FIELD EVALUATION OF QUALITY MANAGEMENT CONCRETE

Final Report
For
MLR-97-3

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Project Development Division

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Field Evaluation of Quality Management Concrete

Final Report
for
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8. ABSTRACT

Quality management concrete allows the contractor to develop the mix design for the portland cement concrete. This research was initiated to gain knowledge about contractor mix designs. An experiment was done to determine the variation in cylinders, beams, and cores that could be used to test the strength of the contractors mix. In addition, the contractors cylinder strengths and gradations were analyzed for statistical stability and process capability.

This research supports the following conclusions:

1. The mold type used to cast the concrete cylinders had an effect on the compressive strength of the concrete. The 4.5" by 9" cylinders had lower strength at a 95 percent confidence interval than the 4" by 8" and 6" by 12" cylinders.

2. The low vibration consolidation effort had the lowest strength of thc three consolidations efforts. In particular, an interaction occurred between the low vibration effort and the 4.5" by 9" mold. This interaction produced very low compressive strengths when compared with the other consolidation efforts.

3. A correlation of 0.64 R^2 was found between the 28 day cylinder and 28 day compressive strengths.

4. The compressive strength results of the process control testing were not in statistical control. The aggregate gradations were mostly in statistical control. The gradation process was capable of meeting specification requirements. However, many of the sieves were off target.

5. The fineness modulus of the aggregate gradations did not correlate well with the strength of the concrete. However, this is not surprising considering that the gradation tests and the strength tests did not represent the same material. In addition, the concrete still has many other variables that will effect its strength that were not controlled.

9.	KEY WORDS Contractors designed pcc Quality control	10.	NO. OF PAGES 108

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DISCLAIMER

INTRODUCTION

The Iowa Department of Transportation project STPN-5-4(40)-2J-91 is the first quality management concrete (QMC) project in the state of Iowa. QMC allows the contractor to develop the mix design for the portland cement concrete (pcc) used in a project. The design must meet minimum requirements outlined in Instructional Memorandum (IM) 530 and Special Provision 1349a (SP-1349a). IM 530 and SP-1349a are provided in Appendix A. A quality control plan is developed and implemented by the contractor for the production of the pcc pavement. Part of the QMC program is an incentive /disincentive payment schedule for 28 day compressive strength tests. Since the concrete is not an Iowa DOT standard mix, a previous record of performance is unavailable. Therefore, this research is intended to obtain additional data from the QMC project.

OBJECTIVE

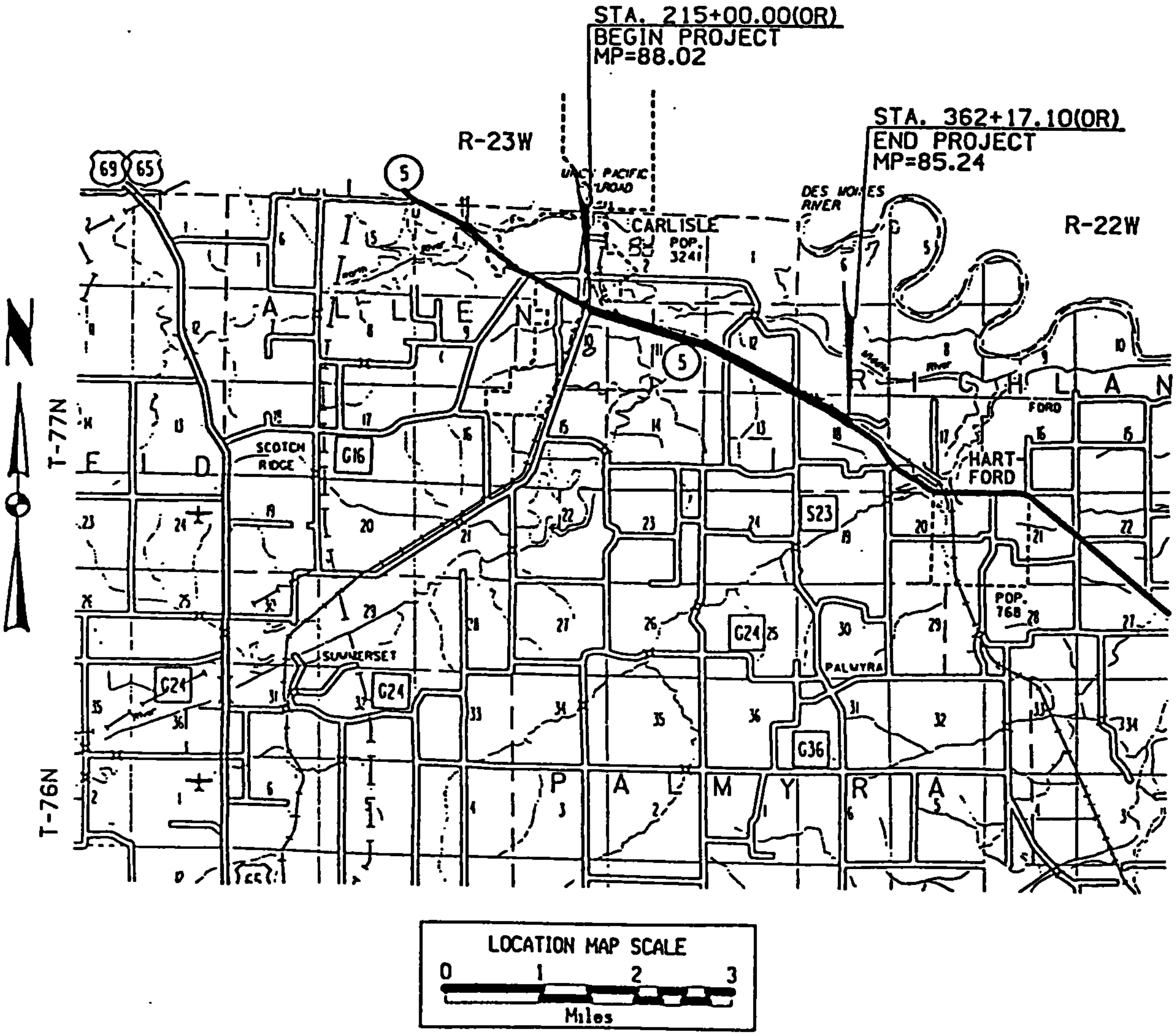
The objective of this research is to determine the potential differences in sampling and testing QMC for strength and to evaluate the contractors test results regarding the QMC PCC mix.

Specific topics to be investigated:

1. The differences in using 4" by 8" vertical, 6" by 12" vertical and 4.5" by 9" inch horizontal cylinders for compressive strength testing.
2. The variation of rodding and vibrating compressive strength specimens.
3. Correlations between strength tests of cylinders and beams.
4. The statistical capabilities of the contractors test results.
5. If changes in gradation correlate to changes in compressive strength during the production of the PCC.

PROJECT LOCATION

The project is located on Highway 5 in Warren county from mile post 88.02 (station 215+00) to mile post 85.24 (station 362+17) in the east bound lanes.



EXPERIMENT DESIGN

The experiment consisted of making 54 cylinders and 24 beams. In addition, 24 cores were taken from the pavement. The samples were taken at six locations (Table 1) during the first two days of paving.

TABLE 1
SAMPLE LOCATIONS

SAMPLE	DATE	STATION
1	10/22/97	223+20
2	10/22/97	225+20
3	10/22/97	229+60
4	10/23/97	248+20
5	10/23/97	251+10
6	10/23/97	258+10

CYLINDERS

At each location nine cylinders were made. A two factorial experimental design was used for the cylinders. The two factors were cylinder size and consolidation effort. Both factors had three levels.

The three cylinder mold types were 8" vertical with a 4" diameter, 12" vertical with a 6" diameter, and 9" horizontal with a 4.5" diameter. The 4" by 8" and 6" by 12" molds were made of plastic. The 4.5" by 9" molds were made of brass.

The three consolidation efforts were rodded, low vibration, and high vibration. The cylinders were made and tested according to IM 315. The vibrator used to consolidate the concrete in the molds was operated at 6500 vpm. The vibrator head had a ⅞ inch diameter. It had an eccentric force of 112 lbf and an amplitude of 0.070 inches while operating at 10600 vpm. All the cylinders were consolidated by vibrating each lift with a single insertion of the vibrator.

The low vibrator consolidation effort was achieved by allowing the vibrator to settle by gravity into a lift until it nearly penetrated to the bottom for the mold for the first lift. For successive lifts the vibrator was allowed to settle until it penetrated the previous lift by approximately ½ of an inch. The vibrator was held stationary in the concrete lift for one second after reaching the desired immersion depth. It was slowly extracted from the lift to prevent the vibrator from creating a void. The entire consolidation process lasted approximately six seconds per lift. On the second day the length of time for the stationary immersion was increased to three seconds. This increased the entire length of vibration to approximately eight seconds. The change was initiated because the concrete was not receiving an adequate consolidation effort to level the surface of all the cylinder mold types as required by IM 315. The 4.5" by 9" cylinders appeared to need the extra immersion time to level the concrete in the mold. This was confirmed when the cylinder molds were removed. The 4.5" by 9" mold had more visible voids than the other two cylinder sizes. High vibration cylinders used a time of ten seconds for the stationary immersion period. The cylinders were cured on grade for 24 to 48 hours before being transported and cured in the Iowa DOT Central Materials moist room. The cylinders were tested according to IM 315 at 28 days of age.

BEAMS

The beams were cast according to IM 328. The beams were stored on grade for 24 to 48 hours, then transported to the Iowa DOT Central Materials moist room. Two from each set of four beams was randomly selected to be tested at 14 days of age. The remaining beams were tested at 28 days of age. The beams were tested according to ASTM C78, third point testing of simple concrete beams.

CORES

Four cores were taken from each of the six testing locations. From each lot of four cores, two were drilled in vibrator trails and two were drilled between vibrator trails. All cores were taken to the Iowa DOT Central Materials moist room after coring. They were tested at 28 days of age according to IM 315.

TEST RESULTS

The raw test results for the cylinders, cores, and beams are in Appendix B. The 6" by 12" cylinder consolidated by rodding in sample number six was damaged during its initial cure on the grade. The compressive strength of this cylinder is disregarded in the following analyses.

EFFECT OF CYLINDER TYPE ON COMPRESSIVE STRENGTH

The cylinders showed a significant difference in test results based on cylinder size. Figure 1 in Appendix C displays the cylinder strength test results by mold. Figure 2 displays the mean compressive strengths of the three mold sizes.

TABLE 2
CYLINDER STRENGTH BY MOLD

	4.5" by 9"	4" by 8"	6" by 12"
Mean	5606 psi	6710 psi	6496 psi
Standard Deviation	1135 psi	639 psi	545 psi
n	18	18	17

TABLE 3
t-TEST RESULTS OF CYLINDER MOLDS

4.5" by 9" vs. 4" by 8"	4" by 8" vs. 6" by 12"	4.5" by 9" vs. 6" by 12"
0.00128	0.2929	0.0063

A t-test result shows the likelihood that the means of the two samples are similar. So, one minus a t-test indicates the probability that the two samples are from different populations. For example a t-test of 0.05 indicates a 0.95 probability or 95 percent likelihood that the two samples are from separate populations. Therefore, the t-tests indicate the 4.5" by 9" cylinders were statistically different from the 4" by 8" and 6" by 12" cylinders with greater than 95% confidence (Table 2 and Table 3).

Another significant item to note is the large standard deviation of the strength results for the 4.5" by 9" cylinders. This standard deviation is nearly twice that of the other two mold sizes. This indicates that the 4.5" by 9" molds may have a greater sensitivity to the three consolidation methods.

EFFECT OF CONSOLIDATION METHOD ON COMPRESSIVE STRENGTH

The vibration method had some impact on the strength of the cylinders (Table 4), but the impact was of less magnitude than the mold size. Figure 3 and Figure 4 in Appendix C display the compressive strength test results by consolidation method.

TABLE 4
CYLINDER STRENGTH BY CONSOLIDATION METHOD

	Rodded	Low Vibration	High Vibration
Mean	6508 psi	5899 psi	6405 psi
Standard Deviation	858 psi	1115 psi	736 psi
n	17	18	18

TABLE 5
t-TEST FOR CONSOLIDATION METHODS

Rodded vs. Low Vibration	Low Vibration vs. High Vibration	Rodded vs. High Vibration
0.07869	0.11885	0.70612

The t-tests do not indicate that any of the consolidation methods are different at a 95 percent confidence level (Table 5). The high vibration and rodded compressive strengths have similar means and standard deviations. The low vibration compressive strengths appear to be split into two populations (Figure 3). The population of higher strength seems similar to the rodded and high vibration consolidation compressive strengths. This indicates that an interaction may be occurring between the low vibration consolidation method and the mold size variable.

A look at the low vibration 4.5" by 9" cylinders also shows a possible interaction. If the compressive strength results for the 4.5" by 9" low vibration consolidation effort cylinders are divided by the average of all the other cylinder strengths in each sample set of nine, the following results are generated (Table 6). Figure 5 in Appendix C shows these results graphically.

TABLE 6
RATIO OF COMPRESSIVE STRENGTHS

Run Order	Day	Length of Consolidation Time After Full Insertion (sec)	4.5" by 9" Low Consolidation Effort Compressive Strength (psi)	Average of Other Compressive Strengths (psi)	Ratio
1	1	1	4162	5661	0.74
2	1	1	3534	6759	0.52
3	1	1	4439	6933	0.64
4	2	3	7092	7186	0.99
5	2	3	6049	5836	1.04
6	2	3	6509	5895	1.10

The ratios clearly show that the increase in consolidation time after complete insertion from one to three seconds increased the relative compressive strength of the 4.5" by 9" low consolidation effort cylinders. The other low consolidation effort cylinder sizes did not experience a significant change. This indicates the 4.5" by 9" horizontal cylinders may be more sensitive to vibratory consolidation effort than the 4" by 8" vertical and 6" by 12" vertical cylinders.

The overall impact of this change in consolidation method can be seen in Figure 6 of Appendix C. The day two low vibration strengths are much closer to the rodded and high vibration consolidation methods than the day one strengths. However, a comparison of consolidation method sorted by mold size does not show an overall improvement for the 4.5" by 9" cylinder molds. The 4.5" by 9" cylinder molds have a lower compressive strength for both days. Figure 7 in Appendix C shows these comparisons.

INTERACTION OF CONSOLIDATION METHOD AND CYLINDER SIZE

Interaction plots of the cylinder size and vibration method are provided in Figure 8 and Figure 9 in Appendix C. The graphs suggest an interaction occurring with the 4.5" by 9" low consolidation effort cylinders. As noted earlier, this interaction is particularly strong for the one second full immersion period used on day one. Table 7 lists the mean compressive strengths for the test combinations.

TABLE 7
MEAN CYLINDER STRENGTHS

Consolidation Method	Cylinder Size	Mean Compressive Strength
Rodded	4.5" by 9" Horizontal	5929
Rodded	4" by 8" Vertical	7033
Rodded	6" by 12" vertical	6573
Low Vibration	4.5" by 9" Horizontal	4689
Low Vibration	4" by 8" Vertical	6449
Low Vibration	6" by 12" vertical	6459
High Vibration	4.5" by 9" Horizontal	6099
High Vibration	4" by 8" Vertical	6648
High Vibration	6" by 12" vertical	6468

A graph of the mean compressive strengths sorted by consolidation effort and cylinder size is provided in Figure 10 of Appendix C. Figure 11 in Appendix C shows all the individual compressive strength test results sorted by run order, cylinder size, and consolidation effort. Figure 10 and Figure 11 both show the interaction that occurs between the 4.5" by 9" cylinder and the low vibration effort. Figure 10 also shows that the 4.5" by 9" cylinders had a lower strength than the other two cylinder sizes for all three levels of consolidation effort.

BEAMS

The 14 day average flexural strength was 619 psi. The 28 day average flexural strength was 690 psi. The value of 690 psi was close to the contractors design value of 700 psi. Figure 12 in Appendix C displays all the flexural strength test results. Table 8 lists the average strengths. All the sets of two beams broken at 14 and 28 days were very close. The pooled sample standard deviation is only 12.8 psi. The pooled sample standard deviation is the average standard deviation of all sets of two beams.

A linear regression analysis of 14 and 28 day flexural strengths was performed to determine if 14 day strengths can predict 28 days. The linear regression resulted in a 0.74 R^2. This indicates a good correlation between the 14 day and 28 day flexural strengths, but the correlation is only good enough to get a working estimate of 28 day strengths. A larger sample size and a more complicated modeling procedure would be required if a more exact estimate of 28 strengths is desired. Figure 13 in Appendix C plots the 14 day flexural strengths against the 28 day flexural strengths.

TABLE 8
BEAM DATA

Run Order	Days of Age at Break	Average Flexural Strength (psi)	Range (psi)	Sample Standard Deviation (psi)
1	14	559	20	14
2	14	615	0	0
3	14	639	10	7
4	14	652	17	12
5	14	606	20	14
6	14	642	15	10
1	28	611	12	9
2	28	698	55	39
3	28	727	3	2
4	28	722	41	29
5	28	703	22	16
6	28	683	2	1

28 DAY FLEXURAL STRENGTHS VERSUS CYLINDER STRENGTH

The 28 day average flexural strengths are graphed against the 28 day average compressive strengths for each lot. A linear regression analysis of the data results in an R^2 of 0.64. The regression equation has a constant of 343 psi and a slope of 0.055 flexural/compressive psi. The correlation shows a positive relationship, but the relationship is not strong enough to accurately predict flexural strength from the compressive strengths for individual lots. Figure 14 in Appendix C is a graph of flexural and compressive strength by lot.

CORE COMPRESSIVE STRENGTHS

The results of the core compressive strengths are displayed in Figure 15 of Appendix C. The average compressive strength of the cores from the vibrator tails was 6309 psi, and the average compressive strength of cores between the vibrator trails was 5855 psi. A two tailed t-test of the cores results in a value of 0.031. This is significant at the 95 percent confidence level. This indicates that if cores are taken from the pavement, the location relative to the vibrators should be noted. Cores taken from a vibrator trail will have a higher compressive strength than cores taken between vibrators.

Future cores taken from the slab to verify strength should be selected from a random location or be taken from between vibrator trails. These methods would reduce the risk of overestimating the strength of the concrete.

PROCESS CONTROL

The second half of this research project involved looking at the process control capabilities of the contractor. The process will be tested by control charts for the mean (X-bar) and range (R) of sample subgroups for process stability. If the process is stable, the ability of the contractors production process to met specifications will be determined.

CYLINDERS

The cylinders for determining strength were made in sets of two. Both cylinders were made from the same batch of concrete on the grade. The cylinders were made and tested according to

IM 315. Each set of two cylinders (a sample subgroup) constituted a test that represented a lot. Fifteen sets of cylinders were made during the construction of the eastbound lanes. The mean compressive strength of the fifteen sets of cylinders was 6859 psi. The average range of the tests was 278 psi. The standard deviation of the average strength of the fifteen sets was 618 psi. Table 9 lists the compressive strength test results.

Process control charts for the range and sample means are provided in Figure 1 and 2 in Appendix D. The control charts have limits of three standard deviations based on the average range. A point outside these limits indicates the process is not in statistical control.

The X-bar chart for the sample averages has five of its fifteen points outside the process limits. This indicates the process is statistically unstable. However, the R chart for the range of strengths obtained in a sample is in control. This indicates the concrete sampled at each test location is uniform, and the sampling procedure and testing are not causing the process to be out of control. Though the contractors process is out of statistical control, the pay factor strength of 6241 psi is high enough to achieve the maximum incentive. The pay factor strength is determined by taking the average test strength minus one standard deviation of the average test strengths. Since the process of concrete strength is not in statistical control, a process capability assessment cannot be completed.

TABLE 9
PROCESS CONTROL CYLINDERS

Sample Identification	Compressive Strength (psi)	Range (psi)	Test Average (psi)
1A 1B	6456 6261	195	6358
2A 2B	7252 7906	654	7579
3A 3B	8419 8578	159	8498
4A 4B	6296 7004	708	6650
5A 5B	6456 6420	36	6438
6A 6B	7163 7517	361	7340
7A 7B	6420 6084	336	6252
8A 8B	6898 6721	177	6809
9A 9B	6084 6190	106	6137
10A 10B	6721 6969	248	6845
11A 11B	6509 7075	566	6792
12A 12B	6173 6314	141	6243
13A 13B	7287 7004	283	7145
14A 14B	7110 7075	35	7092
15A 15B	6792 6615	177	6703

COMBINED GRADATION

The sampling and testing of the aggregate gradations were conducted in accordance to IM's 301, 302, 303, 304, 305, and 306. The gradations were controlled by the percent of material retained on each sieve for the combined gradation. The fine and coarse aggregate gradations were sampled separately. The individual percent retained gradations were then combined mathematically by their relative proportion by weight in the mix. This mathematical combined gradation was used for process control.

Aggregate test specifications allow a tolerance from the target based on the sieve size. The target percent retained for each sieve is determined by the contractor before construction. The targets were based on the laboratory PCC mix design. Table 10 has the gradation targets and limits for the percent retained on each sieve.

SP-1349a allowed for the gradations to use a running average of three for process control. The analysis in this report will use only individual gradation tests. The reason for using the individual gradation is to increase the likelihood of signaling a gradation change. For example the 3/4" sieve has a tolerance of 5 percent. If the process was producing at the target, it would take a change of 26 percent retained on the 3/4" sieve of the coarse aggregate gradation to signal an alarm. So, one fourth of all the coarse gradation must shift from other sieves to the 3/4" sieve before an alarm is signaled. This type of alarm system can potentially miss large shifts in an aggregate gradation. Secondly, the gradations are only tested once per half day of production. If the gradation shift is averaged with other tests, it may take several days to signal an alarm.

TABLE 10
GRADATION TARGET AND TOLERANCES

Sieve	Target Percent Retained	Upper Limit	Lower Limit
37.5 mm (1 ½ inch)	0.0	5.0	0.0
26.5 mm (1 inch)	6.7	11.7	1.7
19 mm (3/4 inch)	15.6	20.6	10.6
13.2 mm (½ inch)	20.3	25.3	15.3
9.5 mm (⅜ inch)	8.0	13.0	3.0
4.75 mm (No. 4)	7.5	12.5	2.5
2.36 mm (No. 8)	6.5	10.5	2.5
1.18 mm (No. 16)	8.8	12.8	4.8
600 µm (No. 30)	11.6	15.6	7.6
300 µm (No. 50)	10.2	13.2	7.2
150 µm (No. 100)	3.2	5.2	1.2
75 µm (No. 200)	0.3	2.3	0.0
Pan	0.8	1.6	0.0

Fifteen combined gradations were produced by the contractor. The results of the combined gradations are in Table 11.

TABLE 11
GRADATION RESULTS

Sieve	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15
1 ½ in.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 in.	2.9	2.8	2.1	2.0	1.4	2.0	1.7	2.3	1.6	2.4	1.3	1.2	1.3	1.5	2.3
¾ in.	12.6	13.8	13.8	13.0	15.7	14.2	14.7	14.6	14.2	13.7	13.2	11.5	12.1	14.5	19.8
½ in.	16.4	15.5	15.8	17.7	16.5	17.0	17.4	16.7	18.8	18.4	17.7	14.9	15.8	15.9	16.0
⅜ in.	12.6	11.7	11.8	12.1	12.8	12.0	12.3	12.3	12.7	13.2	12.6	11.4	13.2	13.3	9.5
No. 4	11.7	12.7	12.1	11.5	10.4	11.3	11.3	10.5	9.1	8.1	10.7	14.4	13.0	8.3	8.4
No. 8	7.5	7.7	8.8	8.6	7.3	7.1	7.9	8.3	8.3	8.5	10.2	11.8	9.3	8.4	8.3
No. 16	8.8	8.1	9.1	9.0	8.3	7.9	8.7	9.7	9.0	7.6	8.4	8.7	9.0	8.1	8.8
No. 30	11.3	11.9	11.1	10.5	10.8	10.3	10.3	10.6	11.3	11.5	11.3	10.8	10.8	10.1	10.7
No. 50	10.7	10.8	10.3	9.8	11.3	11.3	10.3	9.0	9.7	10.7	9.6	9.5	10.3	11.6	9.4
No. 100	3.4	3.6	3.1	4.2	4.6	4.6	3.8	4.6	3.2	3.9	2.9	3.2	3.1	4.7	3.1
No. 200	0.3	0.3	0.3	0.3	0.4	0.4	0.3	0.3	0.2	0.4	0.3	0.3	0.3	0.4	0.3
Pan	0.8	0.8	1.0	1.0	1.0	1.1	1.4	1.2	1.6	1.6	1.8	2.3	1.9	2.1	1.0

GRADATION ANALYSIS

The thirteen sieves were analyzed with the assumption that they were independent from each other. This simplifies the dependence of the sieves in the gradation analysis because each sieve can be out of statistical control for a test without significantly affecting other sieves. Histograms, individuals (I), and moving range charts (MR) were analyzed for each sieve except the 1 ½ inch sieve. The 1 ½ inch sieve never retained any material, so it is in statistical control and meeting specification limits. Additionally a capability analysis was done for each sieve if it was appropriate. All graphs for gradation analysis are in Appendix E. They are arranged by size from the 1 inch sieve to the pan.

Histograms of the sieves were made to look at the distribution of the data and to determine if the process was producing gradations within specification limits. The histogram included all fifteen data points as well as the upper specification limit (USL) and the lower specification limit (LSL). The small sample size does not allow for a good estimate of the data distribution. Larger samples would have greatly aided in identifying if the percent retained on a sieve had a normal distribution. The individuals control charts also serve as run charts for analyzing the data.

The process potential (Cp) indicates if the process is capable of producing within specification limits. If Cp is greater or equal to 1, the process is capable of producing units within specifications all the time. The process performance (Cpk) indicates how the process is actually performing with regard to specification limits. If Cpk is greater than or equal to 1, the process is currently producing all units within specification limits. Both the Cp and Cpk are produced using the overall process standard deviation for each sieve.

1 ½ Inch Sieve

The 1 ½ inch sieve retained no material for all fifteen tests. Thus, no variance is observed. The zero percent retained is the target specification. Thus the 1 ½ inch sieve is in statistical control and operating ideally.

1 Inch Sieve

The histogram show that most of the test results are near the lower specification limit, and six points are below the specification limit. All the test results are within a two percent range. The individuals and moving range charts show the 1 Inch sieve to be in statistical control. No trends are obvious in the individuals chart. The process capability analysis gives a Cp of 3.05 and a Cpk of 0.13. This indicates that the process is not producing on target, and the process is not currently producing within specification all the time. But the process is capable of producing within specification all the time, if it were producing on target.

¾ Inch Sieve

The data appears to be normally distributed except for one test result near the upper specification limit. This same point (15) is outside the control limits for the individuals and moving range charts. Test fifteen was the last test run for the project. The last of the project stockpiles were being used at this point in time. It is possible that this test indicates that the coarse aggregate may have become segregated. The increased aggregate retained on the 3/4 inch sieve is countered by a similar reduction on the ⅜ inch sieve. For this reason point fifteen is removed from the analysis of the ¾ inch sieve. Individual and moving range charts were recalculated using the remaining fourteen points. All fourteen points were in statistical control on the new charts. The process had a Cp of 1.49 and a Cpk of 0.92. This indicates that the process is not producing within specification limits all the time; however, the process is capable of producing within specification limits if it were producing on target.

½ Inch Sieve

The histogram shows the process is producing a gradation in the lower half of the ½ inch sieve specification range. The gradation covers a range of five percent. All data points are within specification limits. The individuals and moving range control charts show all points within control limits. The capability analysis produces a Cp of 1.49 and a Cpk of 0.42. Again, this indicates that the process is not producing within specification limits all the time; however, the process is capable of producing within specification all the time if it were on target.

⅜ Inch Sieve

The process is producing at an average near the upper specification limit. The data appears to be normally distributed except for one point. This is the companion data point for test fifteen on the analysis of the ¾ inch sieve. Two data points are above the upper specification limit. The individuals and moving range charts show point fifteen to be outside the limits of statistical control on the individuals and moving range charts. This point is removed from the analysis as a special case as indicated in the ¾ inch sieve. The new control charts with the remaining fourteen points show the process to be within statistical control. A Cp of 2.82 and a Cpk of 0.32 were determined in the capability analysis. These results indicate the process is capable of producing parts within specification limits, but the process is not currently on target.

No. 4 Sieve

The histogram for the No. 4 sieve indicates the process is producing units near the upper specification limit. Two test results were above the upper specification limit. The individuals control chart is in statistical control; however, the moving range chart has one point (14) above the upper control limit. This moving range result is caused by two tests that are within production limits, and no error in testing can be found. A decision was made to keep this data point. It is possible this data point produces a false alarm. The individuals chart shows that initially there may have been a trend of decreasing percent retained, and the first ten tests had a much smaller variance than the last five tests. This is a case were a longer run length to establish control limits and to observe trends would have been beneficial. A capability analysis was performed for this sieve, but its results should be taken with the recognition that this sieve has some questions to its statistical stability. A Cp of 0.91 and a Cpk of 0.29 resulted from the capability analysis. This indicates the process is not currently capable of producing a gradation within specification limits, and the process is not on target. A slight reduction in variability, or finding the cause of the increased variability in the last five tests would cause the Cp of the process to be greater than 1.

