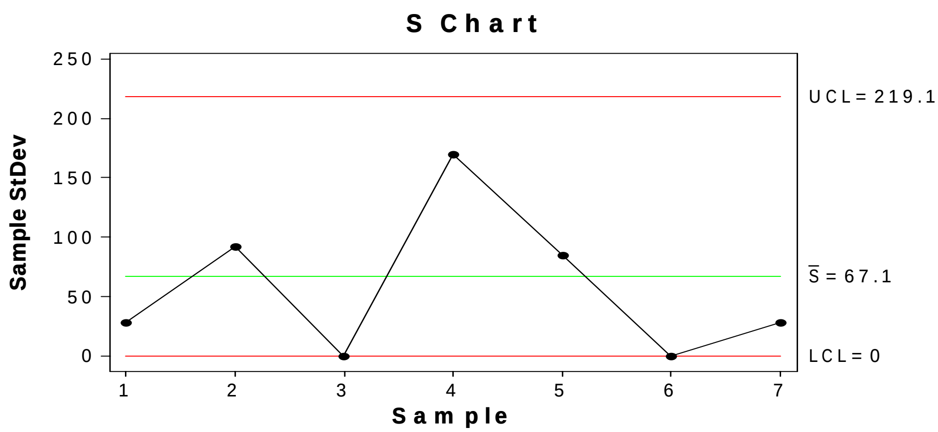




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

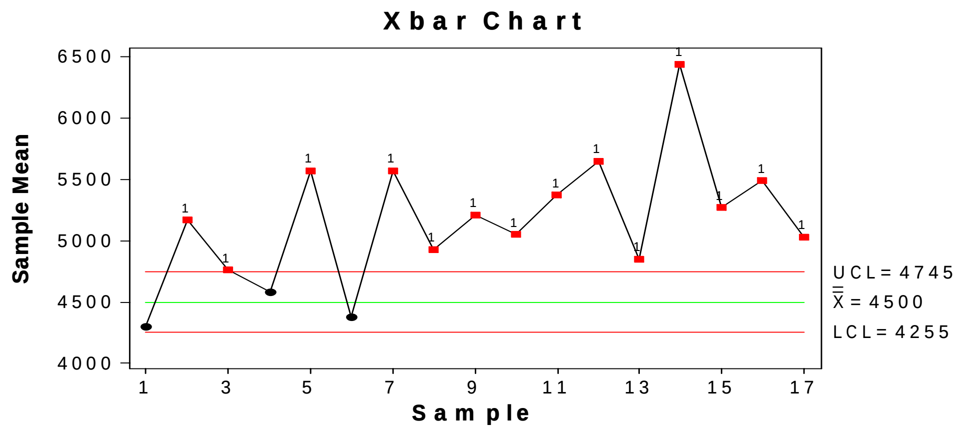
Figure D4. Poison

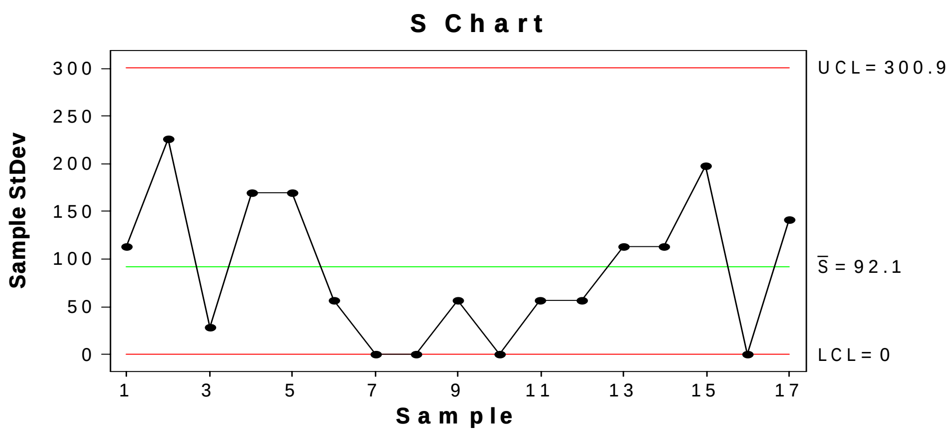




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

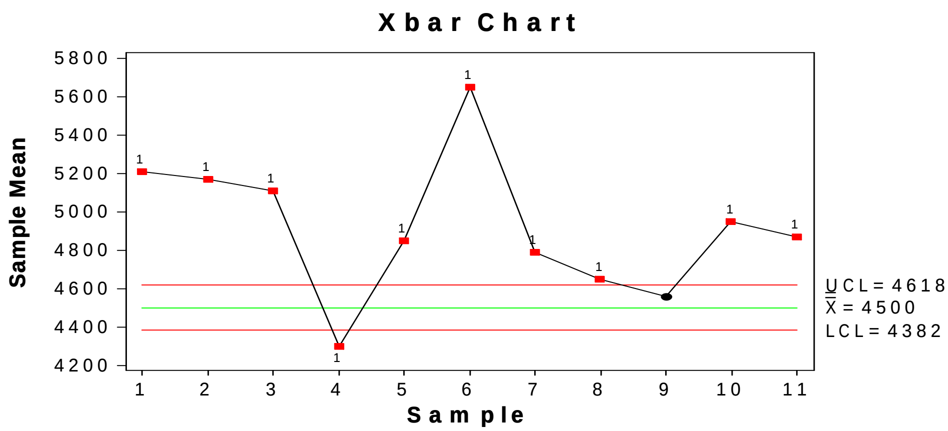
Figure D5. Deveore

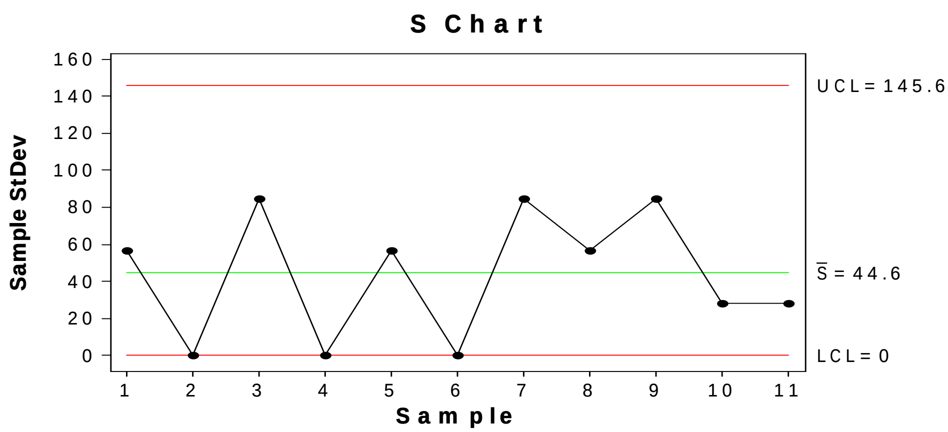




Sample mean and standard deviations represent statistical measures of compressive strength in psi.

Figure D6. Apprentice





Sample mean and standard deviations represent statistical measures of compressive strength in psi.

APPENDIX E (Pay Factors)

Pay Factor	Minimum Required PWL for a Given Pay Factor							
Category II	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10 to n=11
100	59	65	68	71	72	74	75	76
99	58	63	67	69	71	72	73	75
98	57	62	65	67	69	71	72	73
97	55	60	63	66	68	69	70	72
96	54	59	62	64	66	68	69	70
95	53	57	61	63	65	66	67	69
94	51	56	59	62	63	65	66	68
93	50	55	58	60	62	64	65	66
92	49	53	57	59	61	62	63	65
91	48	52	55	58	59	61	62	64
90	46	51	54	56	58	60	61	62
89	45	49	53	55	57	58	60	61
88	44	48	51	54	56	57	58	60
87	43	47	50	53	54	56	57	59
86	41	46	49	51	53	55	56	58
85	40	44	48	50	52	54	55	56
84	39	43	46	49	51	52	54	55
83	38	42	45	48	50	51	52	54
82	36	41	44	46	48	50	51	53
81	35	39	43	45	47	49	50	52
80	33	38	42	44	46	48	49	51
79	32	37	40	43	45	47	48	49
78	30	36	39	42	44	45	47	48
77	28	34	38	41	43	44	46	47
76	27	33	37	39	42	43	45	46
75	35	32	36	38	40	42	43	45

APPENDIX F (Data information)

Series	No	Data Case	
TRACSNo			
1	1	1	H576801CR_Rinker_33341_1333115_4500_672h
	2	2	H552501C_Sunshine_Kingman_S3000A_3000_672h