No. 8 Sieve

Test results for the No. 8 sieve appear to be mounded near the target except for one point. This one point is near the USL. No points are outside the specification limits. The individuals control chart indicates point number 12 is above the upper control limit. This is the same point identified by the histogram. This point was removed from the data set and a second set of control charts was developed. On these charts point number 11 was above the new upper control limit. Points 11 and 12 are from the same days production. It appears that the points may be the result of insufficient sieving on the coarse aggregate. Points 11 and 12 were removed from the analysis. The remaining thirteen tests were in control for both the individuals and the moving range charts. A process capability analysis was performed on the thirteen test points. A Cp of 2.13 and a Cpk of 1.25 were determined. This indicates that the process is currently producing within specification. The process would be improved, if it were producing closer to target.

No. 16 Sieve

The data for the No. 16 sieve is well in the middle of the upper and lower specification limits. The data appears to be normally distributed, and all points are within specification limits. The process has a Cp of 2.45 and a Cpk of 2.23. These results indicate the process is producing near target and will always produce within specification.

No. 30 Sieve

the histogram indicates the process is producing normally distributed data and the data is near the target. No points are outside the specification limits. All points are within the limits of the individuals and moving range control charts. The capability analysis resulted in a Cp of 2.65 and a Cpk of 2.17. These results indicate the process is producing near the target, and the process will always produce gradations within specifications for the No. 30 sieve.

No. 50 Sieve

The histogram indicates the process is producing near the target. The data appears to be normally distributed and all points are within specification limits. The individuals and moving range charts have all points within limits. The process capability resulted in a Cp of 1.28 and a Cpk of 1.25. These results indicate the process is producing at the target, and the process will produce units within specification limits.

No. 100 Sieve

The histogram indicates the data is normally distributed. No data points are outside specification limits. Control charts for individuals and moving range indicate no points outside control limits. The process capability analysis resulted in a Cp of 1.02 and a Cpk of 0.74. The process is not currently producing a gradation that will always be within specification limits, but it is capable of producing units within specification if it were centered on the target.

No. 200 Sieve

The histogram has no points outside the specification limits for the No. 200 sieve. The data is near the target of 0.3. The individuals chart shows no points outside the control limits. The moving range chart shows point 10 to be outside the control limits. The alarm is going to be ignored since the range is only 0.2 percent. Part of the reason for this alarm is that all the test results are 0.2, 0.3, or 0.4 percent, and point tem is the only time a 0.2 and 0.4 are next to each other. The process Cp is 6.84 and the Cpk is 1.9. These results indicate that the process is producing units within specification all the time. The process is actually doing better than the Cpk of 1.9 indicates. The lower limit of zero is what caused the Cpk of 1.9.

Pan

The histogram of the pan indicates the potential for two populations. Seven points are above the upper specification limit. The individuals control chart shows the percent retained increasing during the project. This indicates a possible degradation of the aggregate. The pan, material finer than the No. 200 sieve, is not a stable process.

GRADATION SUMMARY

Table 12 summarizes the results of the capability analysis for the gradations. All the sieves except the No. 4 and pan are capable of producing units within specification all the time. However, the 1 inch, ¾ inch, ½ inch, ⅜ inch , No 4, and No. 100 are not currently producing units within specification because they are off the target. The No.4 and No. 8 sieves appear to have had some special causes possibly related to testing.

TABLE 12
ANALYSIS OF AGGREGATE GRADATIONS

Sieve	Target	USL	LSL	Mean	Cp	Cpk
1 ½ in.	0.0	5.0	0.0	0.0	*	*
1 in.	6.7	11.7	1.7	1.9	3.05	0.13
¾ in.	15.6	20.6	10.6	13.7	1.49	0.92
½ in.	20.3	25.3	15.3	16.7	1.49	0.42
⅜ in.	8.0	13.0	3.0	12.4	2.82	0.32
No. 4	7.5	12.5	2.5	10.9	0.91	0.29
No. 8	6.5	10.5	2.5	8.2	2.13	1.25
No. 16	8.8	12.8	4.8	8.6	2.45	2.33
No. 30	11.6	15.6	7.6	10.9	1.65	2.17
No. 50	10.2	13.2	7.2	10.2	1.28	1.25
No. 100	3.2	5.2	1.2	3.7	1.02	0.74
No. 200	0.3	2.3	0.0	0.3	6.84	1.90
Pan	0.8	1.6	0.0	1.4	*	*

CORRELATION OF FINENESS MODULUS TO CYLINDER STRENGTH

Fineness modulus (FM) are calculated according to ASTM C125. It is determined by obtaining the cumulative percent retained by weight on a specified series of sieves and dividing by 100. The specified sieves for the fineness modulus are No. 100, No. 50, No. 30, No. 16, No. 8, No. 4, ⅜ in., ¾ in., and 1 ½ in. FM is an index of the fineness of an aggregate gradation. The higher the fineness modulus the coarser the aggregate gradation.

An attempt was made to correlate the FM of the 15 gradations with the 15 sets of cylinder tests. One gradation was tested for each set of cylinders during each half day of production. This direct correlation of sample frequency was not intentional. The resulting regression analysis was an R^2 of 0.034. This is not to say that the fineness modulus does not have an impact on strength. Remember that the gradation samples and cylinders probably did not come from the same batch of concrete. Therefore, no conclusion can be made as to the impact gradation had on the concrete strength.

DISCUSSION

The results of the flexural strength tests indicate a possibility of using beams instead of cylinders for process control. The beams had a small within sample standard deviation. Third point loading is used in the design of the pavement, this would allow direct use of project test data to aide in the design process.

The contractors process control was precontrolled by the specification limits. Contractors need to develop there own process control procedures that allow a warning of when the process is unstable or that it is approaching specification limits. This would allow contractors to reduce their risk of exceeding specification limits.

Contractors and the Iowa DOT need to accept the challenge of statistical process control. This includes providing training for statistical process control and accepting new methods of testing, accepting, and controlling construction processes. Contractors will have to learn the effects of mix changes on strength and variability. In addition, suppliers of materials for construction projects must be aware of the impact of their material on a statistical process control. Variability in input materials will lead to increased variability in output.

For statistical process control to work, contractors with smaller variances in production need to realize a benefit. Specifications need to put more of an emphasis on variability. Currently the pay factor equation only uses one standard deviation. In a case like this it is usually easier just to raise the average than reduce the variability. If the payment factor was determined by a logarithm that used more emphasis on the variance (2 or more standard deviations), a greater emphasis would be placed on decreasing variance.

CONCLUSIONS

This research on Quality Management Concrete supports the following conclusions:

1. The mold type used to cast the concrete cylinders had an effect on the compressive strength of the concrete. The 4.5" by 9" mold had lower strength at a 95 percent confidence interval than the 4" by 8" and 6" by 12" cylinders.

2. The consolidation procedure had some impact of the strength of the cylinder strength, but the effect was less significant than the cylinder size. The low vibration consolidation effort had the lowest strength. In particular an interaction occurred between the low vibration effort and the 4.5" by 9" mold. This interaction produced very low compressive strengths when compared with the other consolidation efforts.

3. A correlation of 0.64 R^2 was found between the 28 day cylinder and 28 day compressive strengths.

4. The compressive strength results of the process control testing were not in statistical

control. The aggregate gradations were mostly in statistical control. The gradation process was capable of meeting specification requirements. However, many of the sieves were off target.

5. The fineness modulus of the aggregate gradations did not correlate well with the strength of the concrete. However, this is not surprising considering that the gradation tests and the strength tests did not represent the same material. In addition the concrete still has many other variables that will effect its strength that were not controlled.

APPENDIX A

IM 530 and SP-1349a

QUALITY MANAGEMENT AND ACCEPTANCE
P. C. CONCRETE PAVEMENT
January 14, 1997

GENERAL

This Instructional Memorandum is based on the concept of mutual benefit partnership between the contracting agency and the contractor during progress of the work. A formal partnership agreement may or may not be in effect.

The Contractor shall provide and maintain a quality control system that will produce concrete work of acceptable quality in accordance with the Contract requirements specified herein.

The Engineer will not sample or test for quality control or assist in controlling the Contractor's production operations. The Contractor shall maintain standard equipment and qualified personnel as required by the Specifications to ensure conformance to the Contract requirements. Procedures will be subject to the approval of the Iowa DOT before the work commences.

The Contractor shall perform quality control sampling, testing and inspection during all phases of the concrete work at the rate specified in the Contract documents.

The Contractor shall be responsible for the design and providing process control for a portland cement concrete mixture for use in pavement. The Concrete Design Mixture (CDM) shall be developed by the Contractor and approved by the Engineer.

In recognition of the time required to investigate and determine material and concrete mixture proportions for bidding purposes, the Department will allow a minimum of 8 weeks after announcement before bids will be required or accepted.

An Iowa DOT PCC Level II Certified Technician or Concrete Field Testing Technician Grade I, in accordance with ACI CP-2 shall be responsible for all Field Control sampling and testing and execution of the Quality Control Plan as specified in the specification documents and this Instructional Memorandum. An Iowa DOT PCC Level I Technician may perform the sampling and testing duties for which he or she is certified.

The mix design shall be performed by an individual familiar with mix design procedures and experienced in this field. The Iowa DOT shall concur with the contractor on the designation of the person to perform this design activity.

MIX DESIGN PROCEDURE

The CDM shall be developed using the ACI 211 procedure, PCA procedure, or an alternative method. When a CDM is developed, the absolute volume method shall be used.

A CDM with a record of performance strength may be submitted in lieu of a new CDM. A minimum of 30 strength tests each for 7 day and 28 day strength, shall be required as supporting documentation of the CDM performance. The concrete used for paving under this I.M. shall be produced with the same materials and batched and mixed with the same equipment used to produce the concrete represented by the performance strength documentation.

For each proposed aggregate proportion, the CDM shall be determined from a minimum of three batches for different cementitious contents. The compressive strength test results of these mixtures shall be plotted and a proposed CDM may be determined from a graph of the three mixtures. The graphs shall be based on the 28-day strength and the average of a minimum of two tests per mixture.

FIELD CONTROL

Compression tests shall be performed on one of the following test specimen sizes:

a) 6" x 12" vertically cast cylinders, using either neoprene or sulfur caps
b) 4 1/2" x 9" horizontally cast cylinders with no capping required

NOTE: Use the same size cylinders for both the CDM and field control. Agency assurance testing shall be performed using 4 1/2" x 9" cylinders.

The Maturity Method shall be used to monitor concrete strength development in the field. This shall be the method of process control for concrete strength during construction. A maturity curve shall be developed on the project site at the beginning of concrete production.

QUALITY CONTROL PLAN

The Contractor shall prepare a Quality Control Plan listing the type and frequency of inspection, sampling, and testing deemed necessary to measure and control the various properties of materials and construction governed by the Specifications. As a minimum, the sampling and testing plan shall detail sampling location, sampling procedures, and the test frequency to be utilized. The Quality Control Plan shall be submitted in writing to the Engineer at the time of the preconstruction conference. The Contractor shall not start paving until receipt of the approval of the Quality Control Plan.

The Plan shall identify the personnel responsible for the Contractor's quality control. This should include the company official who will act as liaison with Iowa DOT personnel, as well as the Certified Technician who will direct the inspection program. The certified technician shall be responsible to an upper level company manager and not to those responsible for daily production.

A) Elements of the Plan

The Plan shall address all elements that affect the quality of the concrete, including but not limited to, the following:

1) Mix Design(s)
2) Aggregate Production
3) Quality of Components
4) Stockpile Management
5) Proportioning, including Added Water, and Batch Yield
6) Mixing Time and Transportation, including time from batching to completion of delivery and batch placement rate (batches per hour)
7) Mix Design Properties, as specified in the specifications
8) Placement and Consolidation
9) Compressive Strength/Flexural Strength
10) Finishing and Curing

B) Personnel Requirements

1) The Plan shall detail:

   a) The frequency of sampling and testing, coordination of activities, corrective actions to be taken, and documentation.
   b) How the duties and responsibilities are to be accomplished and documented, and whether more than one Certified Technician is required.
   c) The criteria used by the Technician to correct or reject noncomplying materials, including notification procedures.

2) The Certified Technician(s) shall:

   a) Perform and utilize quality control tests and other quality control practices to ensure that delivered materials and proportioning meet the requirements of the mix design(s).
   b) Periodically inspect all equipment utilized in transporting, proportioning, mixing, placing, consolidating, finishing, and curing to ensure proper operation and that placement, consolidation, finishing, and curing conform with the mix design and other Contract requirements.
   c) The Contractor shall furnish name(s) and credentials of the quality control staff to the Engineer prior to sampling and testing.

DOCUMENTATION

The Contractor shall maintain records of all inspections and tests. The records shall indicate the nature and number of observations made, the number and type of deficiencies found, the quantities approved and rejected, and the corrective action taken. The Contractor's documentation procedures will be subject to the approval of the Iowa DOT prior to the start of the work and to regular monitoring during the progress of the work.

All conforming and non-conforming inspections and test results shall be recorded and shall be available at all times to the Iowa DOT during the performance of the work. Use standard Iowa DOT forms. Batch tickets and gradation data shall be documented in accordance with Iowa DOT requirements. Copies shall be submitted to the Iowa DOT as the work progresses.

Test data for Portland cement concrete, including gradation, shall be charted in accordance with the applicable requirements. The minimum number of charts shall be:

a) Gradation (% retained) for each of the following sieves for the total aggregate gradation: 1 1/2", 3/4", 0.53", 3/8", 4, 8, 30, 50, 100, 200*.
b) Moisture: coarse aggregate(s) and sand.
c) Unit Weight.
d) Water/cement ratio.
e) Batch yield.

* A moving average of 4 tests shall also be plotted on these charts.

The Contractor may use other types of control charts as deemed appropriate. Charting will be completed within 24 hours after testing.

Individual test results shall be plotted for each test point. A solid black line shall connect the points. The moving average for each test variable shall be plotted in red starting with the second test. A dashed red line shall connect the points. The Contracting Authority's acceptance test results shall be plotted with green asterisks. Working range limits shall be indicated on the control charts using a green inked dotted line.

The Contractor shall notify the Engineer whenever the process approaches a specification limit and shall take action which results in the test results moving toward the specification target, away from the limit.

All charts and records documenting the Contractor's quality control inspections and tests shall become property of the Iowa DOT upon completion of the work.

CORRECTIVE ACTION

The Contractor shall take prompt action to correct conditions that have resulted, or could result, in the incorporation of non-complying materials.

NON-COMPLYING MATERIALS

The Contractor shall establish and maintain an effective and positive system for controlling non-complying material, including procedures for its identification, isolation and disposition. Reclaiming or reworking of noncomplying materials shall be in accordance with procedures acceptable to the Iowa DOT.

All non-complying materials and products shall be positively identified to prevent use, shipment, and intermingling with conforming materials and products.

AVOIDANCE OF DISPUTES

Every effort should be made by the Contractor and the Engineer personnel to avoid any potential conflicts in the Quality Assurance Program prior to and during the project using partnering concepts. Potential conflicts should be resolved at the lowest possible levels between the Contractor and Engineer personnel. Correction of problems and performance of the final product should be the primary objective of this resolution process.

LOT DETERMINATION

Testing shall be on a lot basis. A lot shall constitute one day's paving. If less than 500 cy are produced in one day, that day's production shall be grouped with the following day's production.

SP-1349a
(Replaces SP-1349)
(revised 12-31-96)

Iowa Department of Transportation

SPECIAL PROVISIONS

FOR

QUALITY MANAGEMENT - CONCRETE
(QM-C)

Warren County, STPN-5-4(40)--2J-91

Date of Letting: January 14, 1997

THE STANDARD SPECIFICATIONS, SERIES OF 1992, ARE AMENDED BY THE FOLLOWING ADDITIONS AND MODIFICATIONS. THIS IS A SPECIAL PROVISION AND IT SHALL PREVAIL OVER PROVISIONS OF THE STANDARD SPECIFICATIONS.

1349a.01 DESCRIPTION.

This work shall consist of designing and monitoring a portland cement concrete mixture for use in paving.

In recognition of the time required to investigate and determine material and concrete mixture proportions for bidding purposes, the Department will allow a minimum of 8 weeks after announcement before bids will be required or accepted.

These requirements ~~may~~ shall apply to mainline pavement, shoulders of 4 feet or wider, and ramps. The requirements will not apply, at the Contractor's option, to tapers, approach slabs, gaps, variable width pavement, shoulders less than 4 feet wide.

1349a.02 MATERIALS.

All materials except aggregate gradation shall meet requirements for the respective items in Division 41 of the Standard Specifications or the Materials I.M.s.

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1349a.03 LABORATORY DESIGN MIXTURE.

At least thirty calendar days prior to the start of paving, the Contractor shall submit to the Engineer for review and concurrence the proposed Concrete Design Mixture (CDM) proportions which will result in a workable concrete having the following laboratory design mixture properties:

• Cementitious Content Nominal Maximum Coarse Aggregate Size:	3/4" and larger 1/2"	Minimum, 540 lbs./cu. yd. Minimum, 590 lbs./cu. yd.
• Fly Ash Volume, percent		Maximum, 20%, record
• Target Air Content		7 % ± 1%
• Water to cementitious materials ratio		Maximum, 0.45
• Unit Weight, plastic concrete		Record, lbs./cu. ft.
• Compressive Strength - 28 days 7 days Dimensions & Weight of Specimens		Minimum, 5500 psi Record, psi Record
• Flexural Strength, third point - 28 days 7 days Dimensions & Weight of Specimens		Record, psi Record, psi Record
• Maturity Curves * (Compressive & Flexural)		Materials I.M. 383, Record
• Slump		Record, maximum slump acceptable for the design mix
• Concrete Temperature **		Record, °F or °C

* The maturity curves shall be developed using the CDM. The maturity curves may be submitted any time after CDM submittal, but prior to actual mix production.

** Concrete temperature shall be recorded at the time of casting test specimens.

Proportions shall be based upon saturated-surface-dry aggregates. The aggregate portion passing No. 4 sieve shall be no less than 35 percent nor more than 50 percent of the total weight of the aggregate in each cubic yard.

A CDM shall contain proportions of materials, including admixtures. The CDM shall be based on the combination of coarse and fine aggregate for the following sieves: 1-1/2", 1", 3/4", 3/8", No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200. The percent passing the 1-1/2" sieve shall be 100 percent; the percent passing the No. 200 sieve shall not exceed 1.6 percent. A target gradation shall be developed for the CDM.

Water reducing admixture Type A, or water reducing and retarding admixture Type D, as listed in Materials I.M. 403, may be used at the Contractor's option.

The Contractor shall submit CDM with test data including a list of all ingredients, the source of all materials, target gradation, and the proportions, including specific gravities. The Contractor's CDM will be reviewed within 5 working days.

1349a.04 QUALITY CONTROL OF FIELD PRODUCED MIXTURES.

Quality control of the concrete shall be the responsibility of the Contractor. The quality control plan in accordance with Materials I.M. 530, shall be submitted to the Engineer at least ~~30~~ 10 calendar days ~~before paving is to begin~~ prior to the preconstruction conference. Paving shall not begin until the plan is reviewed for conformance with the contract documents. The Contractor shall maintain equipment and qualified personnel who shall direct and perform all field inspection, sampling and testing necessary to determine the various properties of the concrete governed by the contract documents and to maintain the properties described herein.

Quality control sampling and testing for field produced concrete shall be in accordance with Materials I.M. 530.

A. Field Production Limits.

	Limits	Minimum Testing Frequency Contractor Process Control	Test Methods
Unit Weight Plastic Concrete	±3% of CDM Unit Weight	Once/day	I.M. 358
Gradation	Range listed below	Once in AM and Once in PM, normally	I.M. 302,303, 304, 305
Compressive Strength, 28 day	4500 psi, required ave. strength	1 test/1000 cy	I.M. 315
Air Content, Unconsolidated Concrete	Target 7% ±1%	first load and 1/500 cy	I.M. 327

	Limits	Minimum Testing Frequency Contractor Process Control	Test Methods
Water/Cementitious Ratio	Maximum 0.45	once/day	I.M. 527

The aggregate gradation (a moving average of 4 tests) shall comply with the following working ranges:

Sieve Size	Working Range*
#4 sieve or greater	± 5%
#8 to #30 sieve	± 4%
#50 sieve	± 3%
#100 sieve	± 2%

*The Working Range Values are % retained on an individual sieve of the combined material.

B. Acceptable Field Adjustments.

A change in the source of materials or an addition of admixtures or additives shall necessitate a new CDM. The following are small adjustments that may be made without a new CDM being required:

- Increase cementitious content.
- Decrease fly ash substitution rate
- Fine aggregate increase or decrease of 100 pounds or less per cubic yard from the CDM proportions
- Coarse aggregate increase or decrease of 100 pounds or less per cubic yard from the CDM proportions
- Adjustment in water reducer or water reducer retarder admixture dosage; must be agreed upon between the Contractor and Engineer

The Contractor will be allowed to utilize a Class C mix contained in Materials I.M. 529 in the event conditions beyond the Contractors' control prevent completion of the work with the designed mixes. This shall be by mutual agreement between the Contractor and Engineer and at no additional cost to the Contracting Authority.

C. Production Control Parameters.

Slump tests will not be required for concrete produced under QM-C procedures.

A strength test shall be the average of the strengths of two cylinders made from the same batch of concrete and tested at 28 days or at test age designated for determination of minimum compressive strength.

Samples for strength tests shall be taken in accordance with Materials I.M. 327.

Cylinders for strength tests shall be molded , cured, and tested in accordance with Materials I.M. 315, plastic molds may be used.

~~Strength level at 28 days of a CDM shall be considered satisfactory if both of the following requirements are met:~~

~~(a) The running average of three consecutive strength tests equal or exceed the required average strength (4,500 psi).~~

~~(b) No individual strength test (average of two cylinders) fall below the required average strength by more than 500 psi.~~

~~If the likelihood of low strength concrete is confirmed, tests of cores drilled from the area in question may be required in accordance with "Methods of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete" (ASTM C 42). In such cases, three cores shall be taken for each strength test more than 500 psi below the required average strength. The cores shall be immersed in water for at least 40 hours and tested wet.~~

~~Concrete in an area represented by core tests will be considered structurally adequate if the average of three cores is equal to at least 85% of the required average strength and no single core is less than 75% of required average strength. To check testing accuracy, locations represented by erratic core strengths may be retested.~~

~~Acceptance sampling and testing of the concrete will be the responsibility of the Engineer.~~

D. Concrete Strength

1. Invalid Tests.

If the difference in strength between the test results for two cylinders is greater that 500 psi, and there is no obvious imperfections in a core, the following procedure shall be followed.

a. Two cores shall be cut, one from each lane, at the location where the two cylinders were cast.

b. The cores shall be tested for strength and averaged.

c. The averaged core strength shall be used in place of the cylinder strength as noted above.

2. Damaged Core

a. If one of the two cylinders is obviously damaged, test the other cylinder and report the results as the strength for that test.

b. If both cylinders are obviously damaged, use the procedure above to determine the strength.

3. Low Strength Results

If any strength test falls below 3500 psi, the section of pavement represented by that strength shall be removed and replaced at the Contractor's expense. The limits of removal shall be determined by drilling two cores at intervals of 60 feet either side of the location of the low strength cylinders. When the average of the cores is greater that 3500 psi, the limit of removal shall be determined by proportioning the strength to determine the location of the 3500 psi strength. This process shall continue at 60 foot intervals until the average exceeds 3500 psi.

1349a.05 METHOD OF MEASUREMENT.

The Engineer will compute the number of cubic yards of Quality Management - Concrete placed by the Contractor based on design quantities.

1349a.06 BASIS OF PAYMENT.

For the number of cubic yards of Quality Management - Concrete computed as provided above, the Contractor will be paid the predetermined contract unit price per cubic yard. This price will be considered full compensation for furnishing all labor, equipment and materials for the work required by the Contractor to design, test, and provide process control for the production of Quality Management - Concrete.

Payment for the square yards of pavement constructed shall be adjusted in the following manner:

1. Determine the Mean Strength and Standard deviation of all process control 28-day strength tests taken for entire project.

2. The ~~basis of payment~~ Pay Strength will be determined by subtracting one standard deviation from the Mean Strength to determine the Pay Strength. The following chart will be used to determine the pay factor.

PAY SCALE FOR STRENGTH

Pay Strength	% Pay	Pay Strength	% Pay
BELOW 3500	REMOVE	4500 - 4549	100
3500 - 4049	70	4550 - 4599	101
~~4000 - 4049~~	~~70~~	4600 - 4649	102
4050 - 4099	73	4650 - 4699	103
4100 - 4149	76	4700 - 4749	104
4150 - 4199	79	4750 - 4799	105
4200 - 4249	82	4800 - 4849	106
4250 - 4299	85	4850 - 4899	107
4300 - 4349	88	4900 - 4949	108
4350 - 4399	91	4950 - 4999	109
4400 - 4449	94	5000 & ABOVE	110
4450 - 4499	97		

APPENDIX B

Raw Data

CYLINDER COMPRESSIVE STRENGTHS

4" by 8"		6" by 12"		4.5" by 9"	
Sample Consolidation	Strength (psi)	Sample Consolidation	Strength (psi)	Sample Consolidation	Strength (psi)
1 Rodded	6250	1 Rodded	5483	1 Rodded	5055
1 Low Vibration	5680	1 Low Vibration	5879	1 Low Vibration	4162
1 High Vibration	5696	1 High Vibration	5837	1 High Vibration	5521
2 Rodded	6969	2 Rodded	7163	2 Rodded	6627
2 Low Vibration	6778	2 Low Vibration	6296	2 Low Vibration	3534
2 High Vibration	6651	2 High Vibration	6632	2 High Vibration	6954
3 Rodded	7414	3 Rodded	7131	3 Rodded	5810
3 Low Vibration	6476	3 Low Vibration	6933	3 Low Vibration	4439
3 High Vibration	7303	3 High Vibration	6827	3 High Vibration	7570
4 Rodded	8035	4 Rodded	6845	4 Rodded	7357
4 Low Vibration	7542	4 Low Vibration	7092	4 Low Vibration	6942
4 High Vibration	7208	4 High Vibration	7305	4 High Vibration	6250
5 Rodded	6571	5 Rodded	6243	5 Rodded	5194
5 Low Vibration	6030	5 Low Vibration	6049	5 Low Vibration	4766
5 High Vibration	6571	5 High Vibration	6120	5 High Vibration	5194
6 Rodded	7001	6 Rodded	3523	6 Rodded	5533
6 Low Vibration	6189	6 Low Vibration	6509	6 Low Vibration	4892
6 High Vibration	6460	6 High Vibration	6084	6 High Vibration	5106

BEAM THIRD POINT FLEXURAL STRENGTH

Sample Identification	Age at Testing Days	Modulus of Rupture psi
1 A	14	549
1 B	14	569
2 B	14	615
2 D	14	615
3 B	14	644
3 C	14	634
4 C	14	660
4 D	14	644
5 B	14	616
5 C	14	596
6 A	14	650
6 D	14	635
1 C	28	617
1 D	28	604
2 A	28	726
2 C	28	671
3 A	28	728
3 D	28	725
4 A	28	701
4 B	28	743
5 A	28	715
5 D	28	692
6 B	28	683
6 C	28	684

CORE COMPRESSIVE STRENGTH

Sample Identification	Location In = In Vibrator Trail Between = Between Vibrator Trails	Distance from North Edge of Slab to Center of Core (Inches)	Strength (psi)
1 A	In	42	7239
1 B	In	106	6683
1 C	Between	98.5	6698
1 D	Between	32.5	6301
2 A	In	42	6587
2 B	In	106	6380
2 C	Between	98.5	5776
2 D	Between	32.5	6221
3 A	In	42	6428
3 B	In	106	6969
3 C	Between	98.5	5823
3 D	Between	32.5	6277
4 A	In	42	6317
4 B	In	106	5887
4 C	Between	98.5	5712
4 D	Between	32.5	5919
5 A	In	42	5569
5 B	In	106	5776
5 C	Between	98.5	5696
5 D	Between	32.5	5267
6 A	In	42	5951
6 B	In	106	5919
6 C	Between	98.5	5314
6 D	Between	32.5	5251

CORE COMPRESSIVE STRENGTH

Sample Identification	Location On = In Vibrator Trail Between = Between Vibrator Trails	Distance from North Edge of Slab to Center of Core (Inches)	Strength (psi)
1 A	On	42	7239
1 B	On	106	6683
1 C	Between	98.5	6698
1 D	Between	32.5	6301
2 A	On	42	6587
2 B	On	106	6380
2 C	Between	98.5	5776
2 D	Between	32.5	6221
3 A	On	42	6428
3 B	On	106	6969
3 C	Between	98.5	5823
3 D	Between	32.5	6277
4 A	On	42	6317
4 B	On	106	5887
4 C	Between	98.5	5712
4 D	Between	32.5	5919
5 A	On	42	5569
5 B	On	106	5776
5 C	Between	98.5	5696
5 D	Between	32.5	5267
6 A	On	42	5951
6 B	On	106	5919
6 C	Between	98.5	5314
6 D	Between	32.5	5251

PLASTIC AIR TESTS

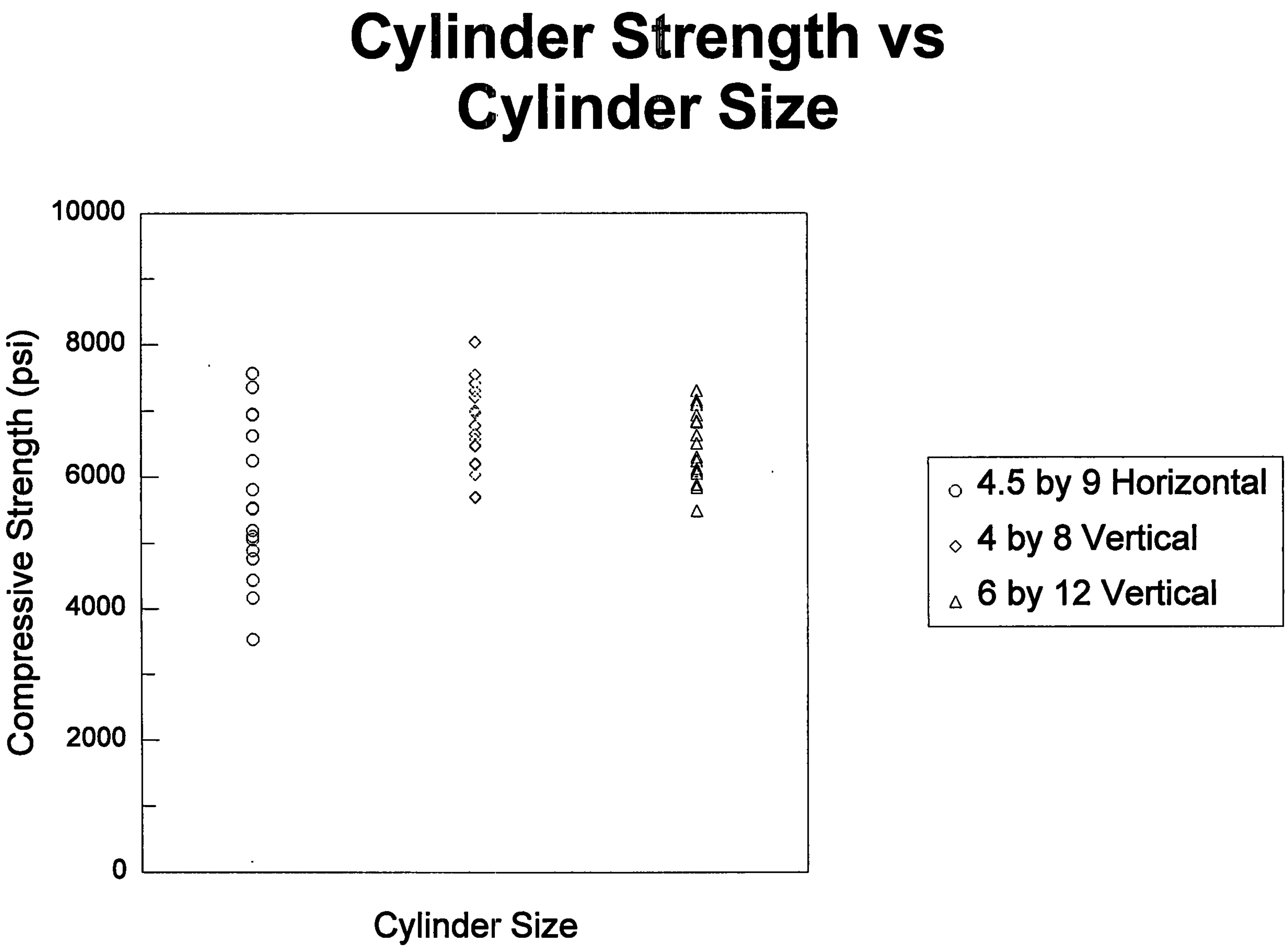
Sample Identification	Iowa DOT percent	Contractor percent
1	8.2	7.5
2	7.7	
3	5.9	
4	5.7	6.1
5	6.6	
6	7.8	

VIBRATOR SPACINGS OF PAVER

Vibrator Number	Distance from North Edge of Slab (Inches)	Vibrator Model
1	9	HV-2P
2	23	HV-2P
3	42	HV-2P
4	60	HV-2P
5	77	HV-2P
6	91.5	HV-2P
7	106	HV-2P
8	122	HV-2P
9	135	HV-2P
10	152	HV-2P
11	165	HV-2P
12	179	HV-2P
13	193	HV-2P
14	209	HV-2P
15	225.5	HV-2P
16	241	HV-2P
17	257	HV-2P
18	273	HV-2P
19	291	HV-2P
20	307.5	HV-2P

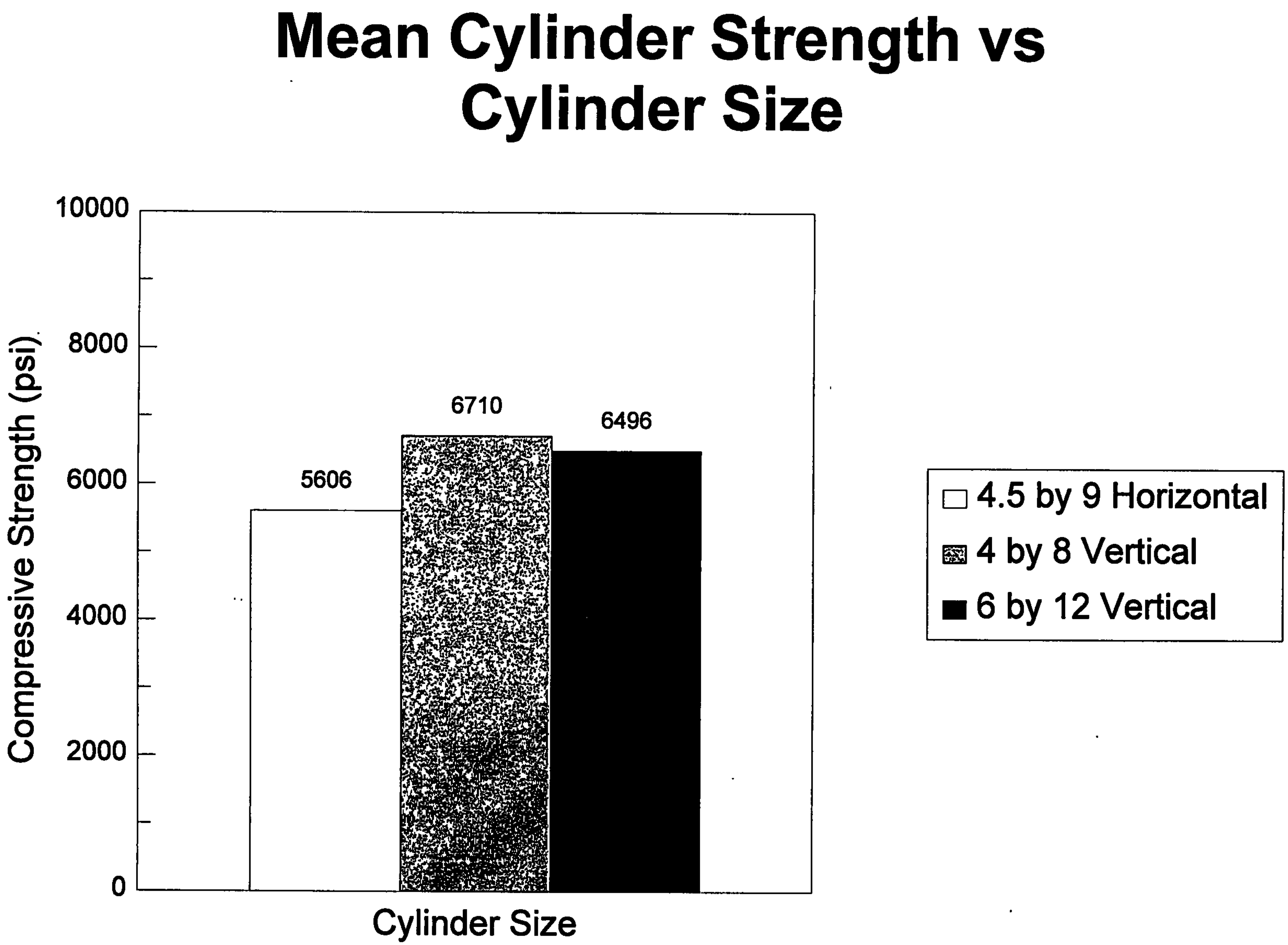
Notes: The paver paved West to East. All vibrator heads were 7 ¾ inches long. The pavement was 314.5 inches in width.

FIGURE 1



Cylinder Strength vs
Cylinder Size
Compressive Strength (psi)
10000
8000
6000
4000
2000
0
Cylinder Size
4.5 by 9 Horizontal
4 by 8 Vertical
6 by 12 Vertical

FIGURE 2



Mean Cylinder Strength vs
Cylinder Size
10000
8000
6000
4000
2000
0
Compressive Strength (psi)
5606
6710
6496
Cylinder Size
4.5 by 9 Horizontal
4 by 8 Vertical
6 by 12 Vertical

FIGURE 3

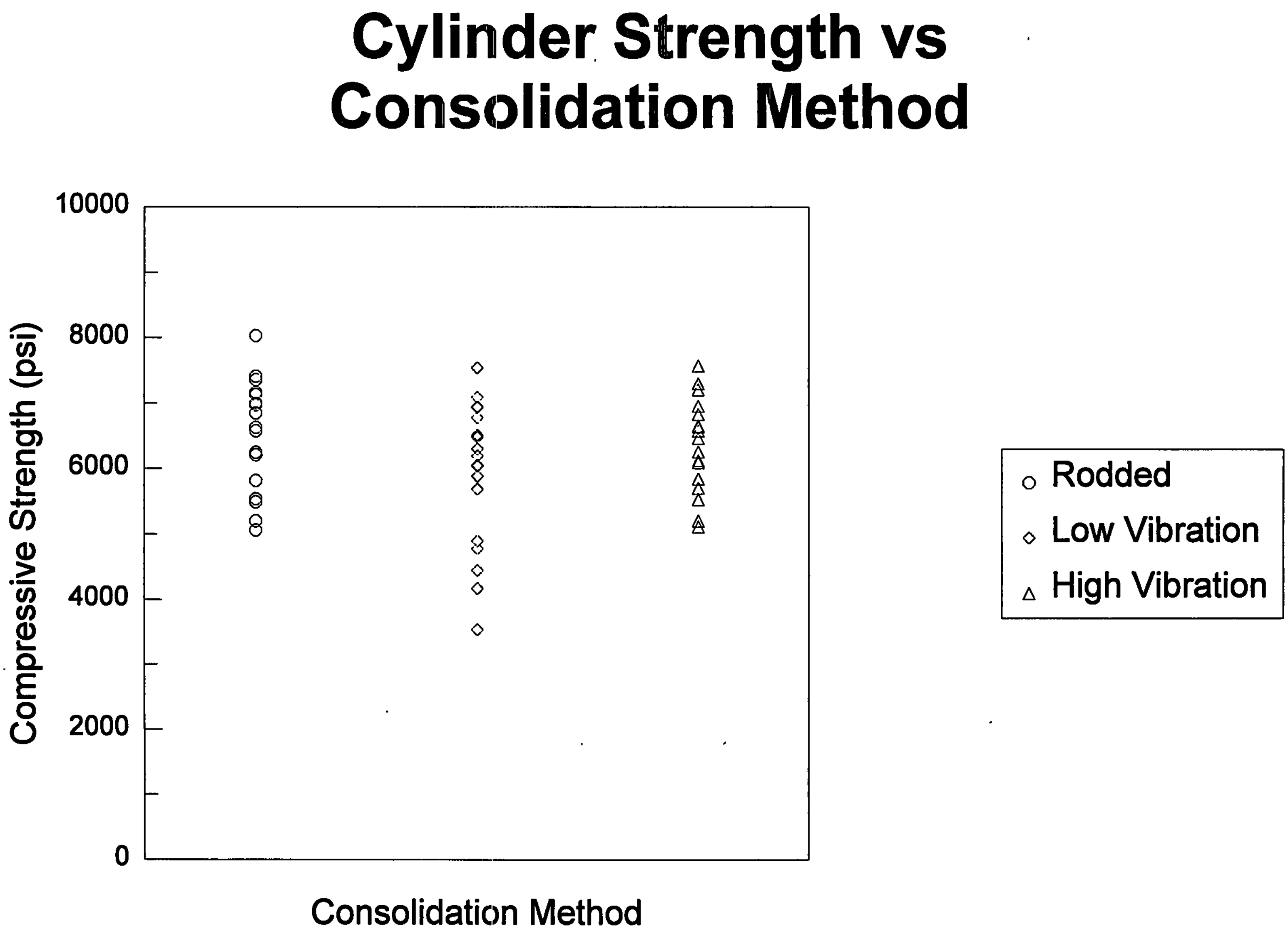

Cylinder Strength vs
Consolidation Method
Compressive Strength (psi)
10000
8000
6000
4000
2000
0
Consolidation Method
Rodded
Low Vibration
High Vibration

FIGURE 4

Mean Cylinder Strength vs Consolidation Method

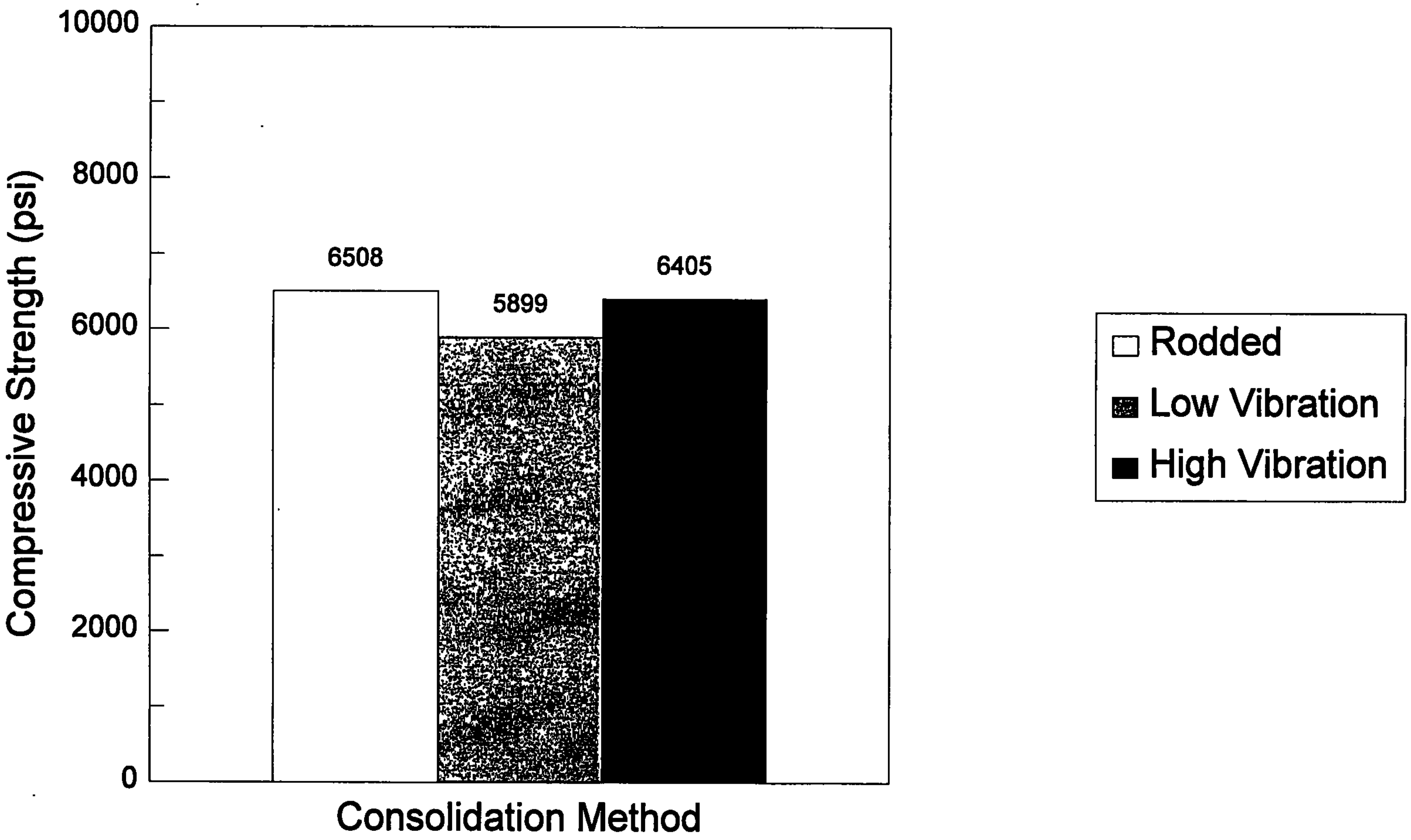


FIGURE 5

Ratio of Low Vibration 4.5" by 9" Cylinder to Average of Other Cylinders

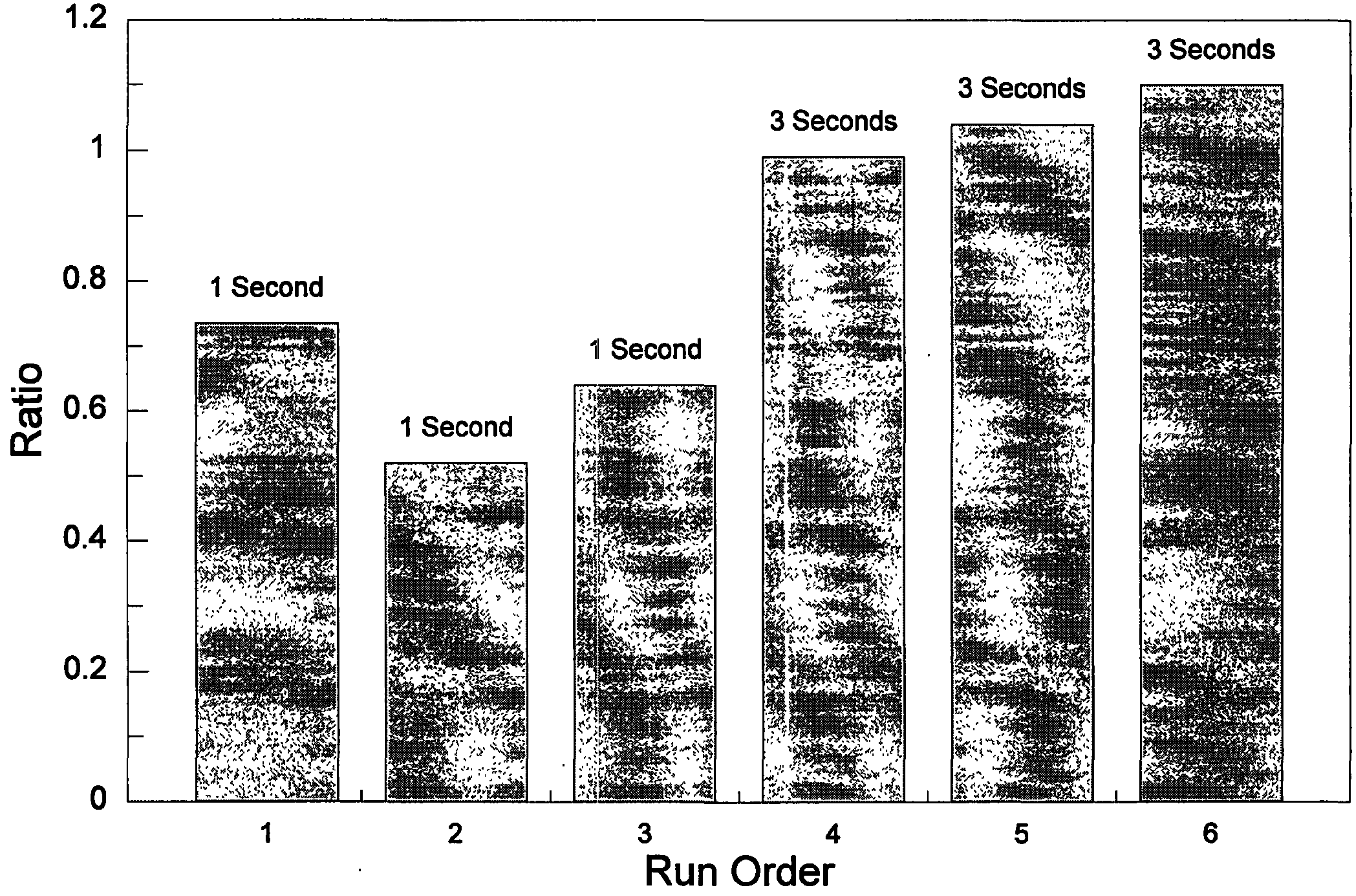


FIGURE 6

Mean Cylinder Strength vs Consolidation Method by Day

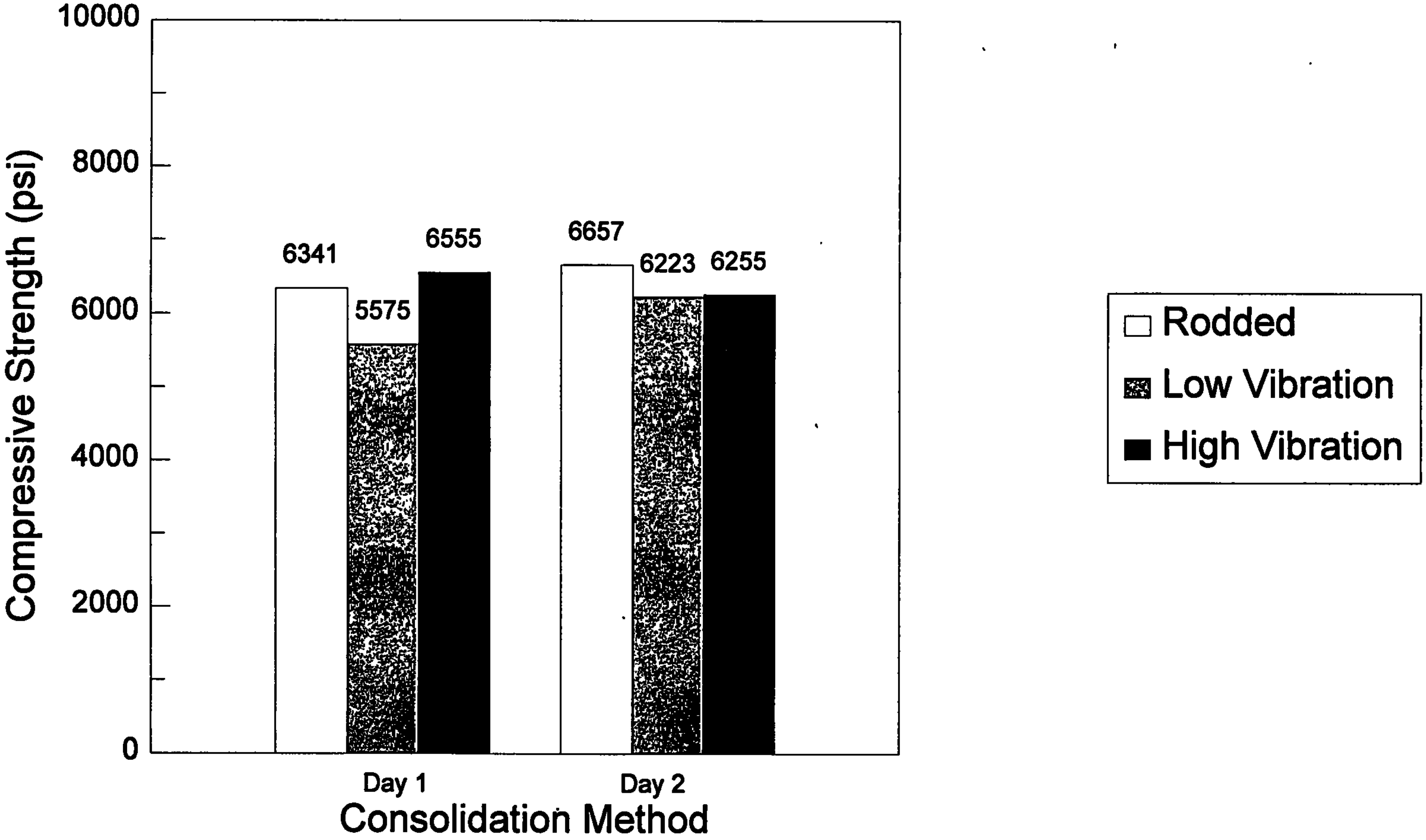
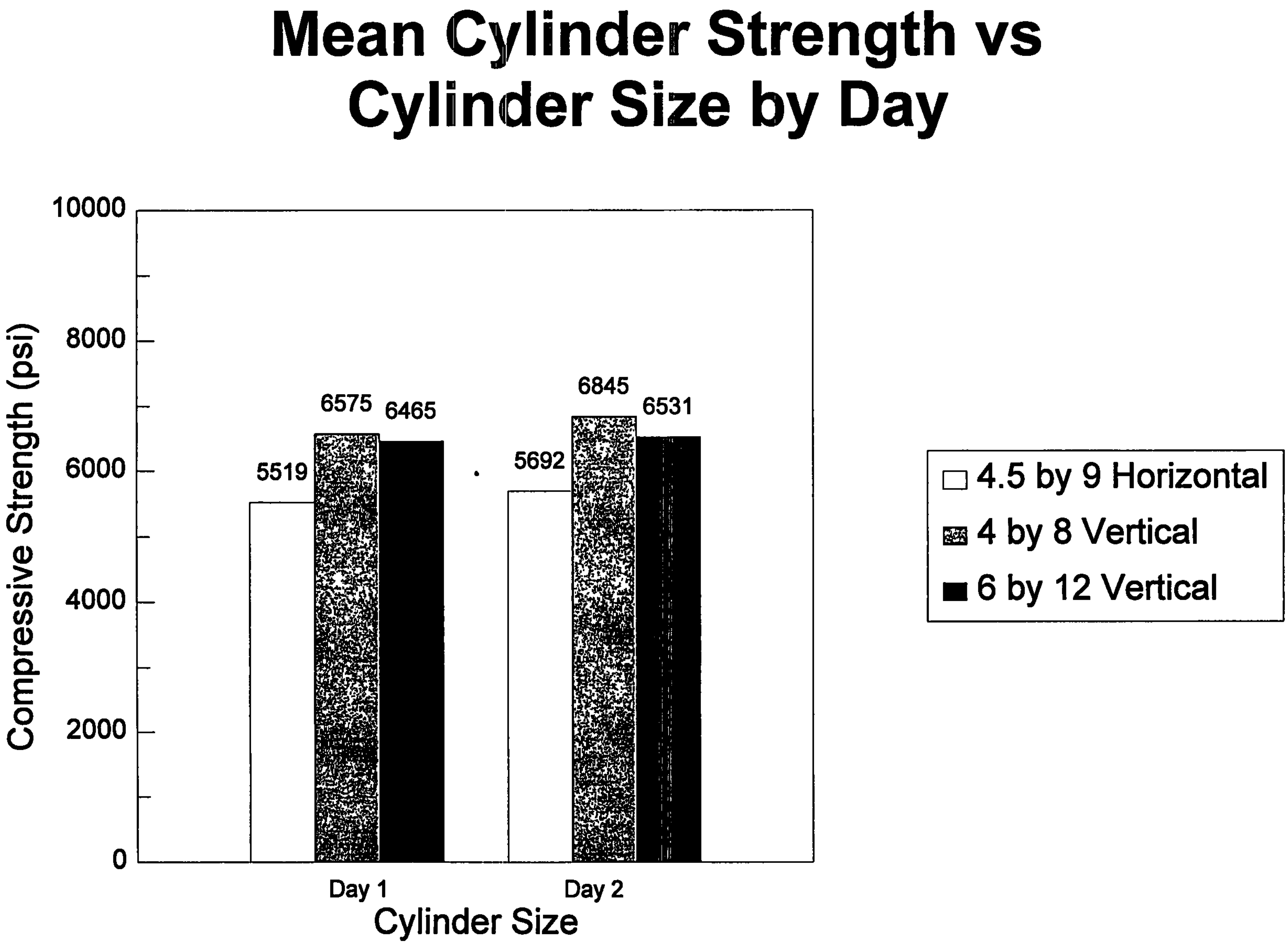


FIGURE 7



Mean Cylinder Strength vs
Cylinder Size by Day
10000
8000
6000
4000
2000
0
Compressive Strength (psi)
5519
6575
6465
5692
6845
6531
Day 1
Day 2
Cylinder Size
4.5 by 9 Horizontal
4 by 8 Vertical
6 by 12 Vertical