	3	3	H407601C_Rinker_55041_14016_3500_672h
	4	4	H407601C_RinkerMat_60141_1332439_4000_672h
	5	5	H416001CR_CAMPBELL_LAKEHAVASU_2500S_2500_672h
	6	6	H416001CR_CAMPBELL_LAKEHAVASU_3500S_3500_672h
	7	7	H319003C_McNeil_Constco_TUCSON_0203-10_4000_672h
	8	8	H319003C_McNeil_Constco_TUCSON_0203-15_4000_672h
	9	9	H313401CR_McNeil_ConstCo_TUCSON_9710-3_4000_672h
Project			
2	14	1	A11_ChandlerReady_3_130624_3000_672h
	15	2	A13_ChandlerReady_3_4425_2500_672h
	16	3	A21_ChandlerReady_1_140204_4000_672h
	17	4	B11_Rinker_11241_14030_3500_672h
	18	5	B12_Rinker_11241_1333066_4000_672h
	19	6	B13_Rinker_11241_14504_4500_672h
	20	7	B21_Rinker_33341_14016_3000_672h
	21	8	B22_Rinker_33341_1333004_3500_672h
	22	9	C11_AZMat_ValVista_15030_4500_672h
	23	10	C12_AZMat_ValVista_13008_2500_672h
	24	11	C13_AZMat_ValVista_14030A_4000_672h
	25	12	C21_AZMat_QueenCreek_13008_3000_672h
	26	13	C22_AZMat_QueenCreek_14030_3000_672h
	27	14	C23_AZMat_QueenCreek_13530_3000_672h
	28	15	D12_HansonAggreofAZ_ValleyPlant_C40501_4000_672h
	29	16	D13_HansonAggreofAZ_ValleyPlant_C35501A_3500_672h
	30	17	D21_HansonAggreofAZ_40_D402521_4000_672h
	31	18	D23_HansonAggreofAZ_40_840913_4000_672h
	32	19	E11_TPAC_PHX_447_5000_672h
	33	20	E12_TPAC_PHX_444_5500_672h
	34	21	E13_TPAC_PHX_448M_5500_672h
	35	22	E21_TPAC_TUCSON_2245_4500_672h
	36	23	E22_TPAC_TUCSON_2248_5000_672h
	37	24	E23_TPAC_TUCSON_2250_6000_672h
Bridge			
3	42	1	Apprentice_S4500
	43	2	Deveore_S4500
	44	3	Poison_S4500
	45	4	Quail_springs_S4500
	46	5	sandy_blevens_s4500
	47	6	wilson_wash_S4500

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