FIGURE 8

Interaction of Cylinder Size and Consolidation Method

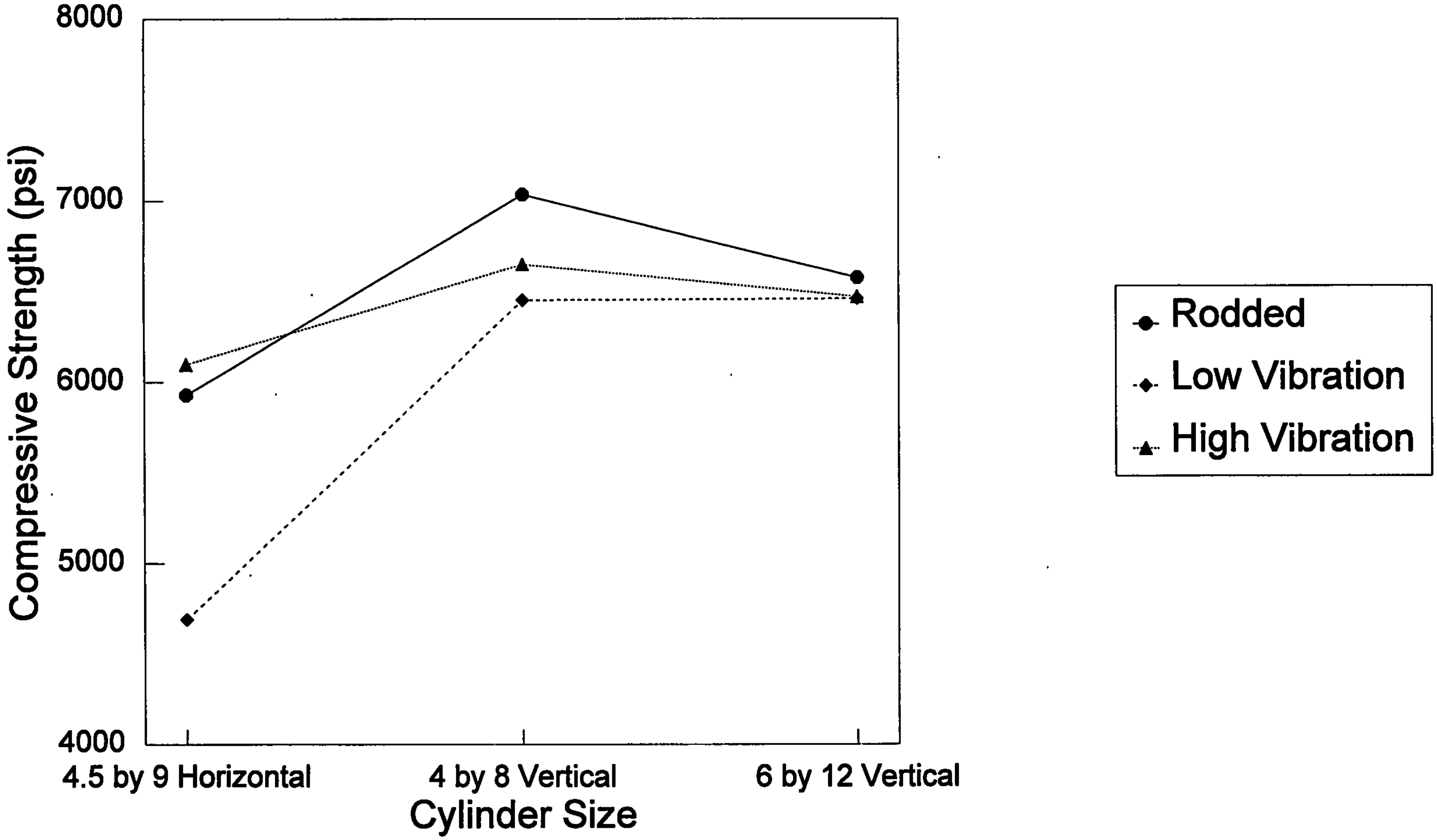


FIGURE 9

Interaction of Cylinder Size and Consolidation Method

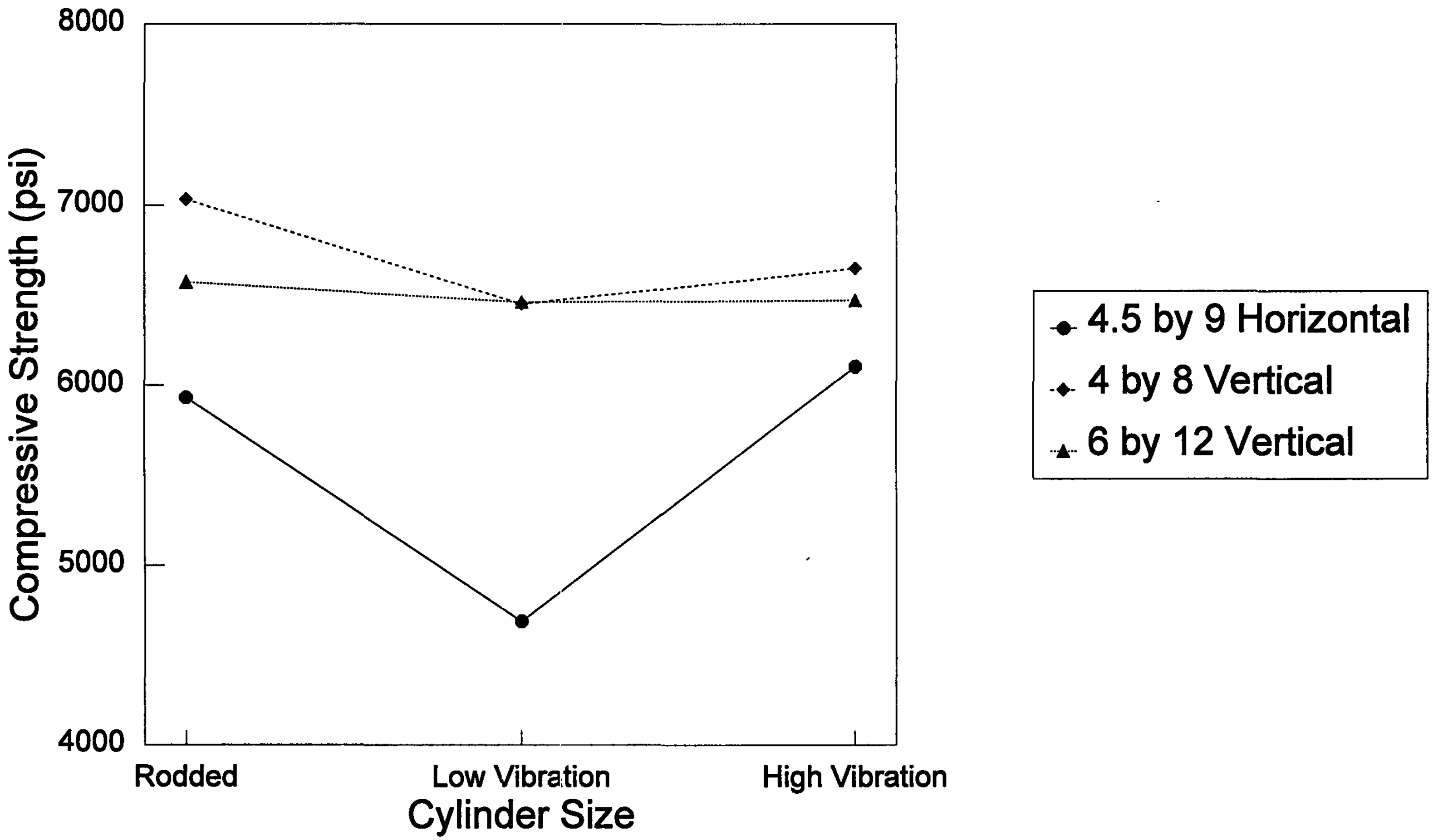


FIGURE 10

Mean Cylinder Strength vs Cylinder Size

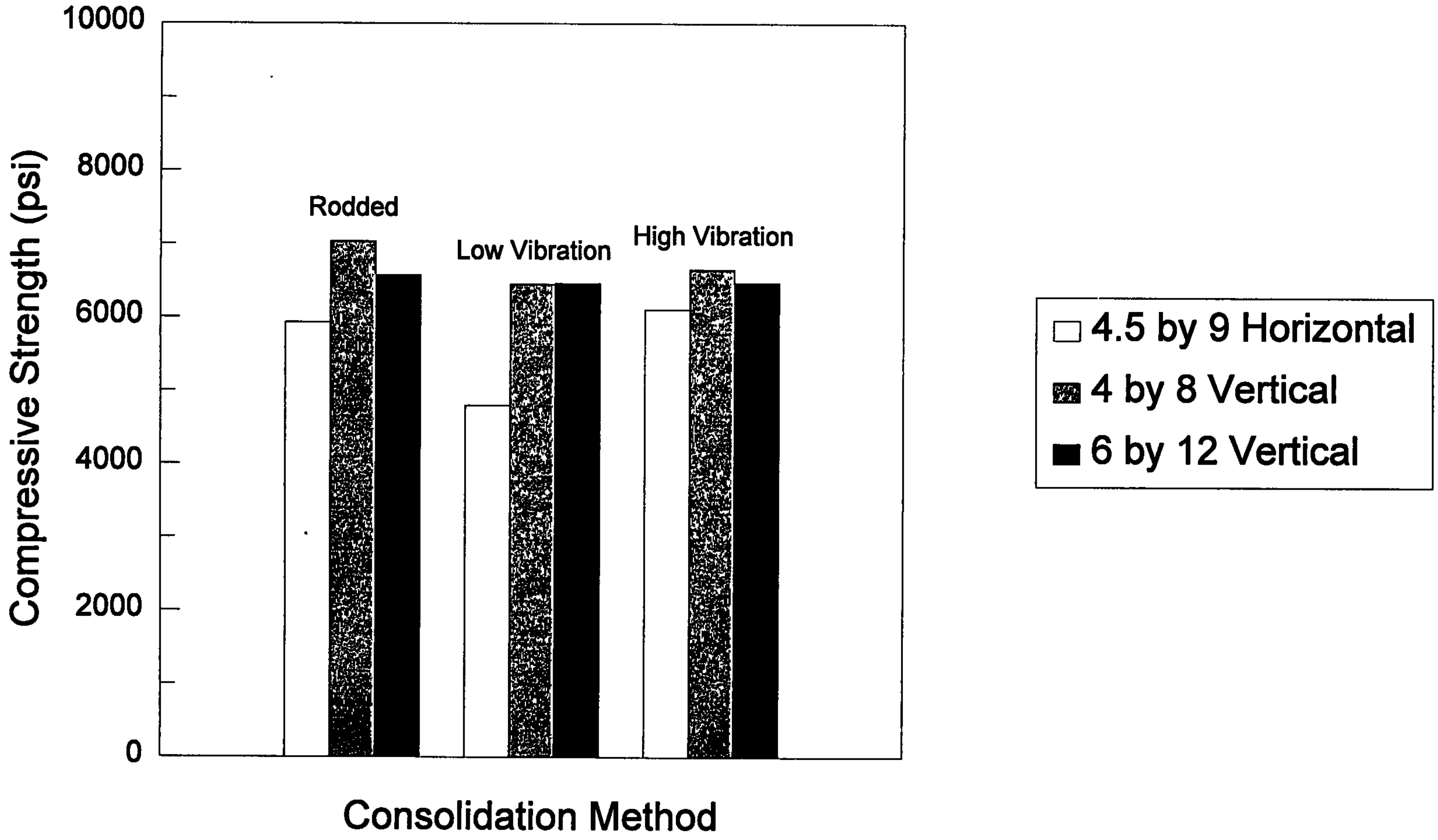


FIGURE 11

Cylinder Strength vs Run Order

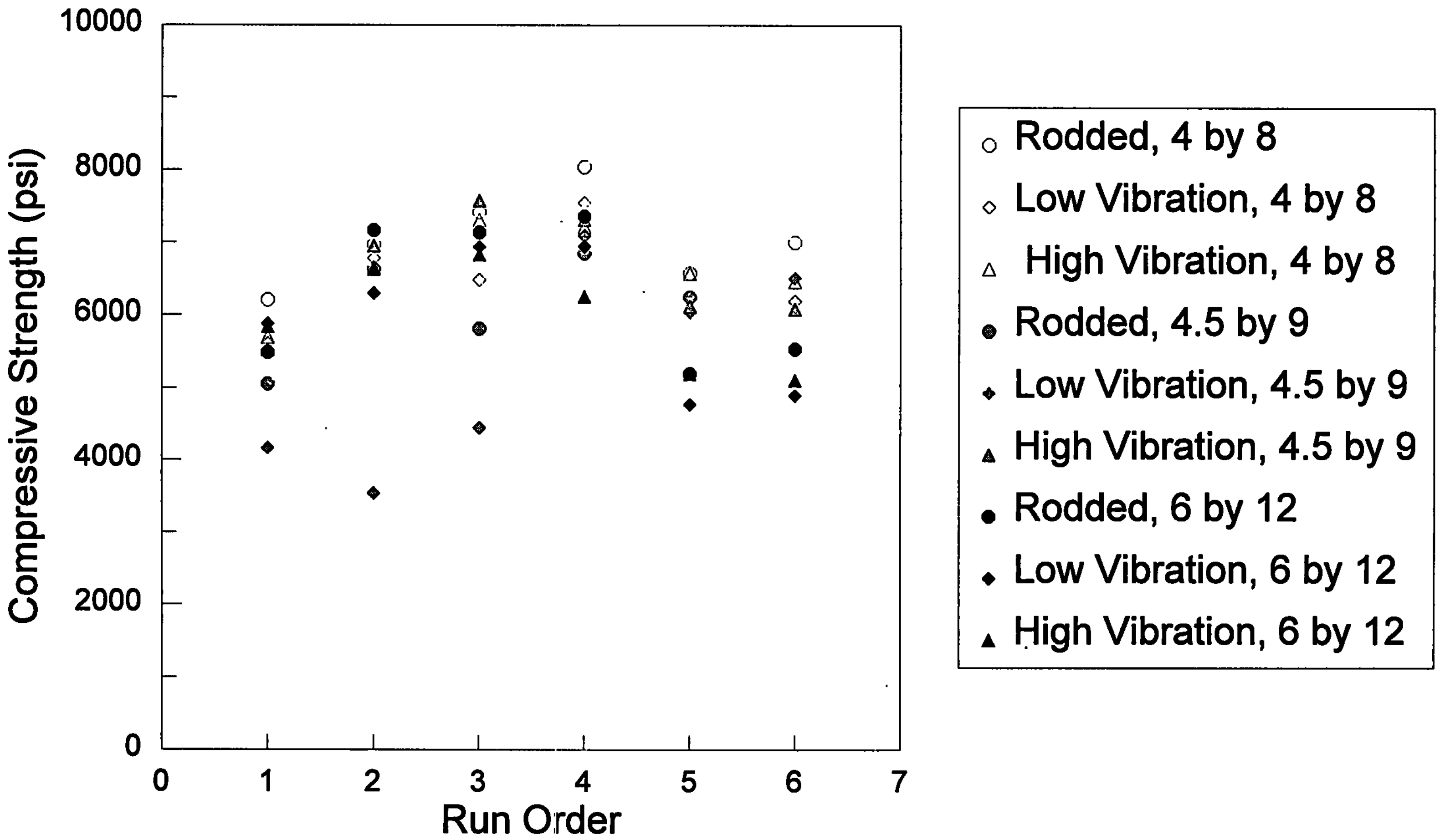
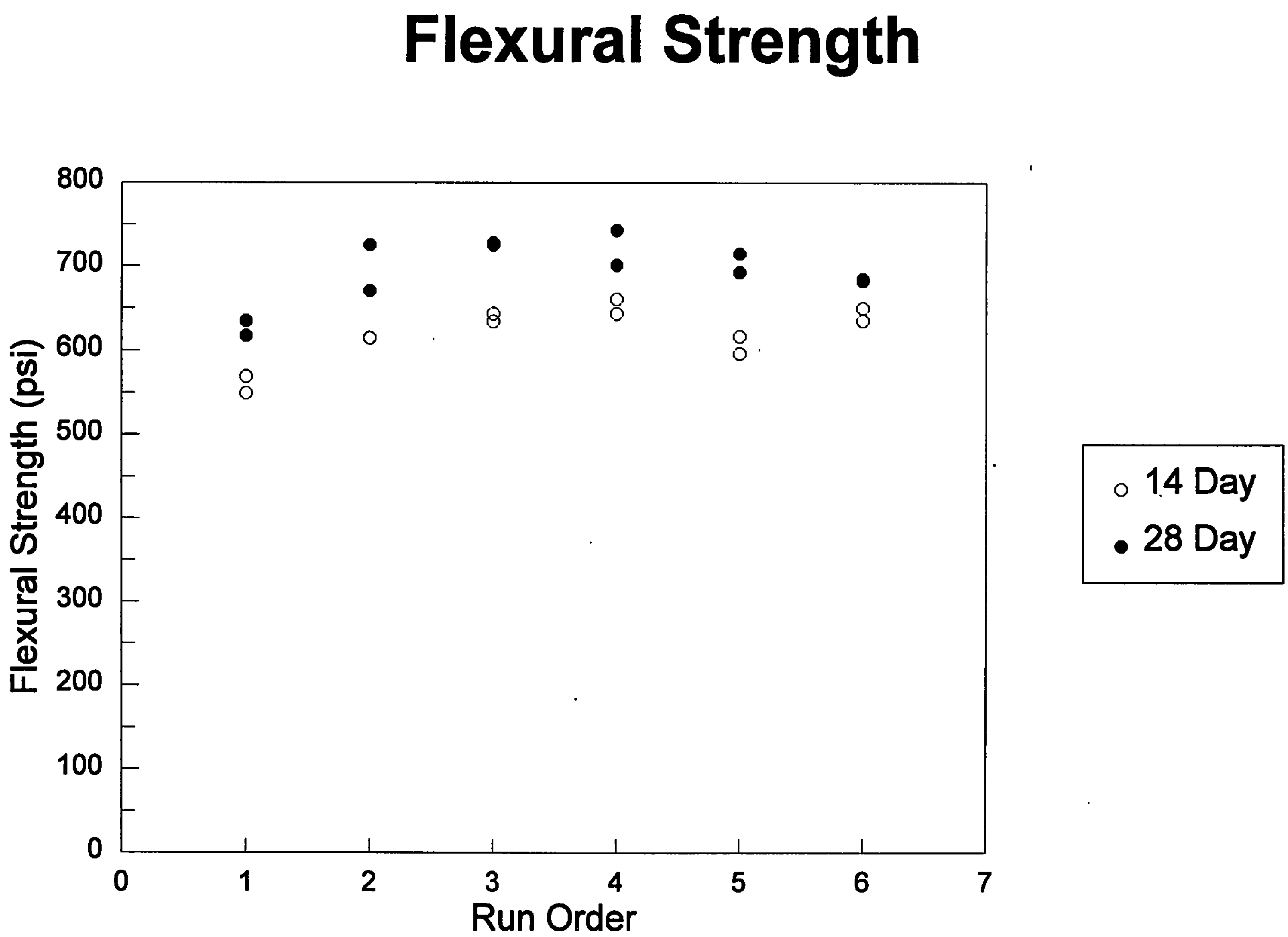
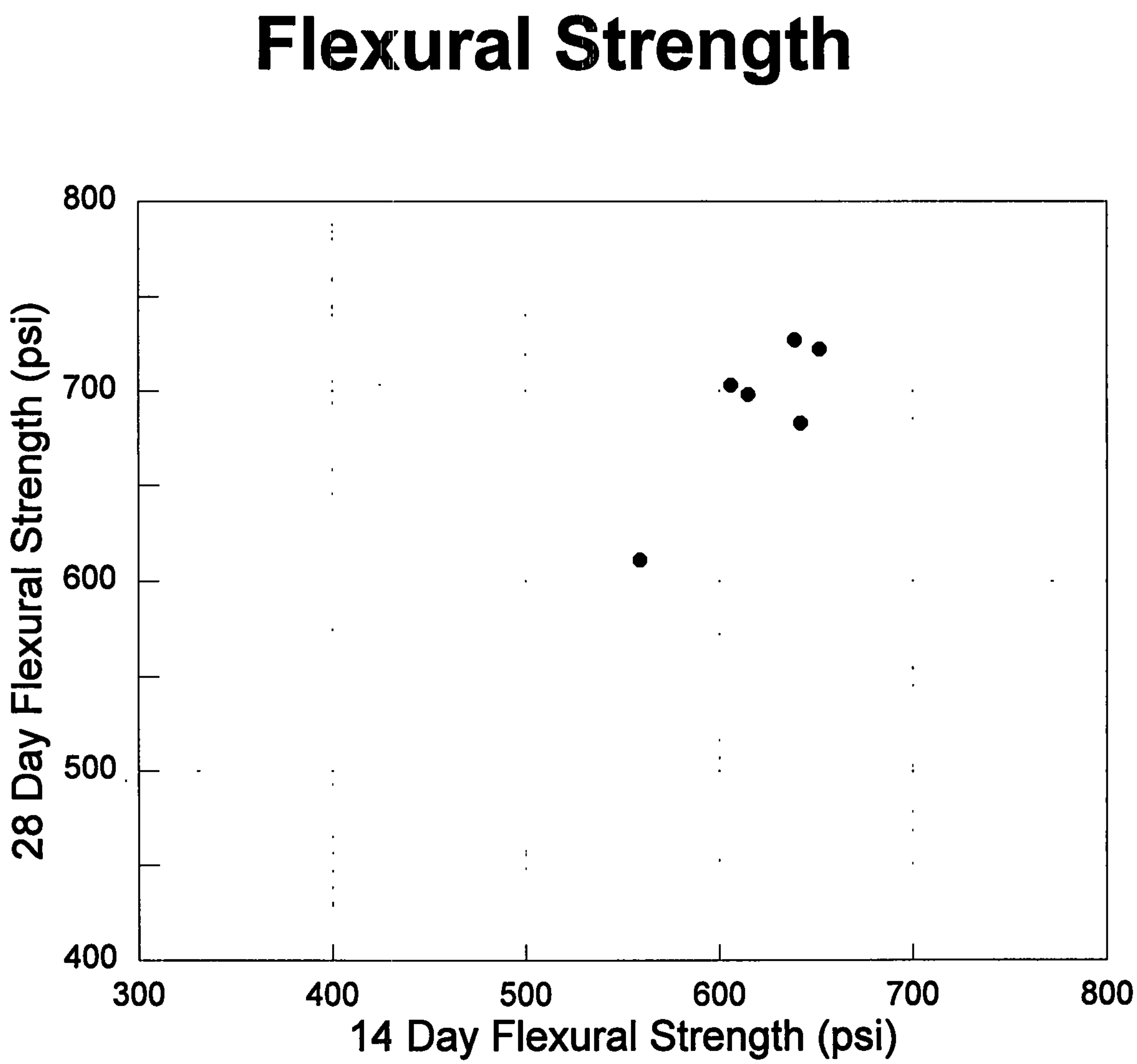


FIGURE 12



Flexural Strength
Flexural Strength (psi)
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
Run Order
14 Day
28 Day

FIGURE 13



Flexural Strength
800
700
600
500
400
300
400
500
600
700
800
28 Day Flexural Strength (psi)
14 Day Flexural Strength (psi)

FIGURE 14

Beam vs Cylinder Strengths at 28 Days of Age

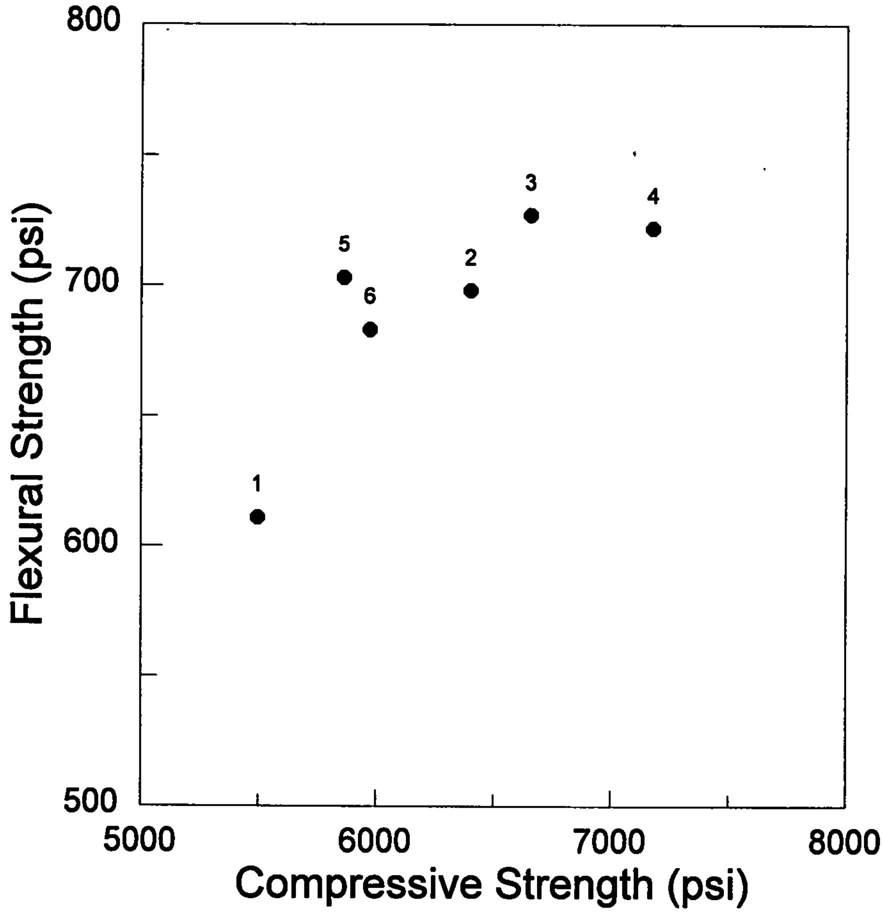
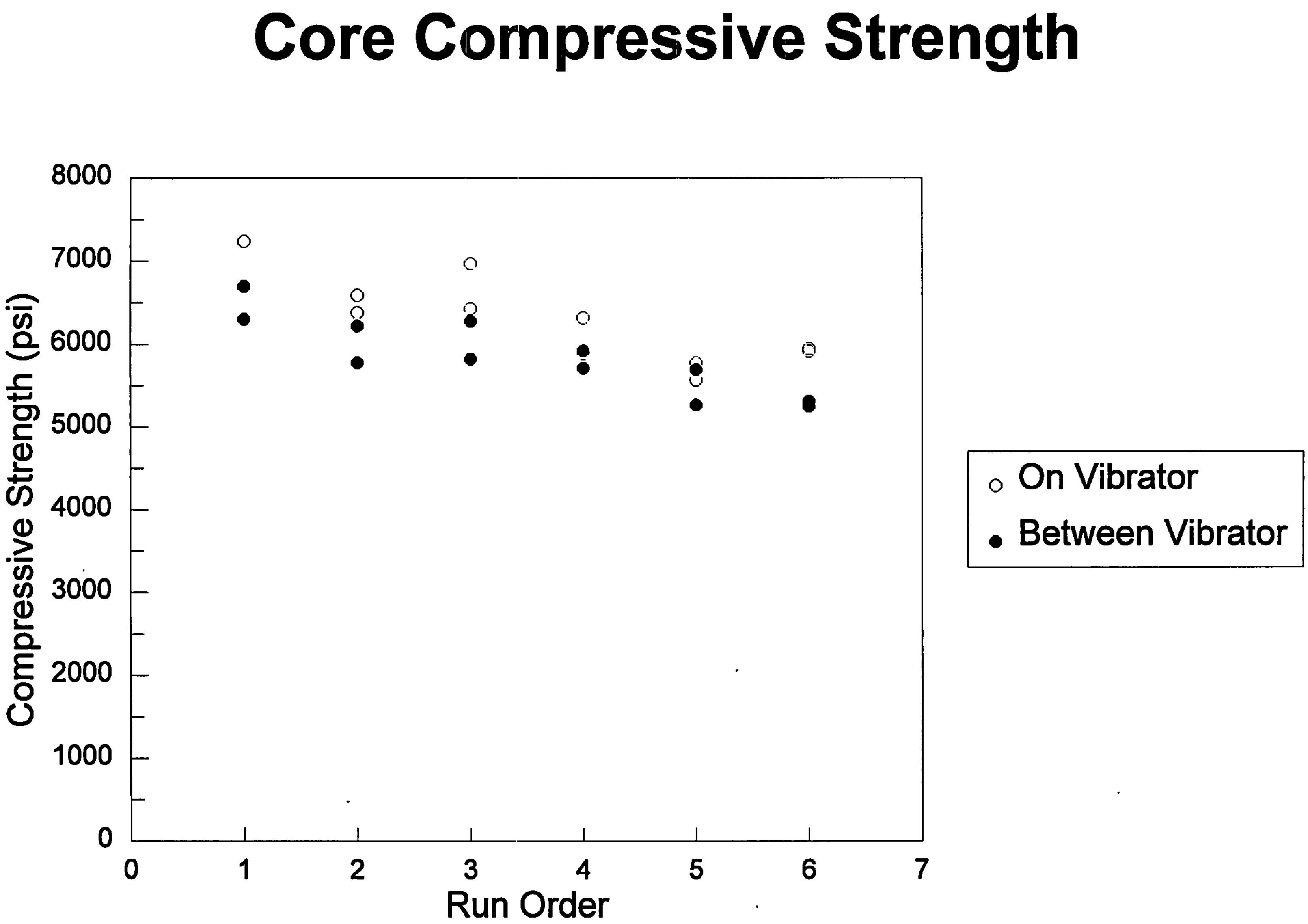
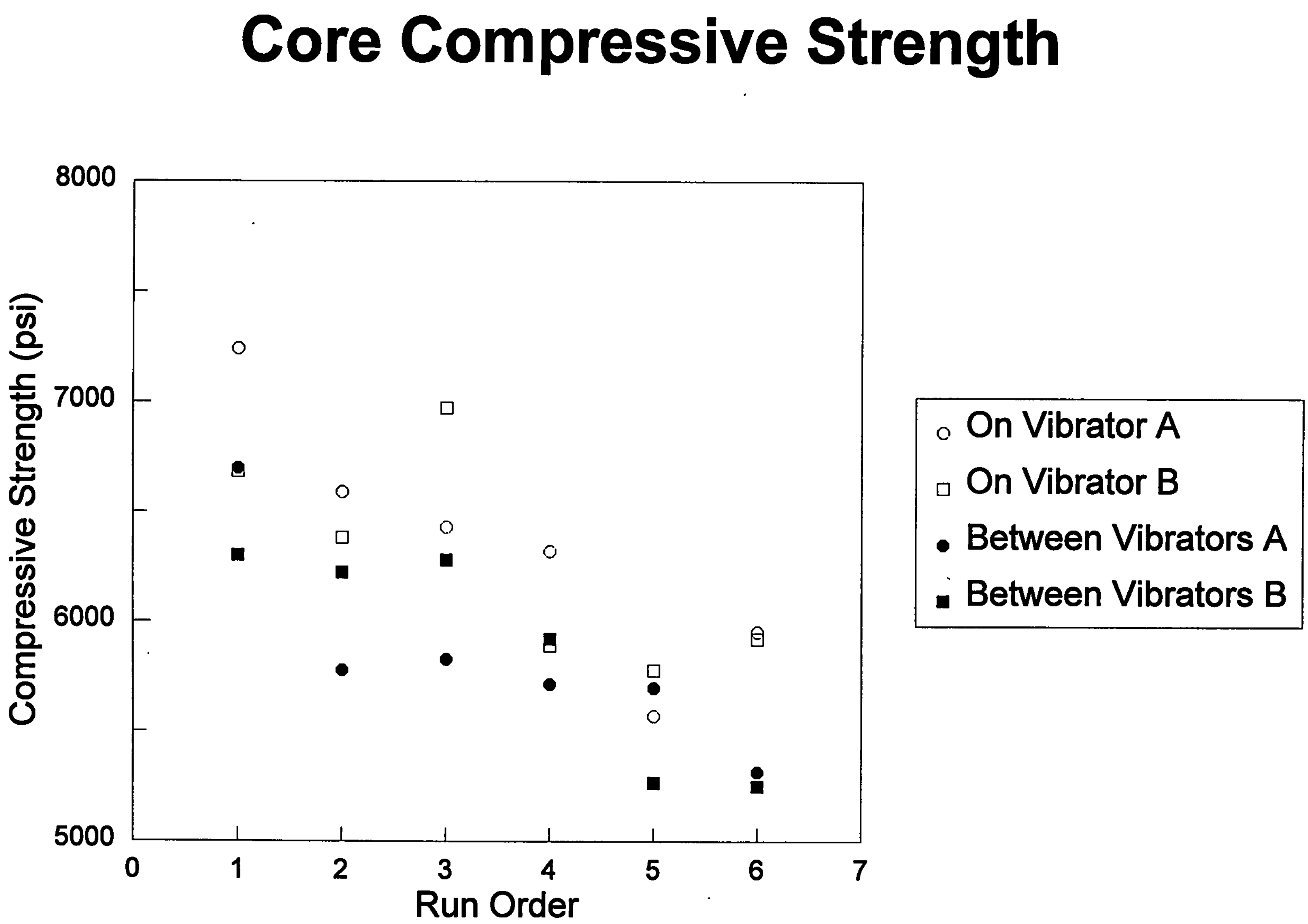


FIGURE 15



Core Compressive Strength
8000
7000
6000
5000
4000
3000
2000
1000
0
Compressive Strength (psi)
0
1
2
3
4
5
6
7
Run Order
On Vibrator
Between Vibrator

FIGURE 16



Core Compressive Strength
Compressive Strength (psi)
8000
7000
6000
5000
0
1
2
3
4
5
6
7
Run Order
On Vibrator A
On Vibrator B
Between Vibrators A
Between Vibrators B

APPENDIX D

Control Charts for Cylinders

FIGURE 1

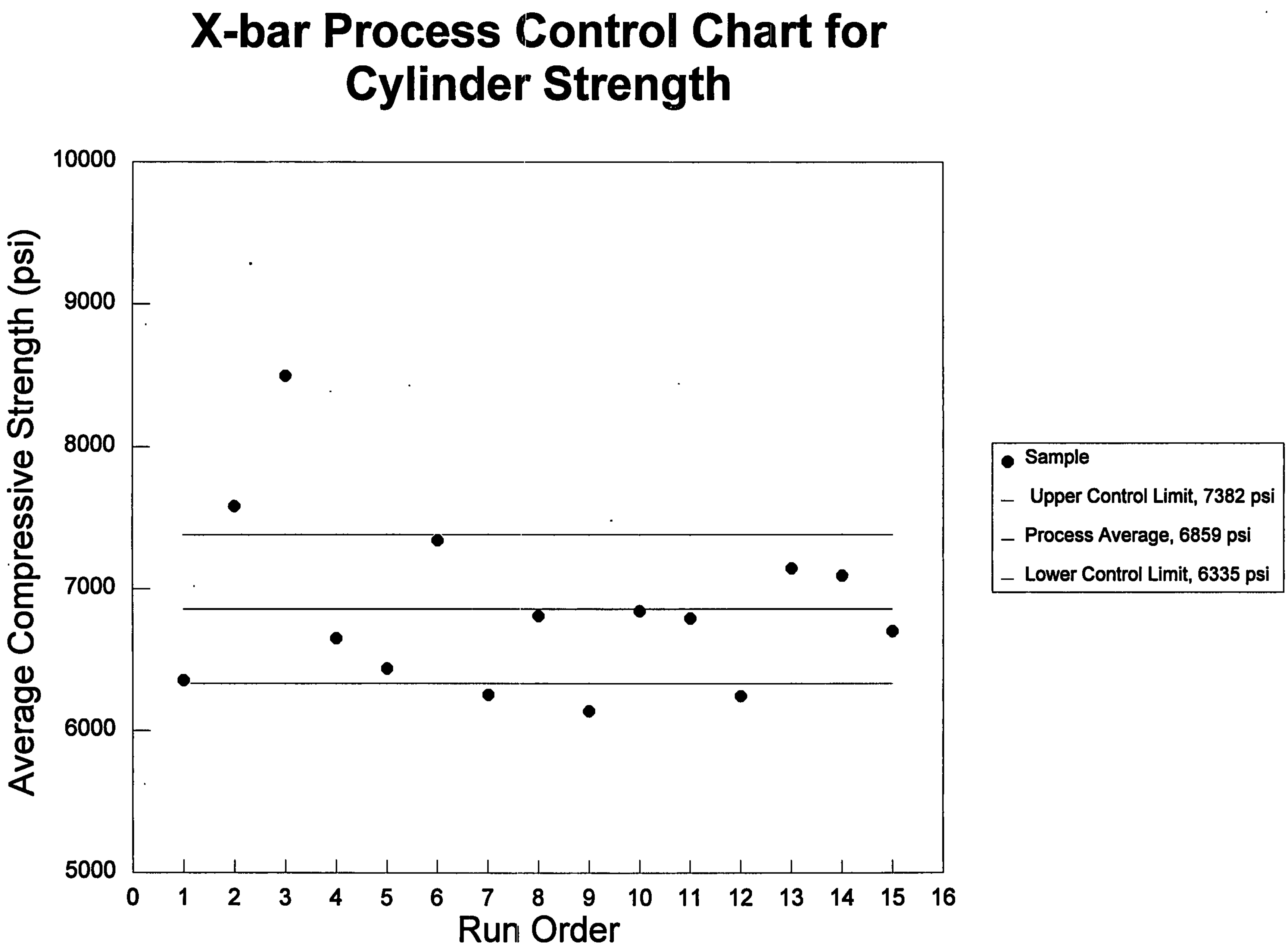
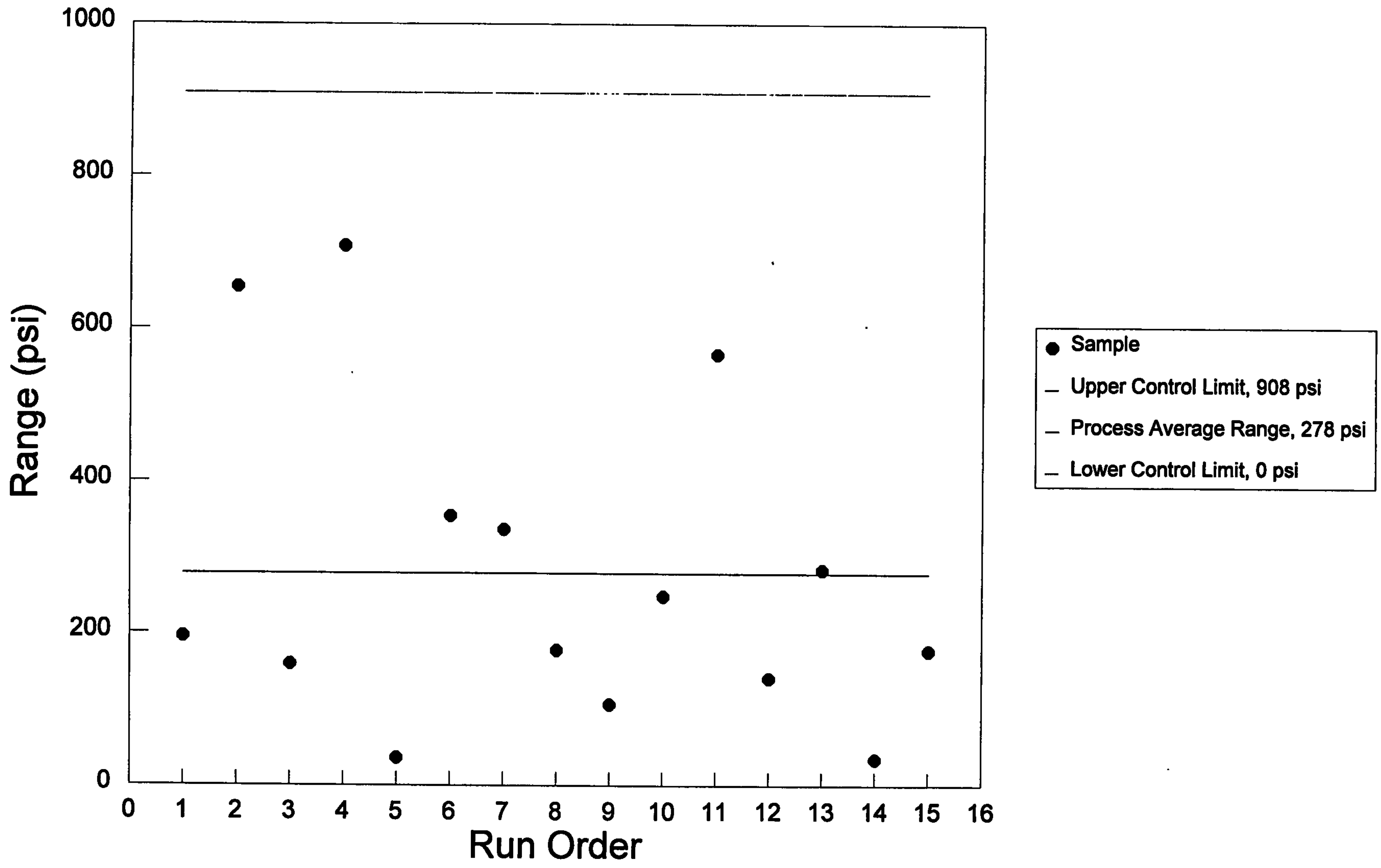

X-bar Process Control Chart for Cylinder Strength
10000
9000
8000
7000
6000
5000
Average Compressive Strength (psi)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Run Order
Sample
Upper Control Limit, 7382 psi
Process Average, 6859 psi
Lower Control Limit, 6335 psi

FIGURE 2

Range Process Control Chart for Cylinder Strength



CYLINDERS
28 DAY COMPRESSIVE STRENGTH

SAMPLE ID	LOAD (lbs)	STRENGTH TESTED (psi)	AVERAGE STRENGTH (psi)	STATION SB/EB	
1 A	182500	6456		223+25	
1 B	177000	6261	6358	223+25	
2 A	205000	7252		228+25	
2 B	223500	7906	7579	228+25	*
3 A	238000	8419		247+75	
3 B	242500	8578	8498	247+75	
4 A	178000	6296		262+00	
4 B	198000	7004	6650	262+00	*
5 A	182500	6456		268+25	
5 B	181500	6420	6438	268+25	
6 A	202500	7163		273+00	
6 B	212500	7517	7340	273+00	
7 A	181500	6420		280+50	
7 B	172000	6084	6252	280+50	
8 A	195000	6898		287+00	
8 B	190000	6721	6809	287+00	
9 A	172000	6084		302+40	
9 B	175000	6190	6137	302+40	
10 A	190000	6721		313+50	
10 B	197000	6969	6845	313+50	
11 A	184000	6509		323+25	
11 B	200000	7075	6792	323+25	*
12 A	174500	6173		335+00	
12 B	178500	6314	6243	335+00	
13 A	206000	7287		337+00	
13 B	198000	7004	7145	337+20	
14 A	201000	7110		352+00	
14 B	200000	7075	7092	352+00	
15 A	192000	6792		357+00	
15 B	187000	6615	6703	357+00	

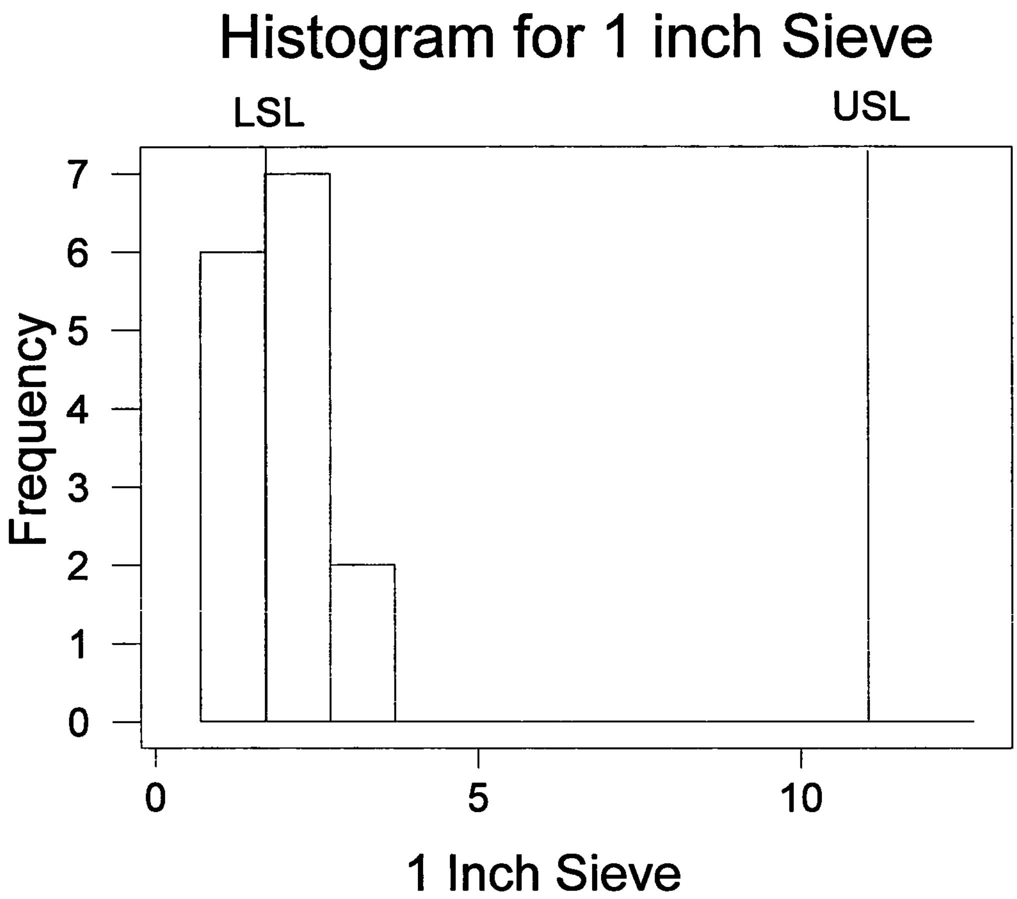
AVG **6859**

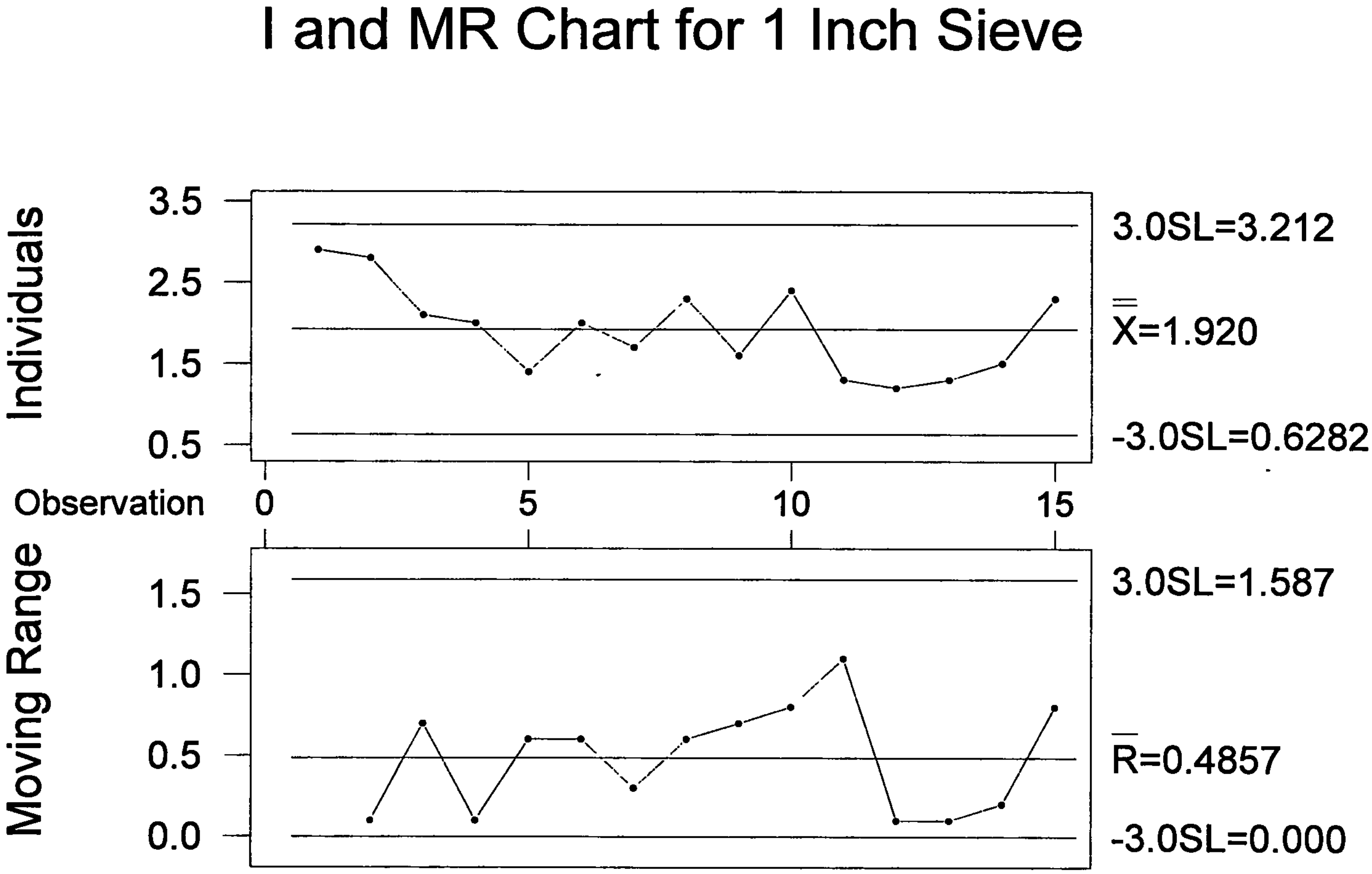
SAMPLE STD **618**

PAY FACTOR **6241**

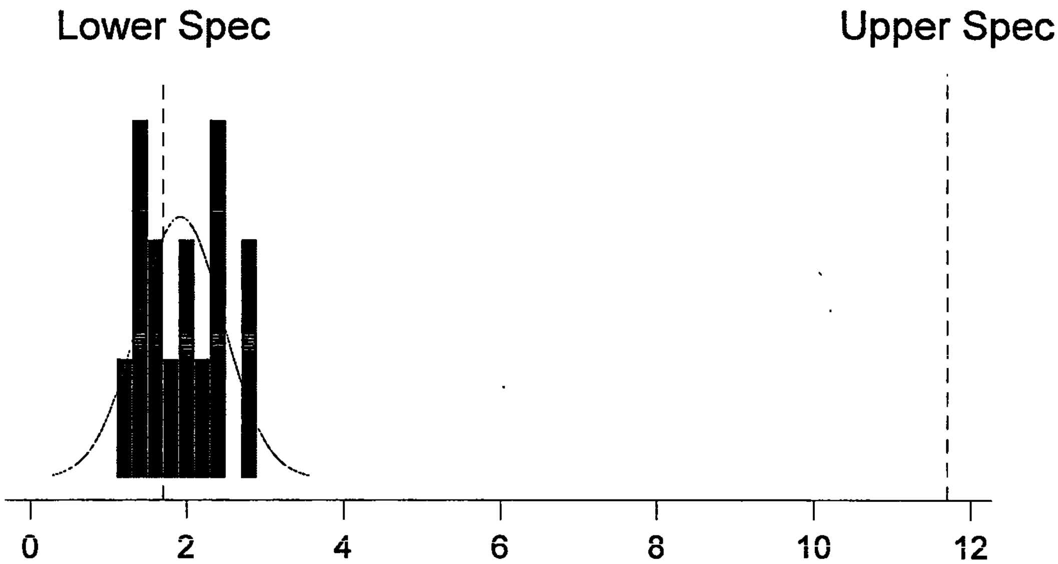
APPENDIX E

Control Charts for Aggregate Gradations

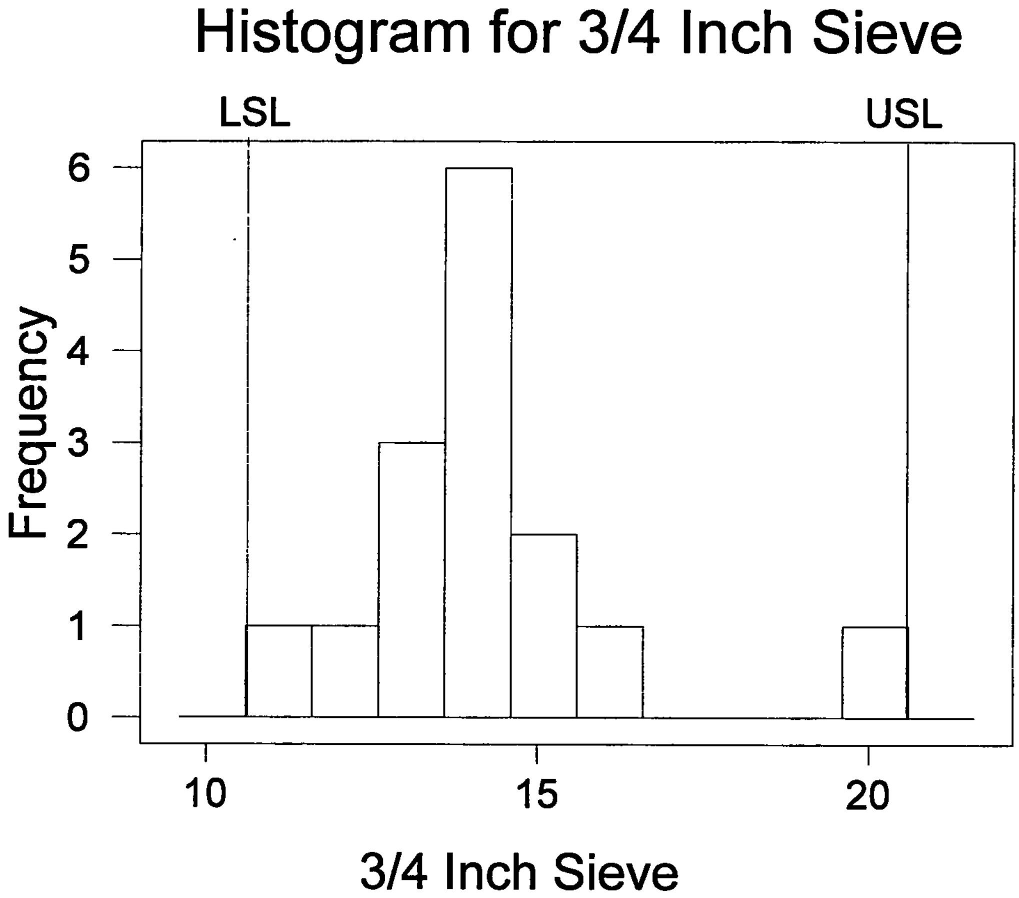

Histogram for 1 inch Sieve
LSL
USL
Frequency
7
6
5
4
3
2
1
0
0
5
10
1 Inch Sieve


I and MR Chart for 1 Inch Sieve
Individuals
3.5
2.5
1.5
0.5
3.0SL=3.212
X=1.920
-3.0SL=0.6282
Observation
0
5
10
15
Moving Range
1.5
1.0
0.5
0.0
3.0SL=1.587
R=0.4857
-3.0SL=0.000

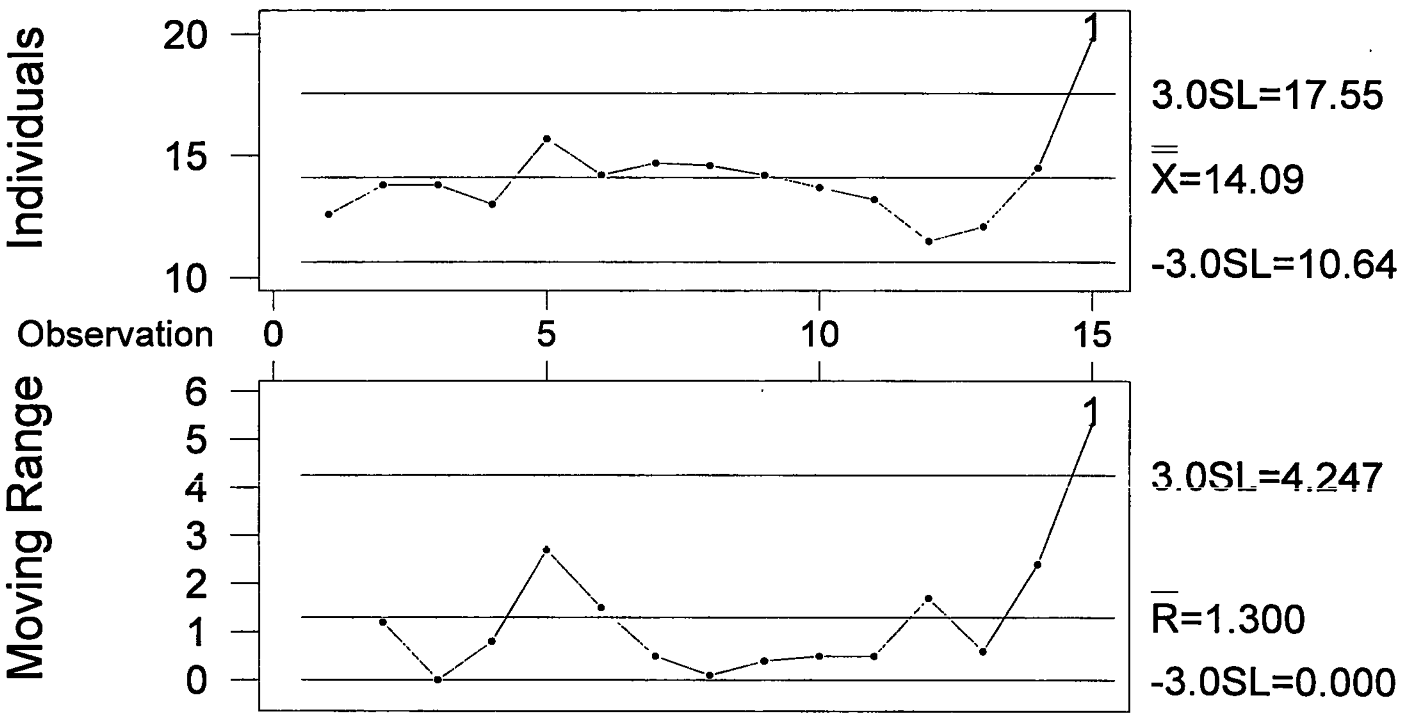
Process Capability Analysis for 1 Inch Sieve



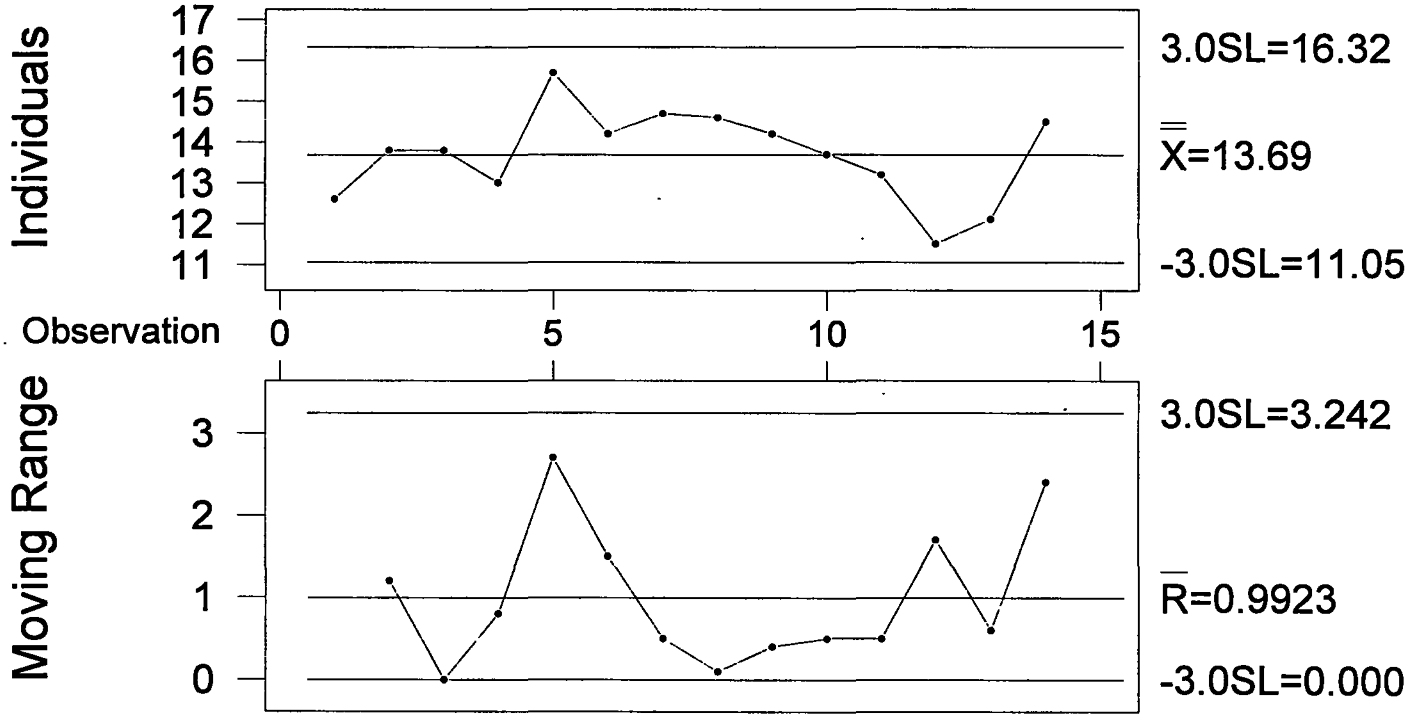
Pp	3.05	Targ	6.700	Mean	1.92000	%>USL Exp	0.00	PPM>USL Exp	0
PPU	5.96	USL	11.700	Mean+3s	3.56003	Obs	0.00	Obs	0
PPL	0.13	LSL	1.700	Mean-3s	0.27997	%<LSL Exp	34.37	PPM<LSL Exp	343684
Ppk	0.13	k	0.956	s	0.54668	Obs	40.00	Obs	400000
Cpm	0.33	n	15.000						


Histogram for 3/4 Inch Sieve
LSL
USL
Frequency
0
1
2
3
4
5
6
10
15
20
3/4 Inch Sieve

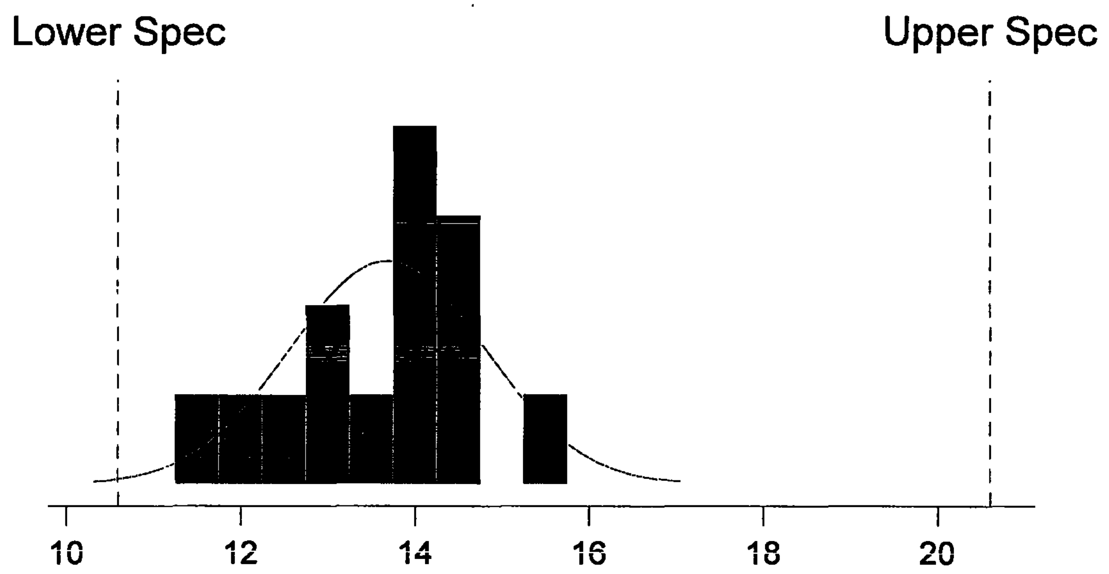
I and MR Chart for 3/4 Inch Sieve



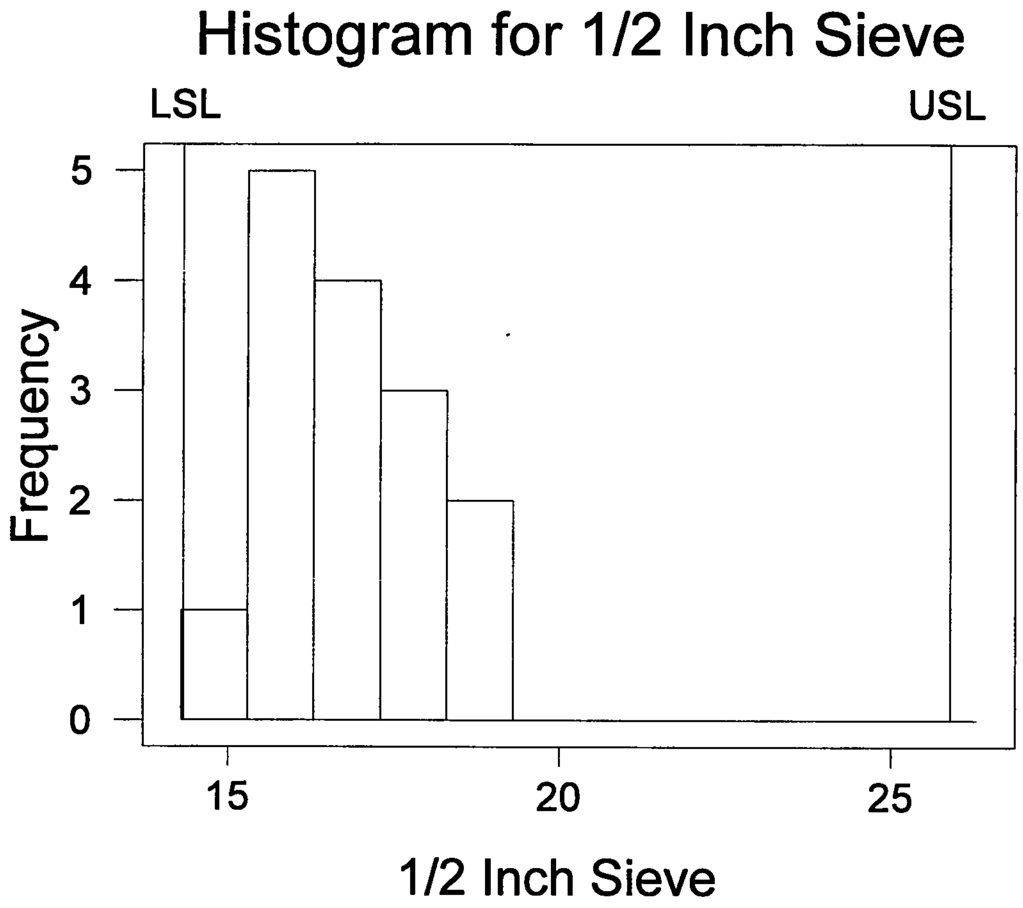
I and MR Chart for 3/4 Inch Sieve



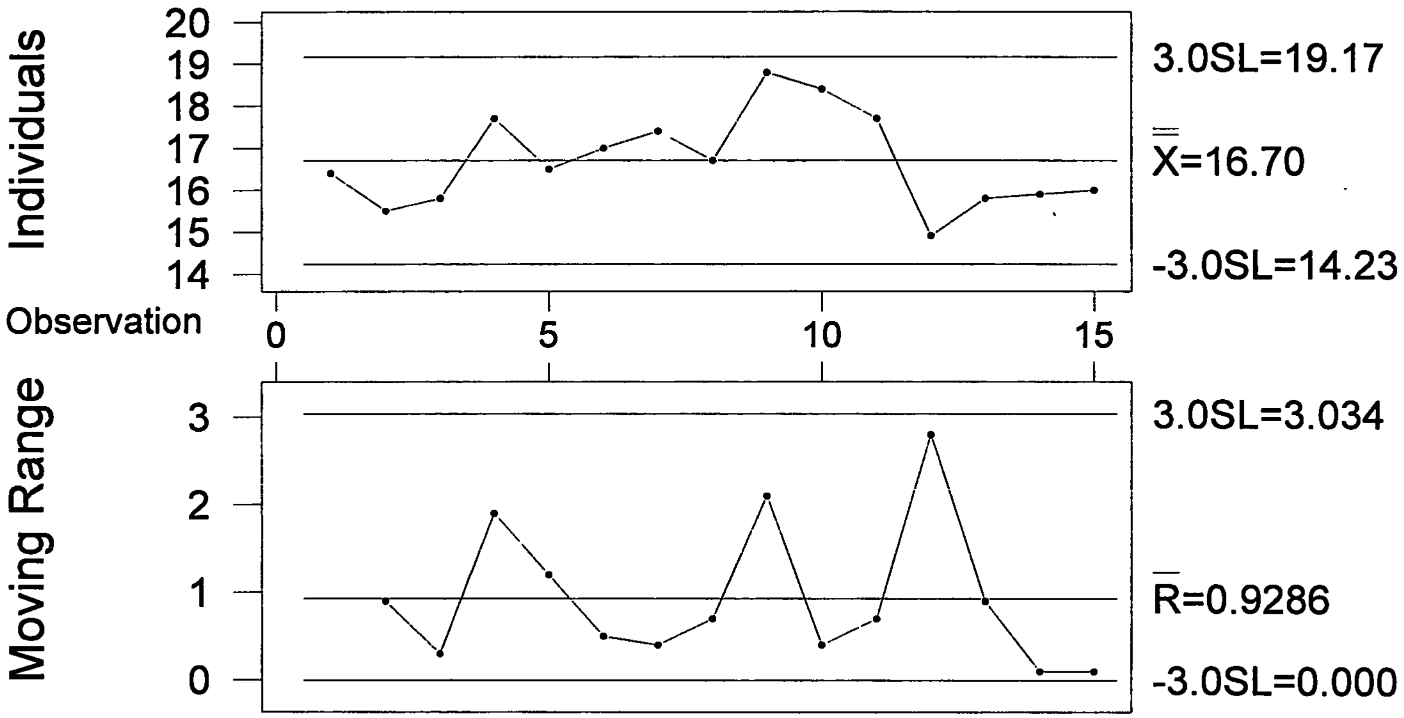
Process Capability Analysis for 3/4 Inch Sieve



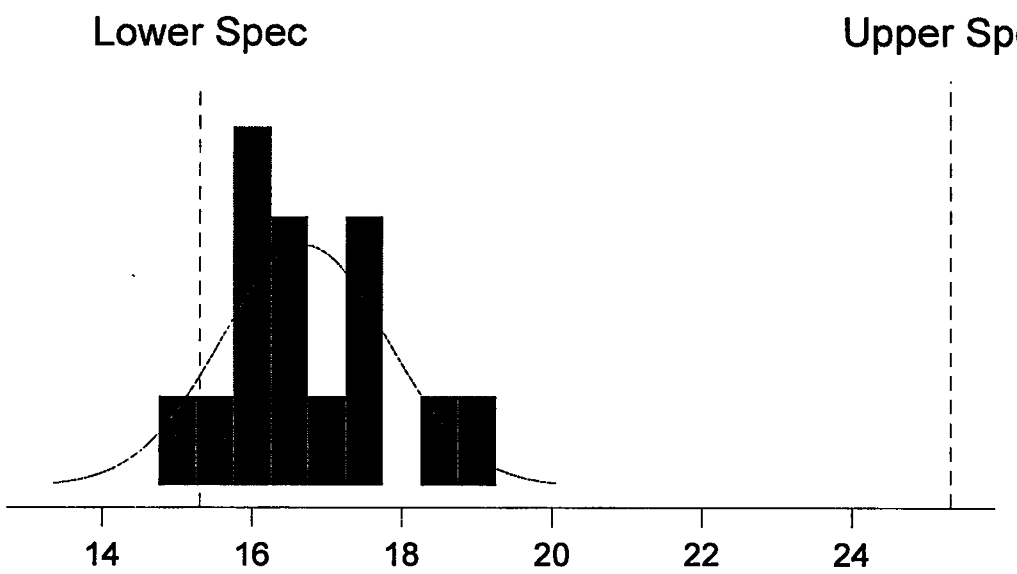
Pp	1.49	Targ	15.6000	Mean	13.6857	%>USL Exp	0.00	PPM>USL Exp	0
PPU	2.06	USL	20.6000	Mean+3s	17.0467	Obs	0.00	Obs	0
PPL	0.92	LSL	10.6000	Mean-3s	10.3247	%<LSL Exp	0.29	PPM<LSL Exp	2941
Ppk	0.92	k	0.3829	s	1.1203	Obs	0.00	Obs	0
Cpm	0.73	n	14.0000						


Histogram for 1/2 Inch Sieve
LSL
USL
Frequency
0
1
2
3
4
5
15
20
25
1/2 Inch Sieve

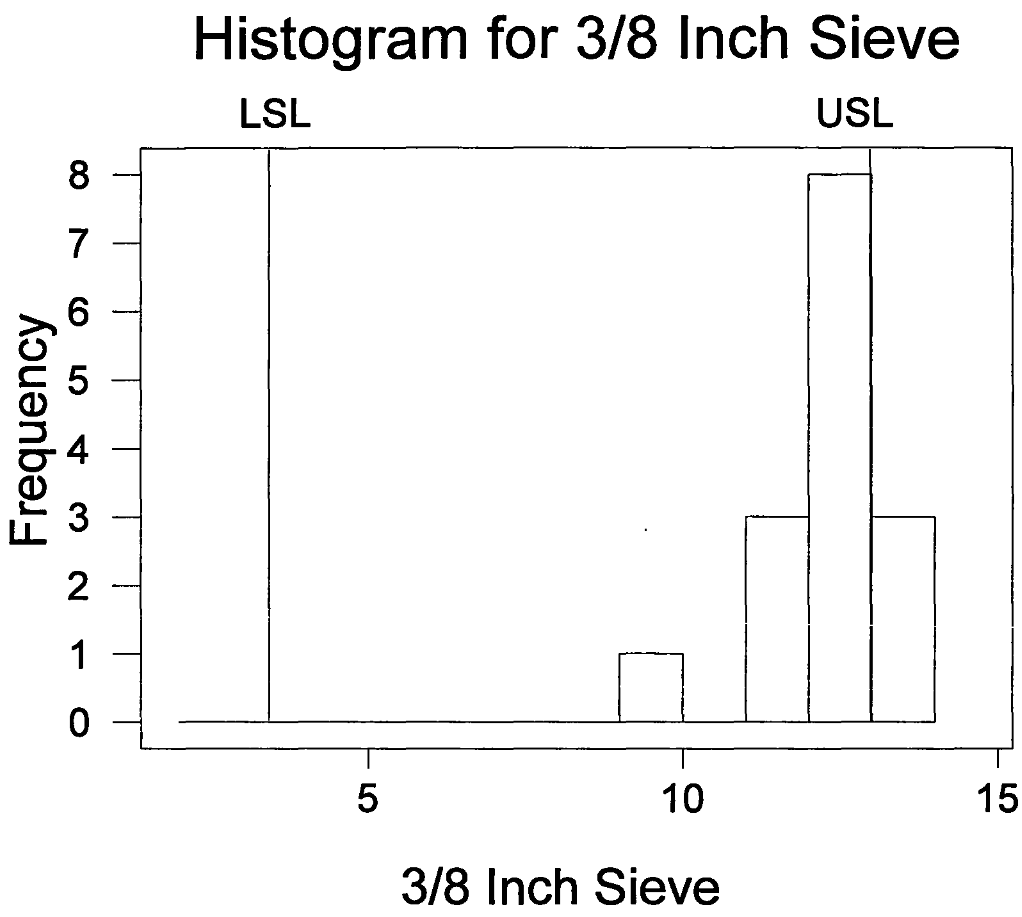
I and MR Chart for 1/2 Inch Sieve



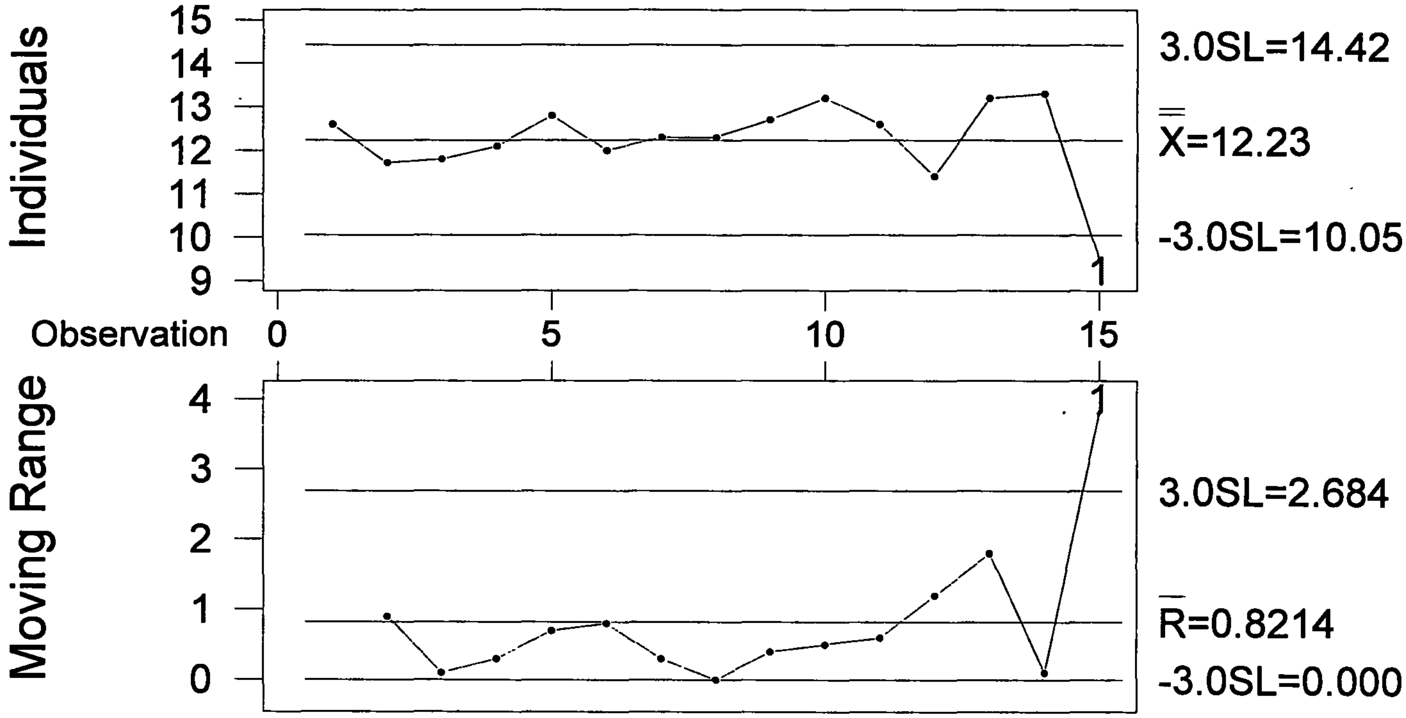
Process Capability Analysis for 1/2 Inch Sieve



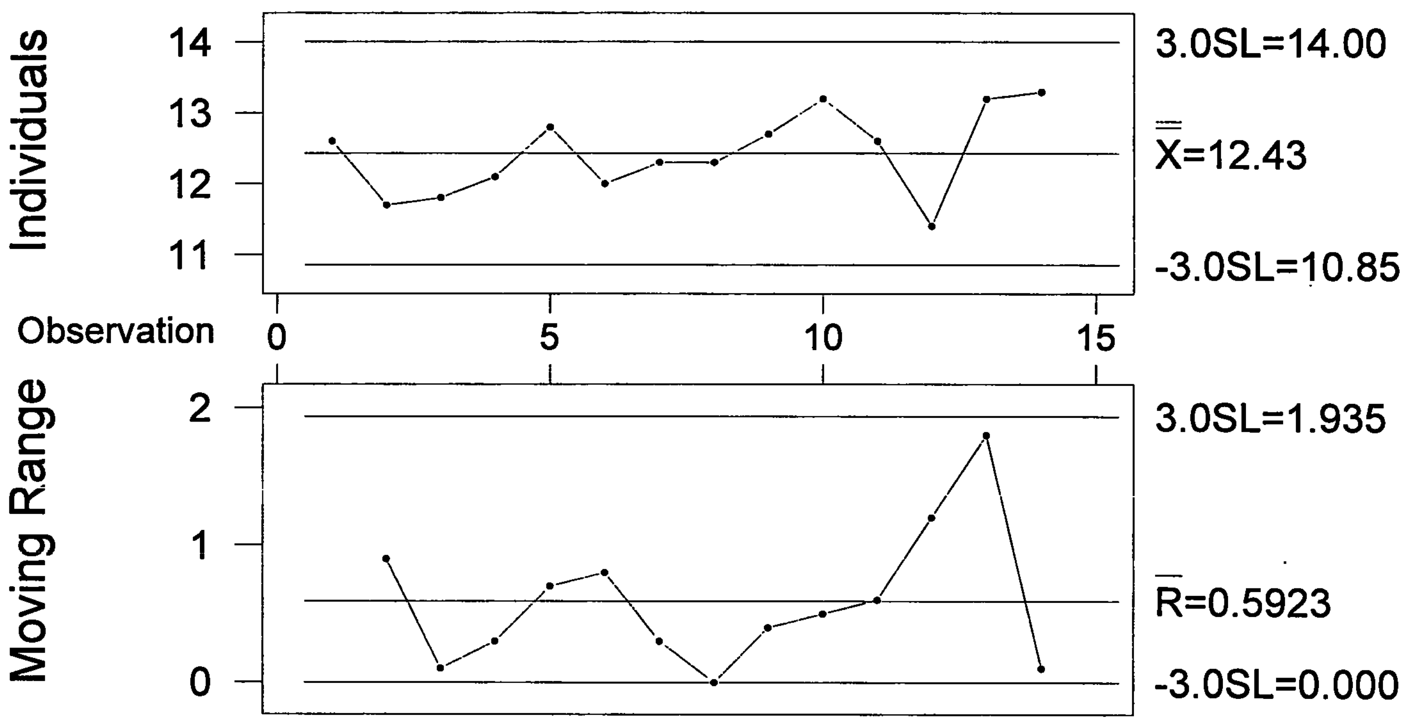
Pp	1.49	Targ	20.30	Mean	16.7000	%>USL Exp	0.00	PPM>USL Exp	0
PPU	2.57	USL	25.30	Mean+3s	20.0483	Obs	0.00	Obs	0
PPL	0.42	LSL	15.30	Mean-3s	13.3517	%<LSL Exp	10.49	PPM<LSL Exp	104857
Ppk	0.42	k	0.72	s	1.1161	Obs	6.67	Obs	66667
Cpm	0.43	n	15.00						


Histogram for 3/8 Inch Sieve
LSL
USL
Frequency
0
1
2
3
4
5
6
7
8
5
10
15
3/8 Inch Sieve

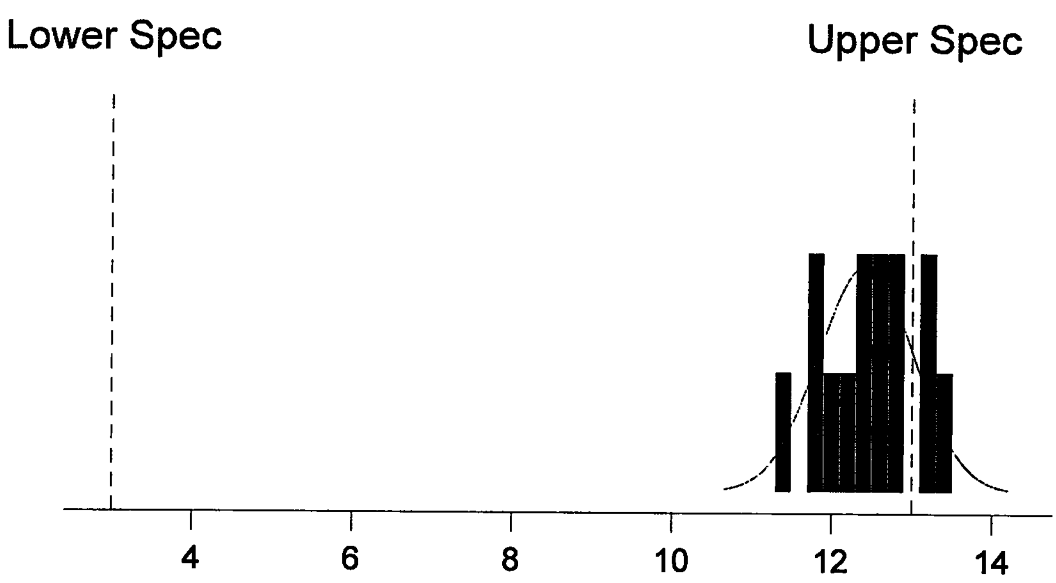
I and MR Chart for 3/8 Inch Sieve



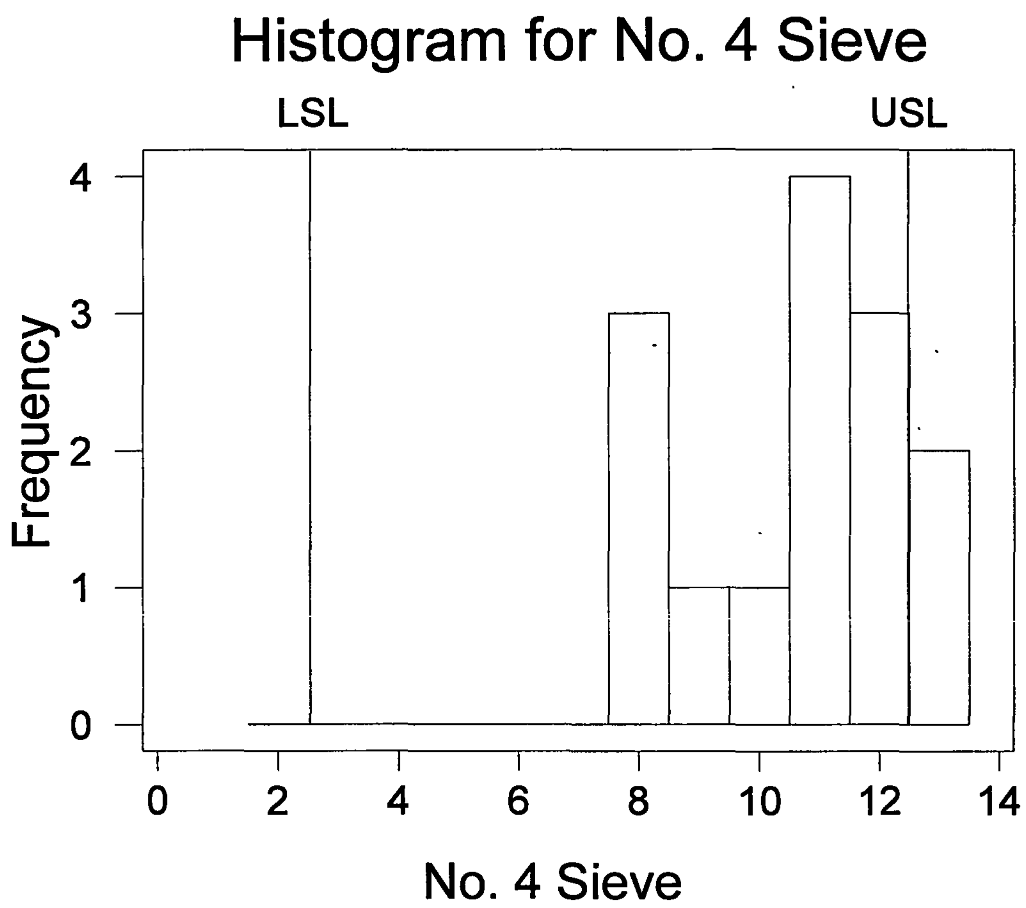
I and MR Chart for 3/8 Inch Sieve



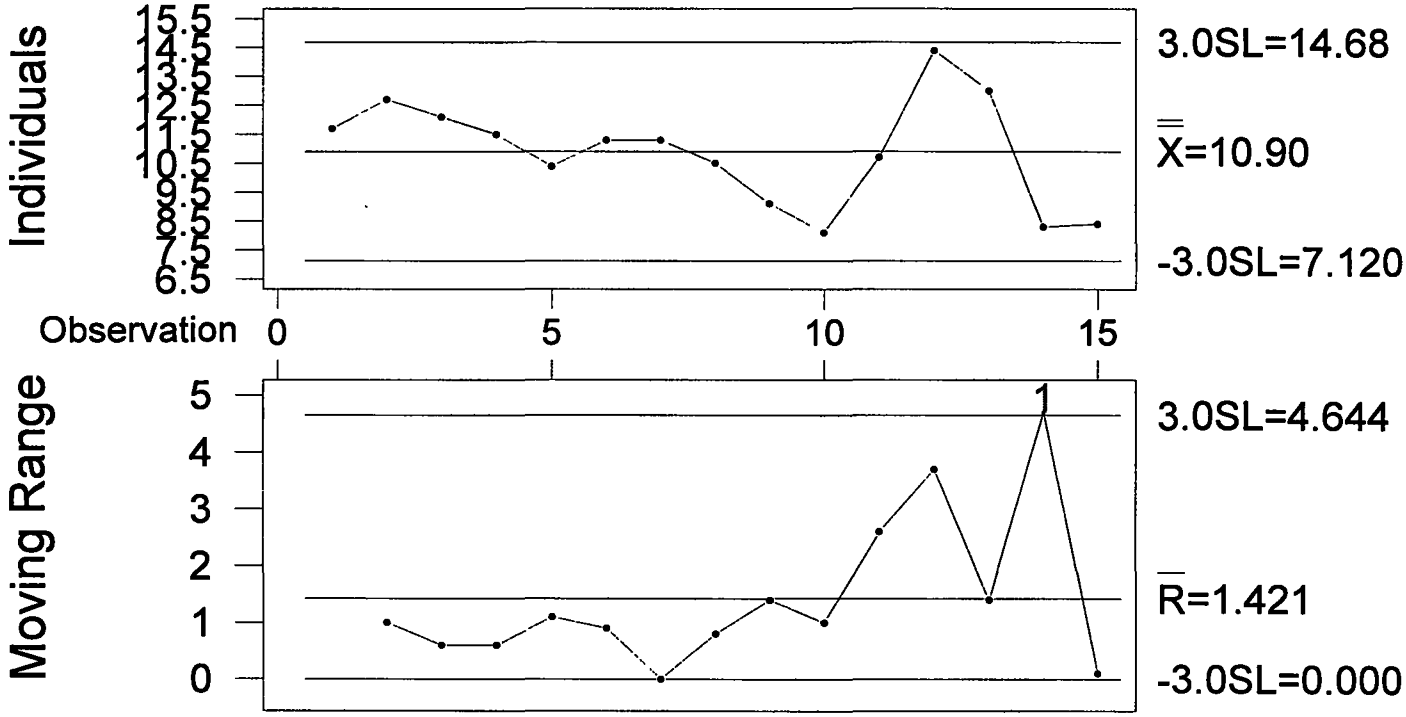
Process Capability Analysis for 3/8 Inch Sieve



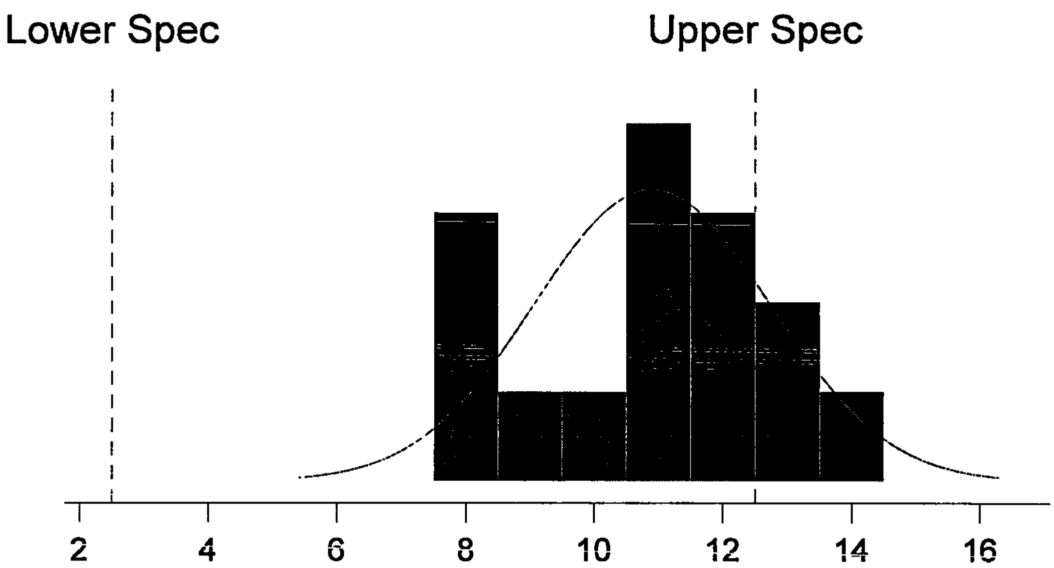
Pp	2.82	Targ	8.0000	Mean	12.4286	%>USL Exp	16.65	PPM>USL Exp	166479
PPU	0.32	USL	13.0000	Mean+3s	14.1992	Obs	21.43	Obs	214286
PPL	5.32	LSL	3.0000	Mean-3s	10.6579	%<LSL Exp	0.00	PPM<LSL Exp	0
Ppk	0.32	k	0.8857	s	0.5902	Obs	0.00	Obs	0
Cpm	0.36	n	14.0000						


Histogram for No. 4 Sieve
LSL
USL
Frequency
0
1
2
3
4
0
2
4
6
8
10
12
14
No. 4 Sieve

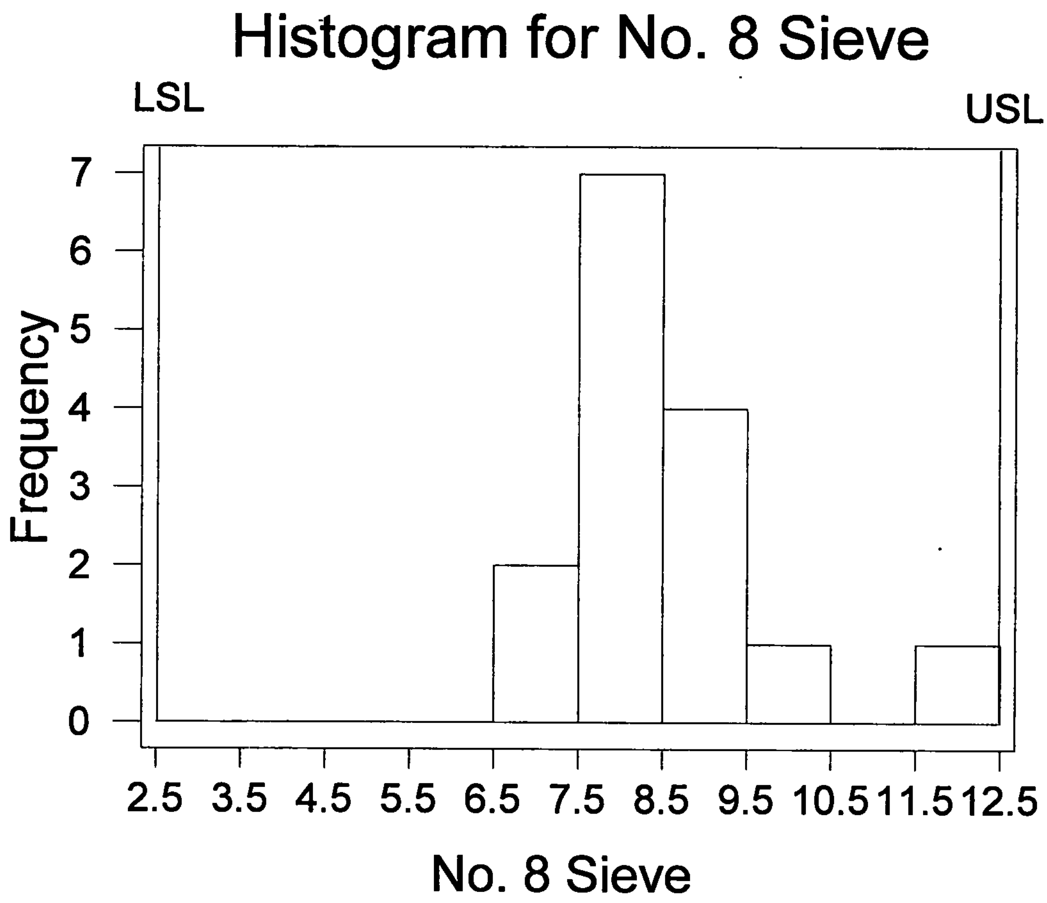
I and MR Chart for No. 4 Sieve



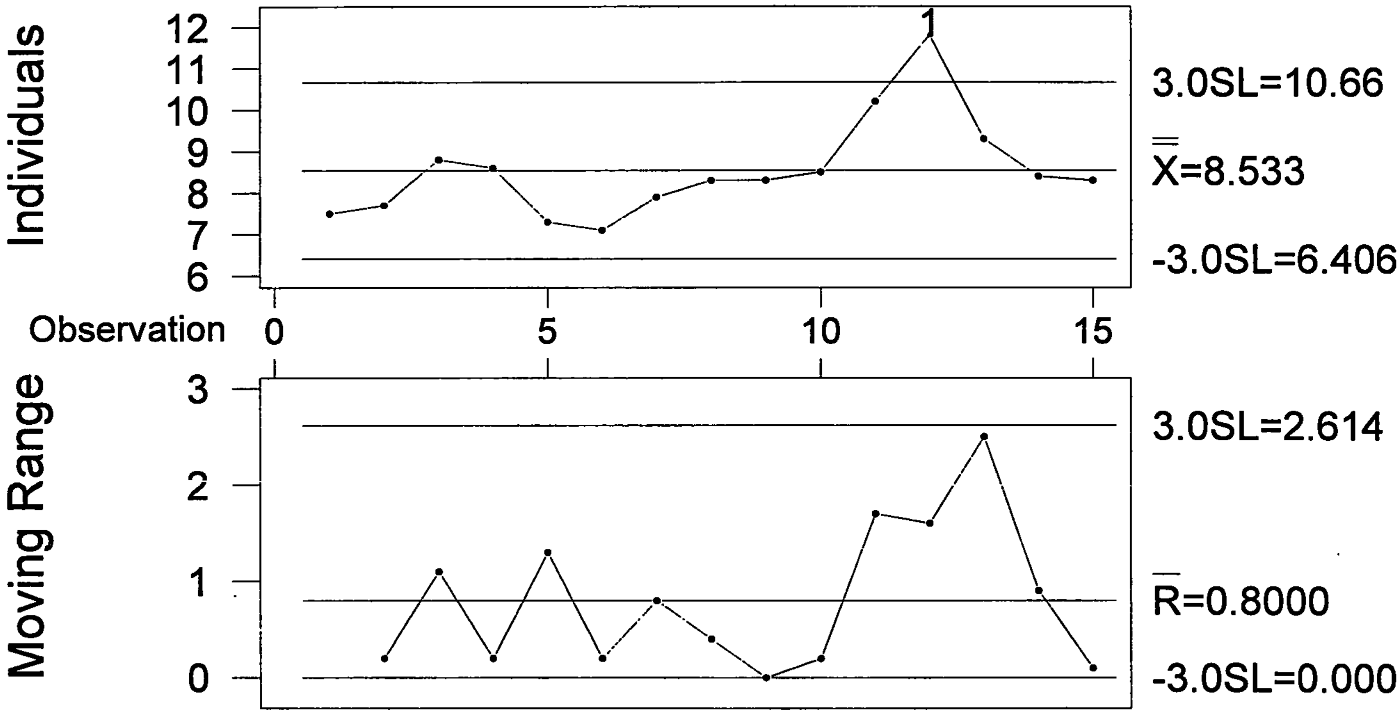
Process Capability Analysis for No. 4 Sieve



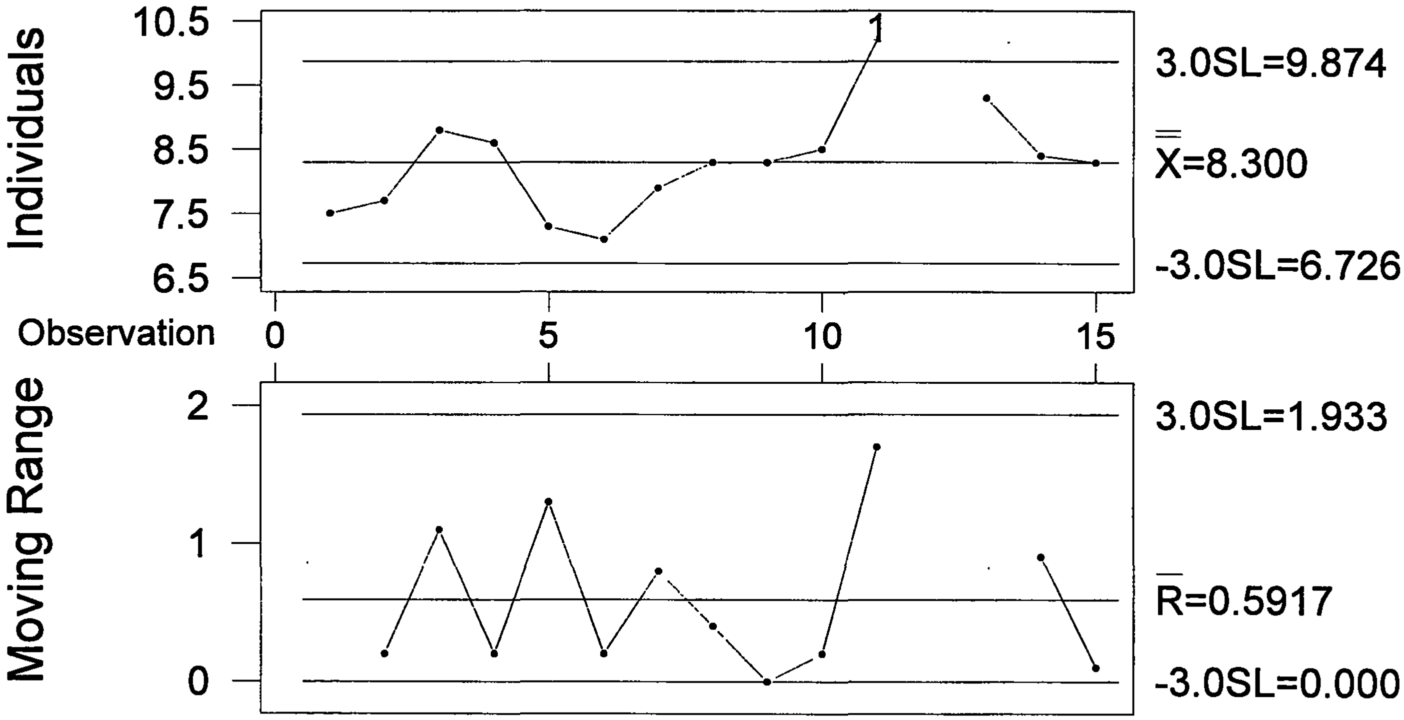
Pp	0.91	Targ	7.50	Mean	10.9000	%>USL Exp	19.18	PPM>USL Exp	191770
PPU	0.29	USL	12.50	Mean+3s	16.4084	Obs	20.00	Obs	200000
PPL	1.52	LSL	2.50	Mean-3s	5.3916	%<LSL Exp	0.00	PPM<LSL Exp	2
Ppk	0.29	k	0.68	s	1.8361	Obs	0.00	Obs	0
Cpm	0.42	n	15.00						


Histogram for No. 8 Sieve
LSL
USL
Frequency
0
1
2
3
4
5
6
7
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
No. 8 Sieve

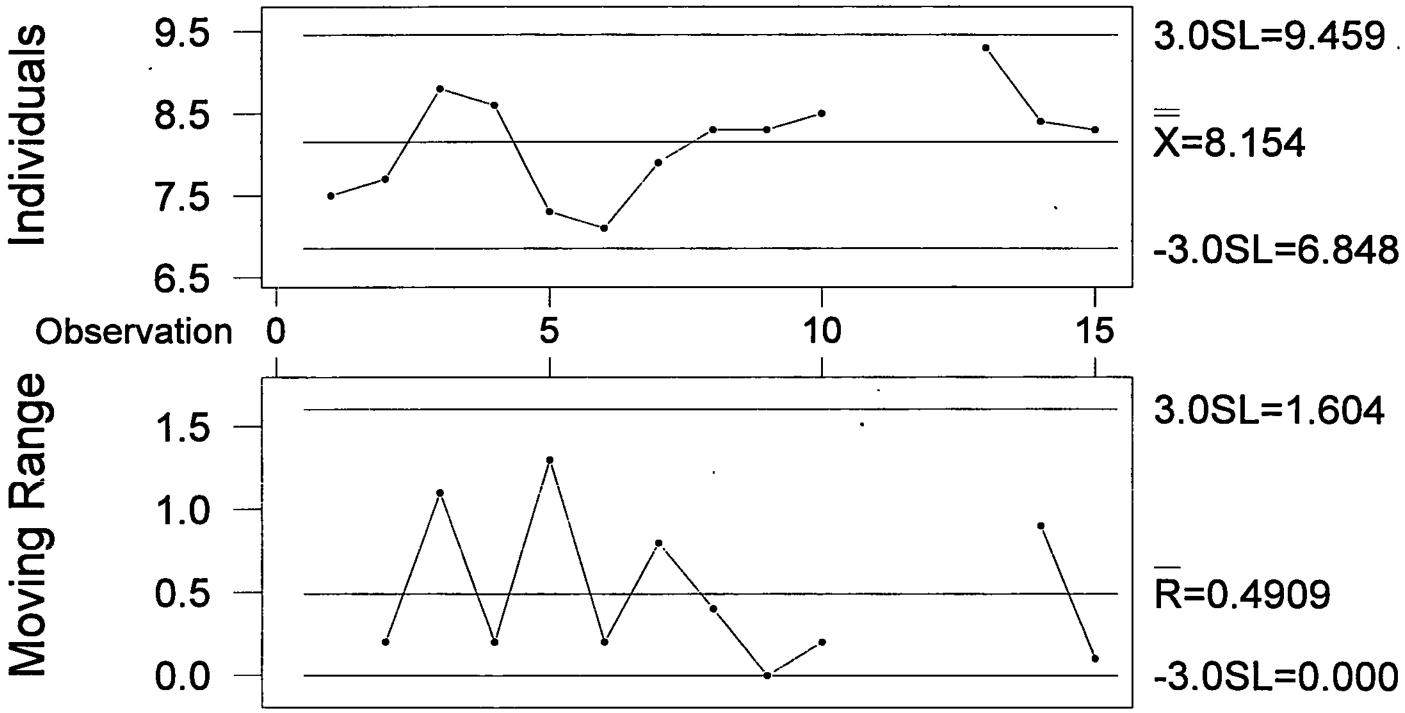
I and MR Chart for No. 8 Sieve



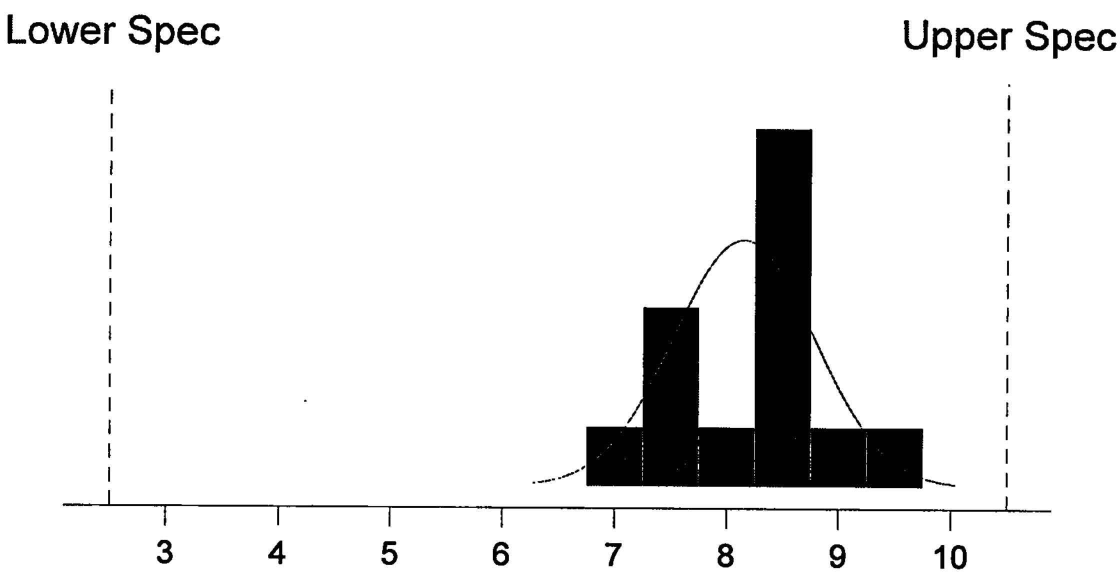
I and MR Chart for No. 8 Sieve



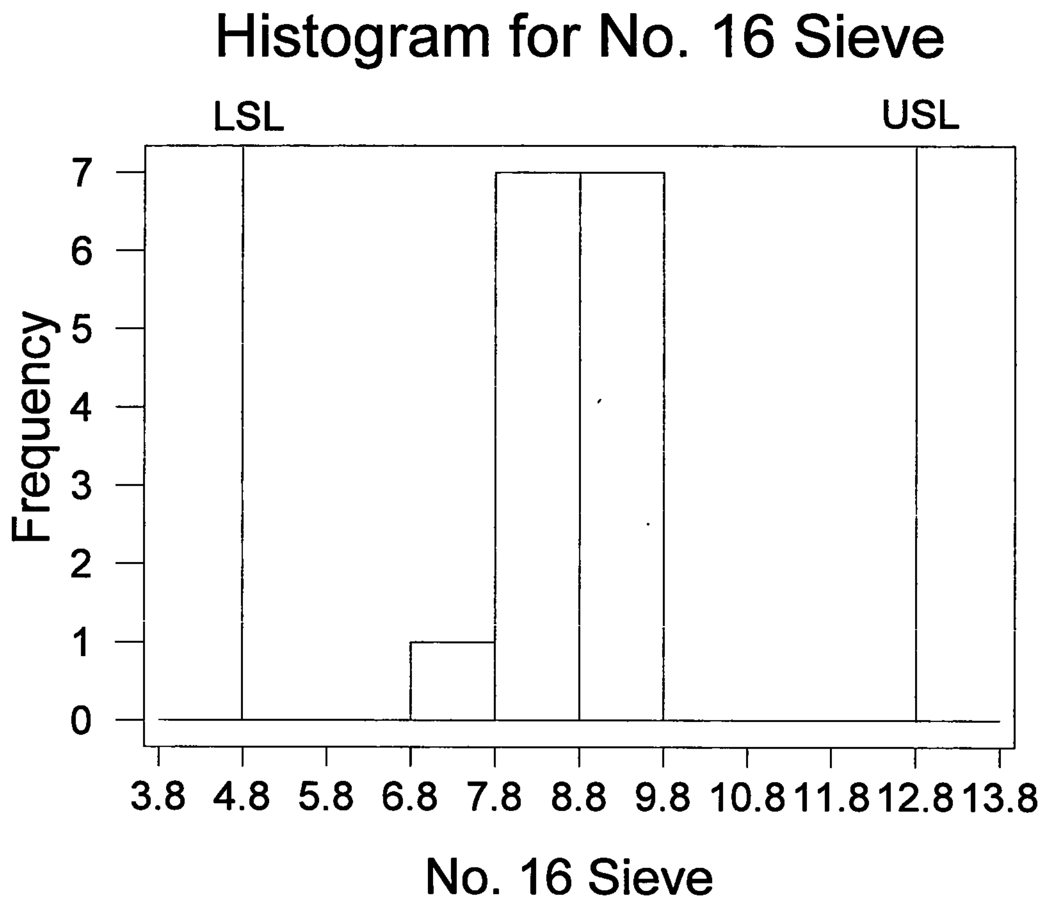
I and MR Chart for No. 8 Sieve



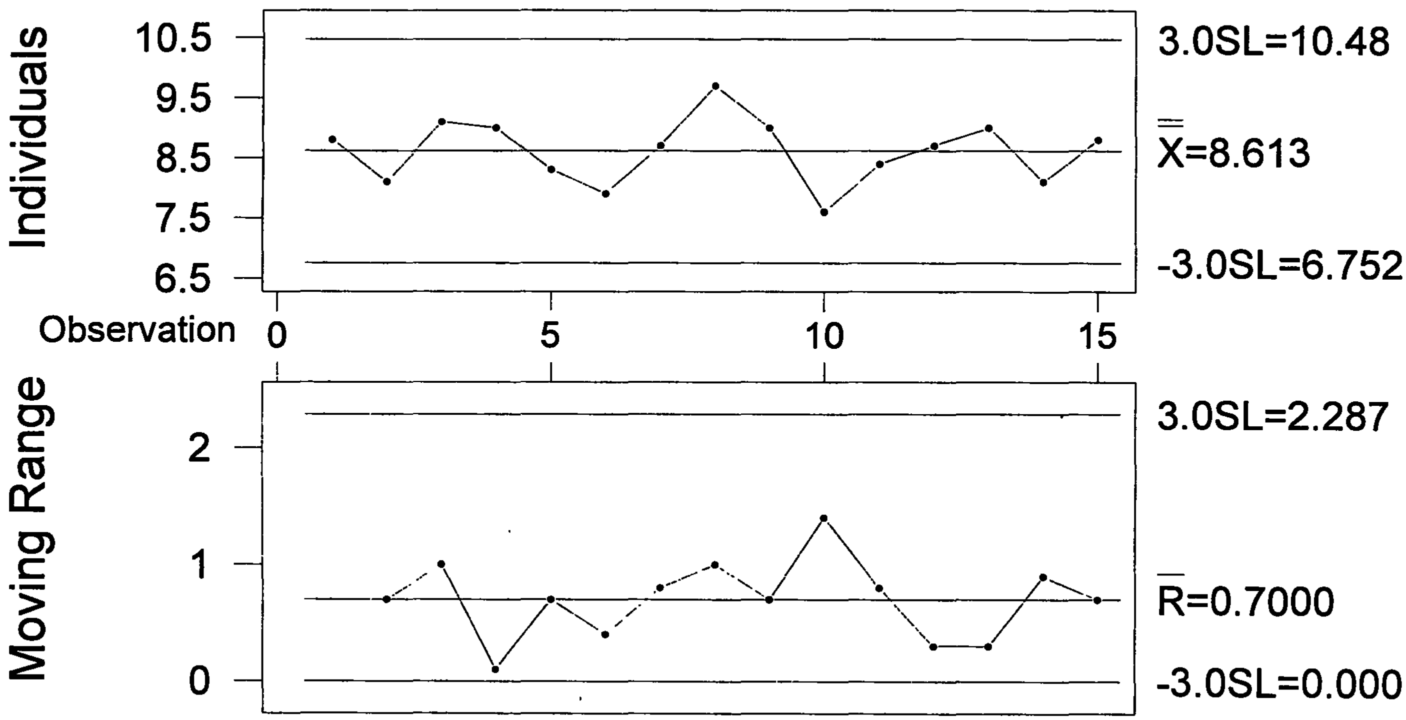
Process Capability Analysis for No. 8 Sieve



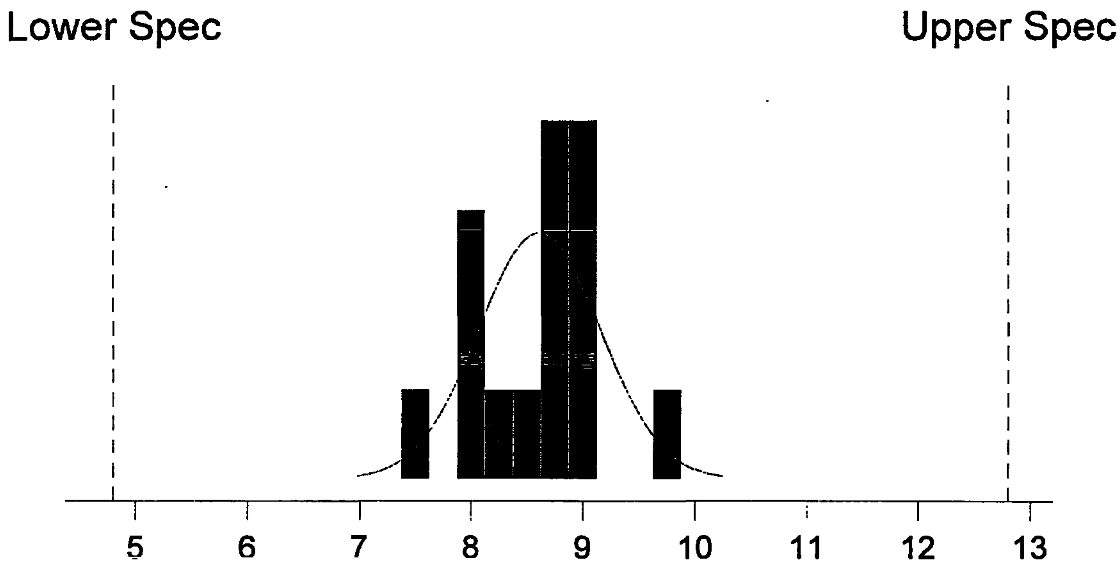
Pp	2.13	Targ	6.5000	Mean	8.1538	%>USL Exp	0.01	PPM>USL Exp	91
PPU	1.25	USL	10.5000	Mean+3s	10.0338	Obs	0.00	Obs	0
PPL	3.01	LSL	2.5000	Mean-3s	6.2739	%<LSL Exp	0.00	PPM<LSL Exp	0
Ppk	1.25	k	0.4135	s	0.6267	Obs	0.00	Obs	0
Cpm	0.73	n	13.0000						


Histogram for No. 16 Sieve
LSL
USL
Frequency
0
1
2
3
4
5
6
7
3.8
4.8
5.8
6.8
7.8
8.8
9.8
10.8
11.8
12.8
13.8
No. 16 Sieve

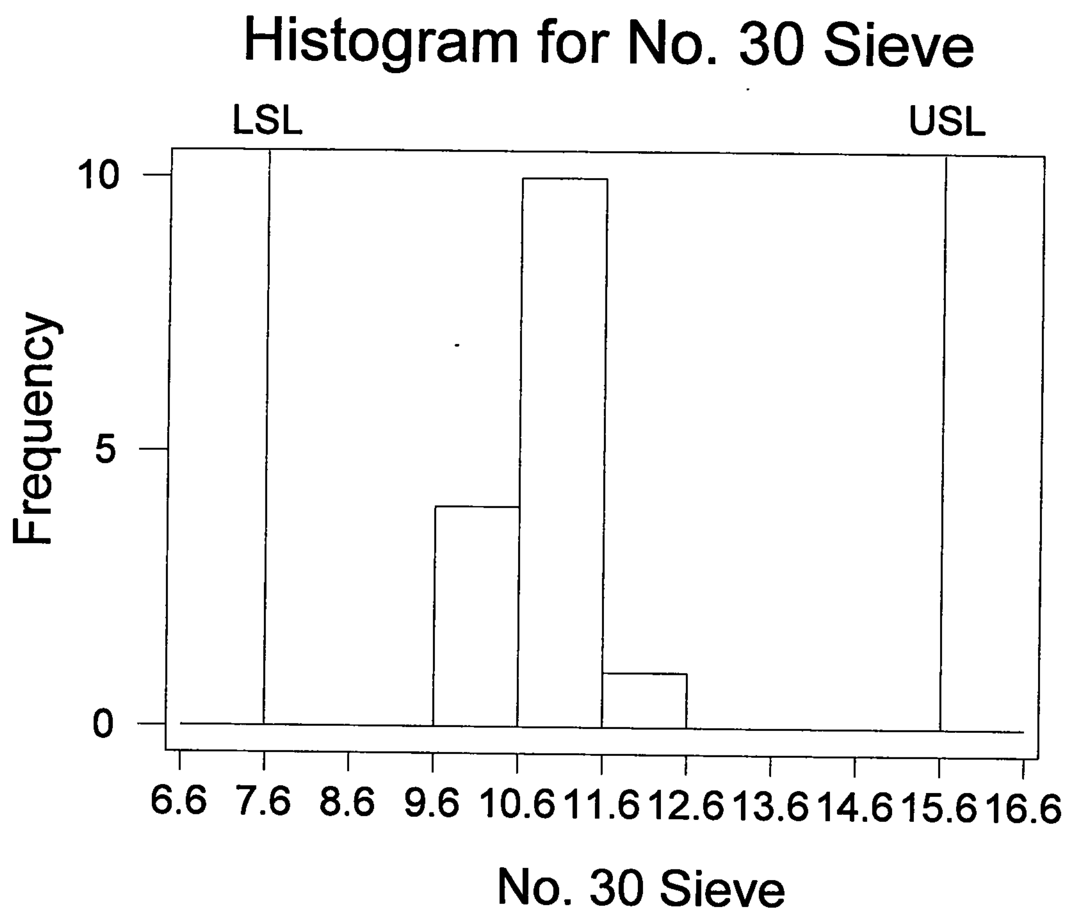
I and MR Chart for No. 16 Sieve



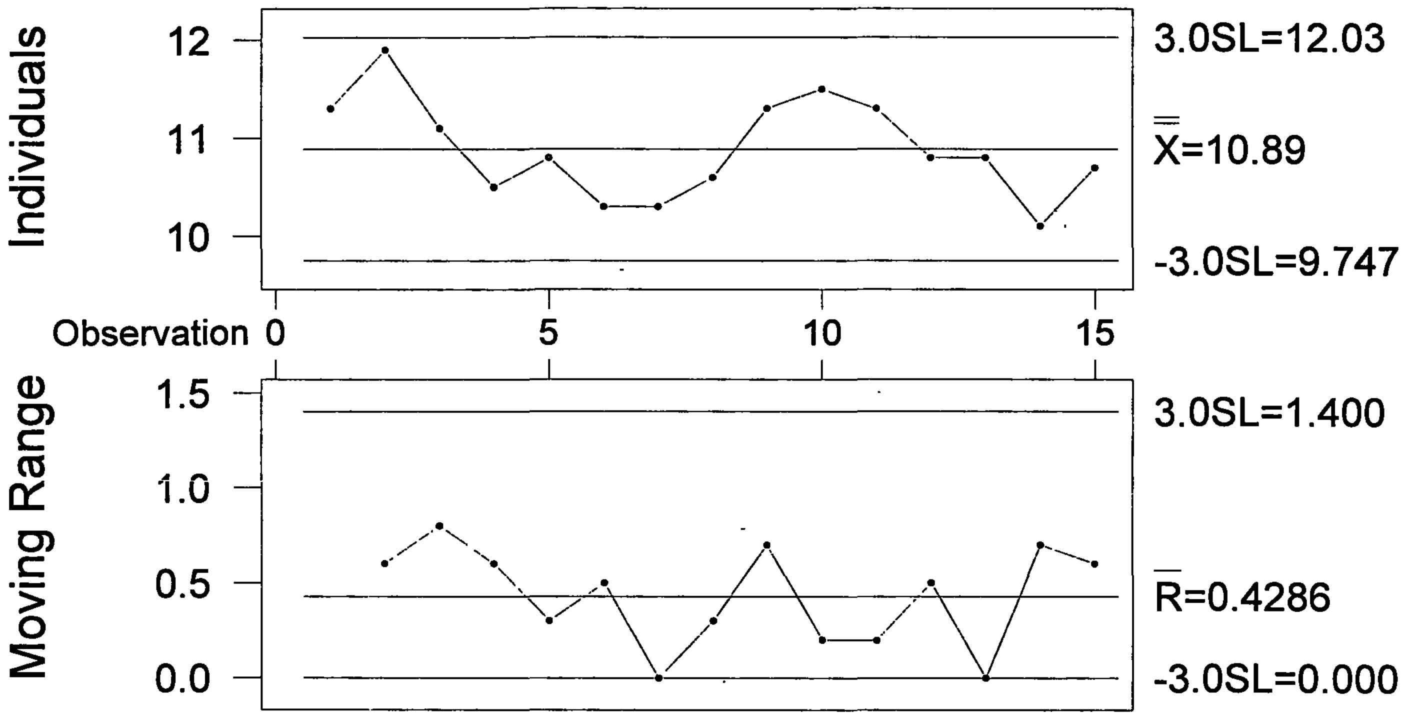
Process Capability Analysis for No. 16 Sieve



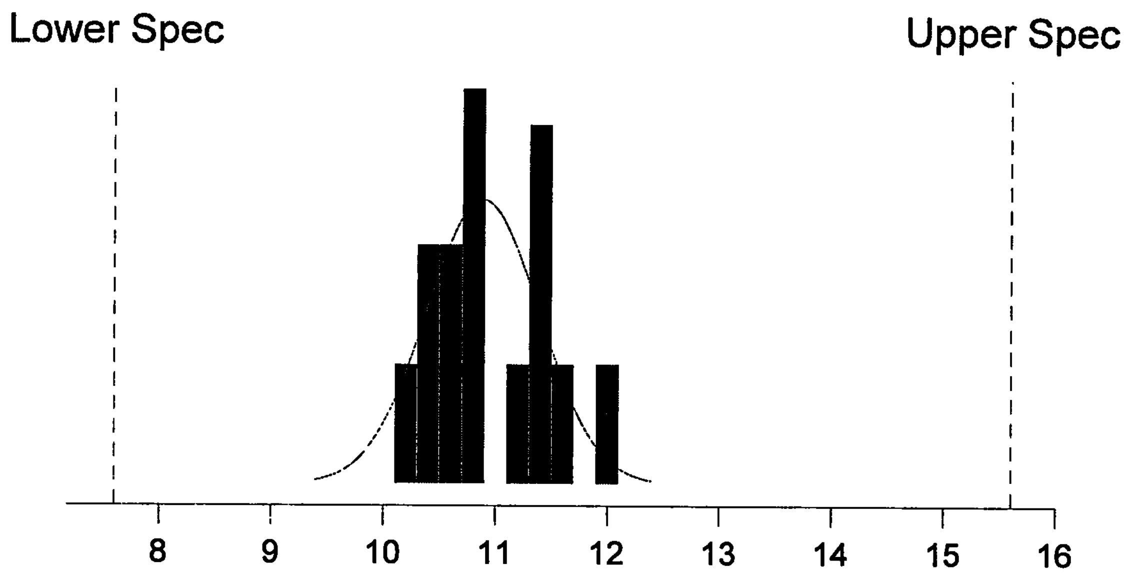
Pp	2.45	Targ	8.8000	Mean	8.6133	%>USL Exp	0.00	PPM>USL Exp	0
PPU	2.56	USL	12.8000	Mean+3s	10.2481	Obs	0.00	Obs	0
PPL	2.33	LSL	4.8000	Mean-3s	6.9785	%<LSL Exp	0.00	PPM<LSL Exp	0
Ppk	2.33	k	0.0467	s	0.5449	Obs	0.00	Obs	0
Cpm	2.31	n	15.0000						


Histogram for No. 30 Sieve
LSL
USL
10
5
0
Frequency
6.6
7.6
8.6
9.6
10.6
11.6
12.6
13.6
14.6
15.6
16.6
No. 30 Sieve

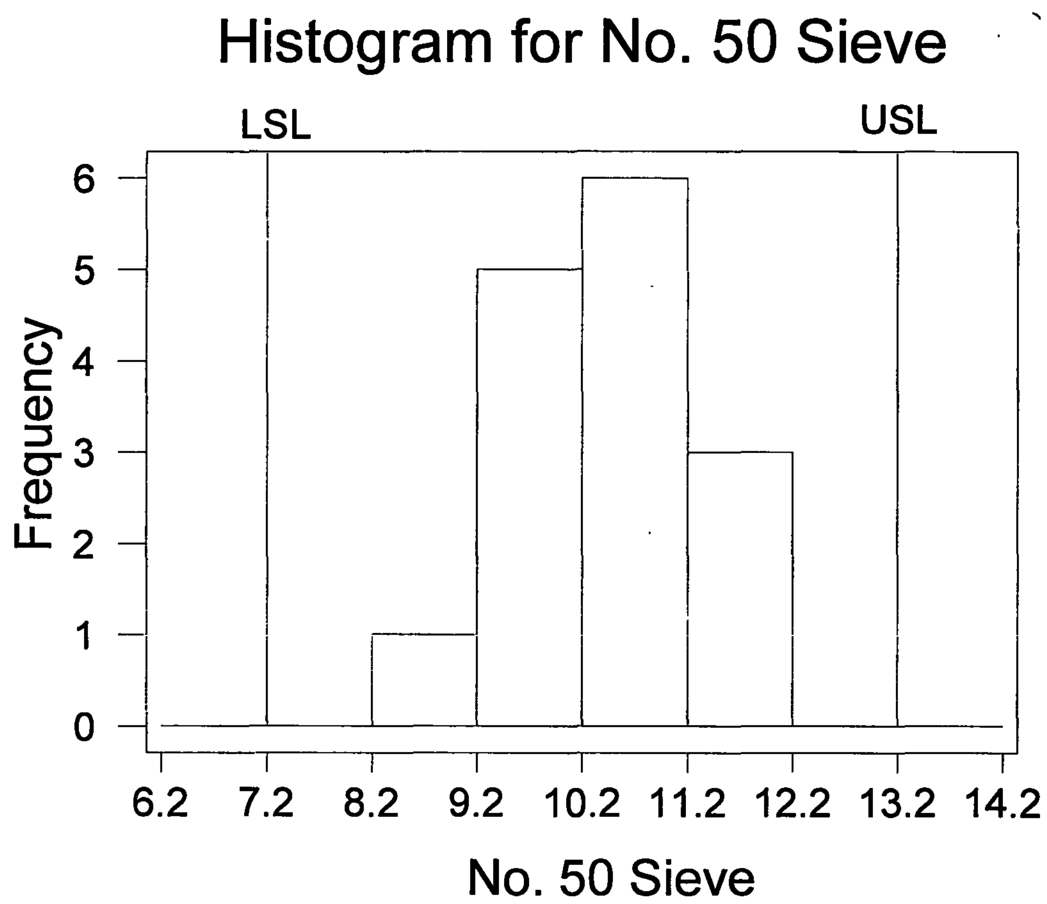
I and MR Chart for No. 30 Sieve



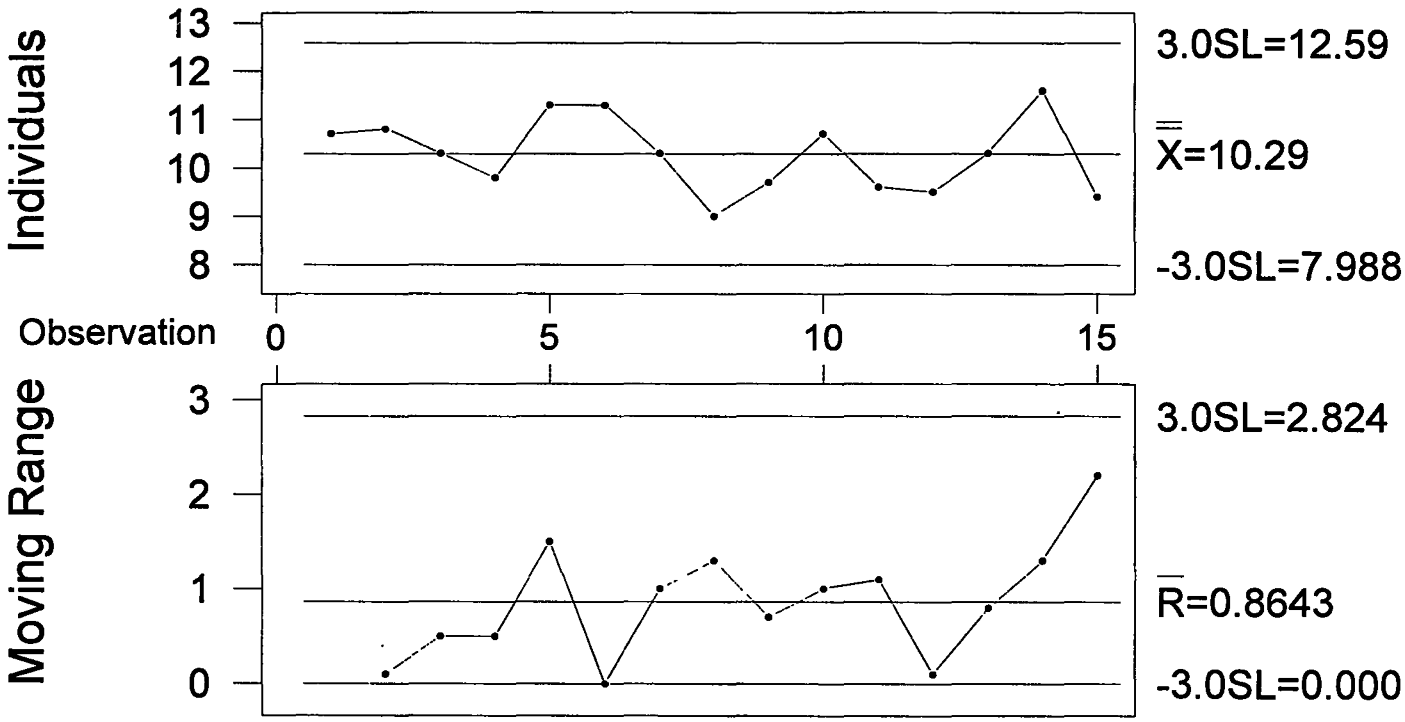
Process Capability Analysis for No. 30 Sieve



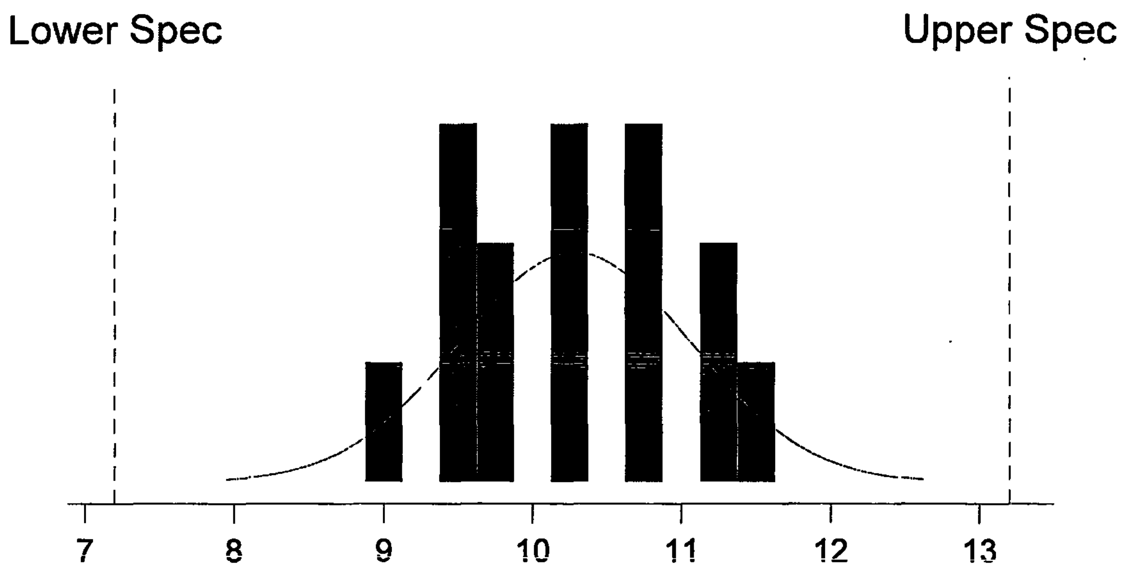
Pp	2.65	Targ	11.6000	Mean	10.8867	%>USL Exp	0.00	PPM>USL Exp	0
PPU	3.12	USL	15.6000	Mean+3s	12.3989	Obs	0.00	Obs	0
PPL	2.17	LSL	7.6000	Mean-3s	9.3744	%<LSL Exp	0.00	PPM<LSL Exp	0
Ppk	2.17	k	0.1783	s	0.5041	Obs	0.00	Obs	0
Cpm	1.49	n	15.0000						


Histogram for No. 50 Sieve
LSL
USL
6
5
4
3
2
1
0
Frequency
6.2
7.2
8.2
9.2
10.2
11.2
12.2
13.2
14.2
No. 50 Sieve

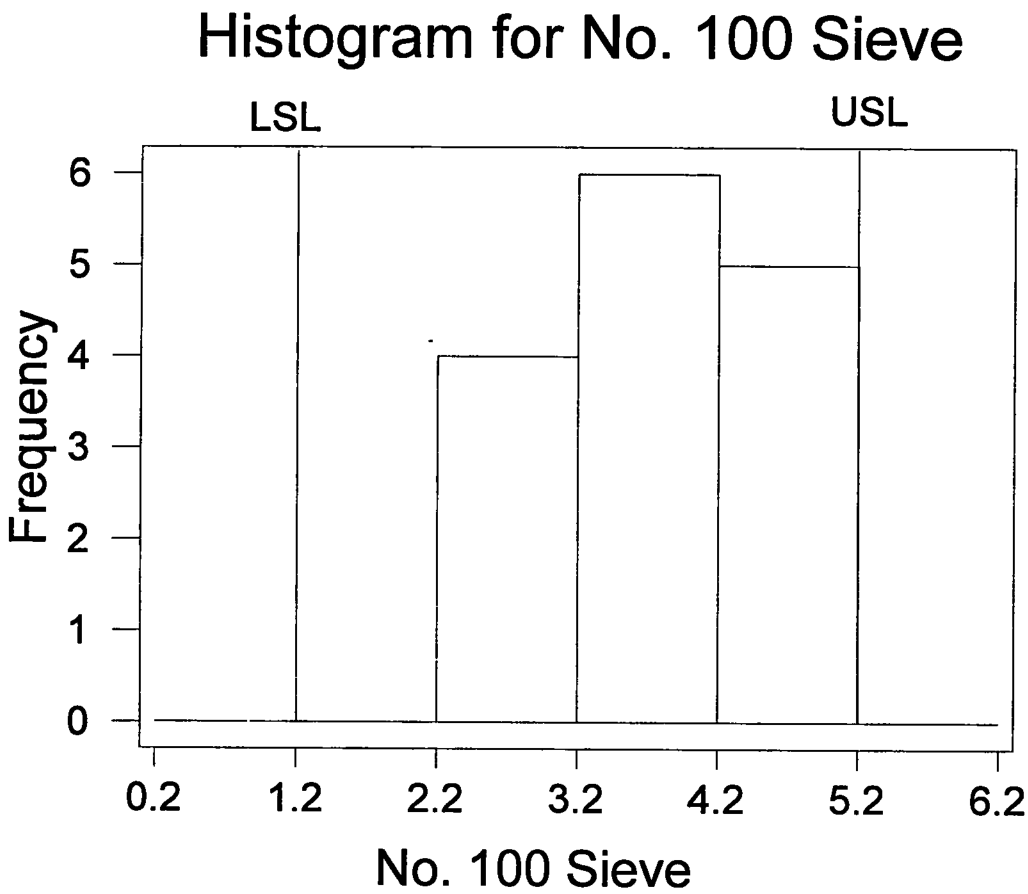
I and MR Chart for No. 50 Sieve



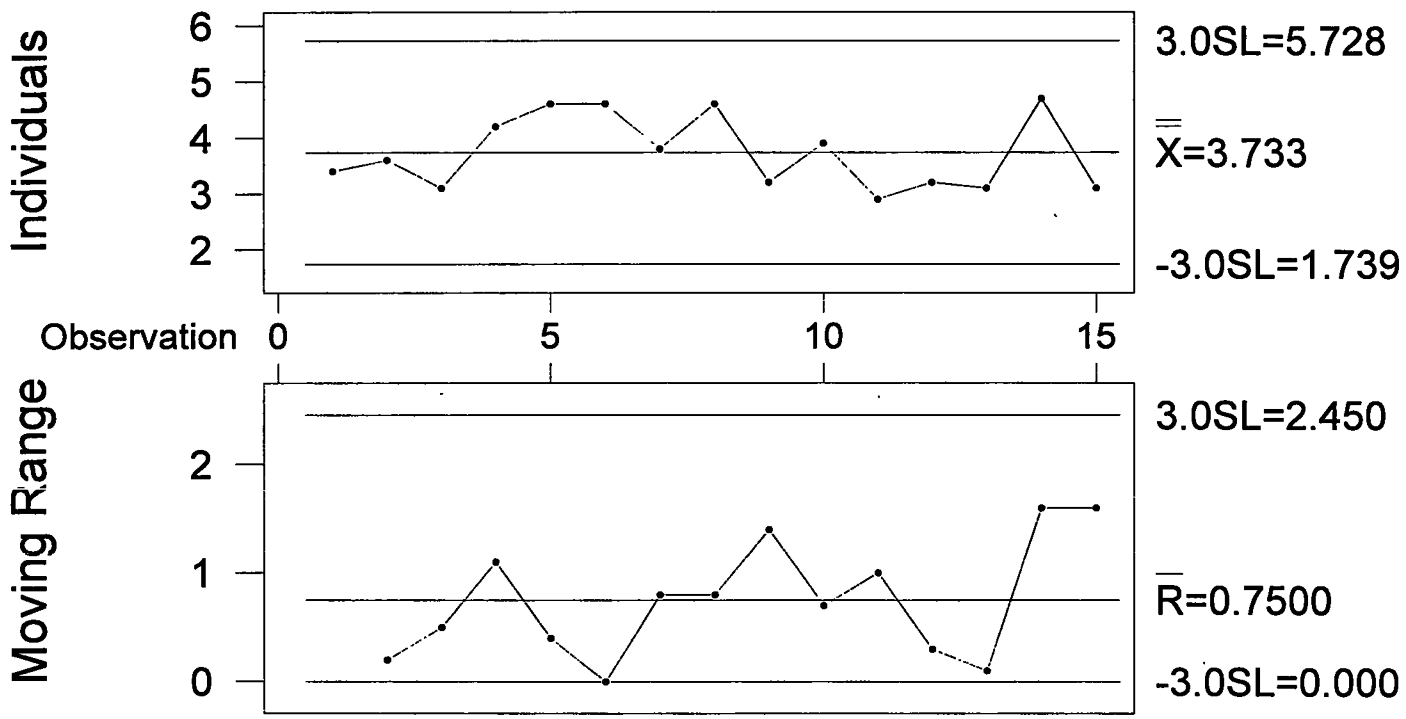
Process Capability Analysis for No. 50 Sieve



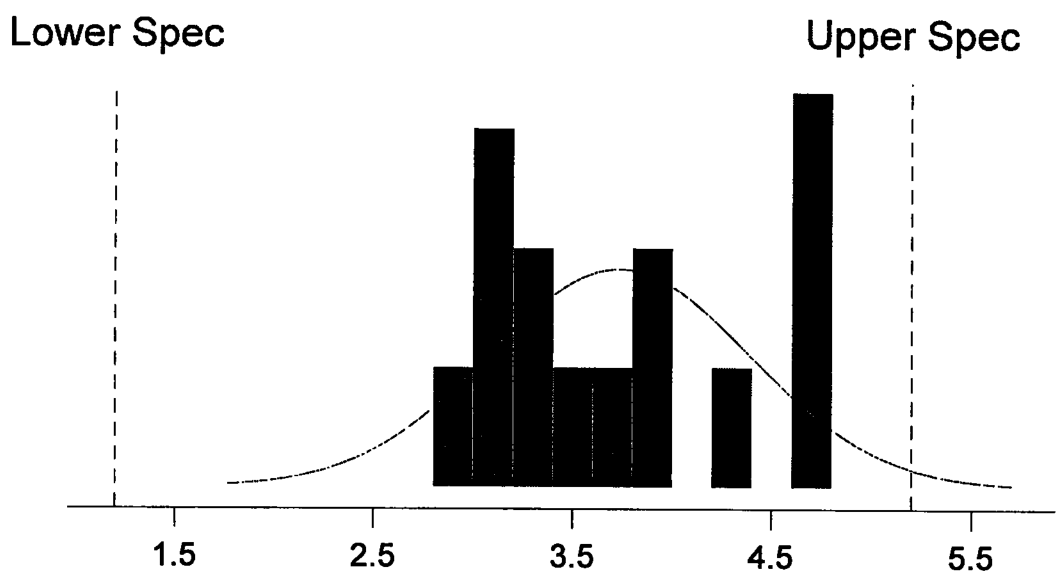
Pp	1.28	Targ	10.2000	Mean	10.2867	%>USL	Exp	0.01	PPM>USL	Exp	92
PPU	1.25	USL	13.2000	Mean+3s	12.6239		Obs	0.00		Obs	0
PPL	1.32	LSL	7.2000	Mean-3s	7.9495	%<LSL	Exp	0.00	PPM<LSL	Exp	37
Ppk	1.25	k	0.0289	s	0.7791		Obs	0.00		Obs	0
Cpm	1.28	n	15.0000								


Histogram for No. 100 Sieve
LSL
USL
Frequency
0
1
2
3
4
5
6
0.2
1.2
2.2
3.2
4.2
5.2
6.2
No. 100 Sieve

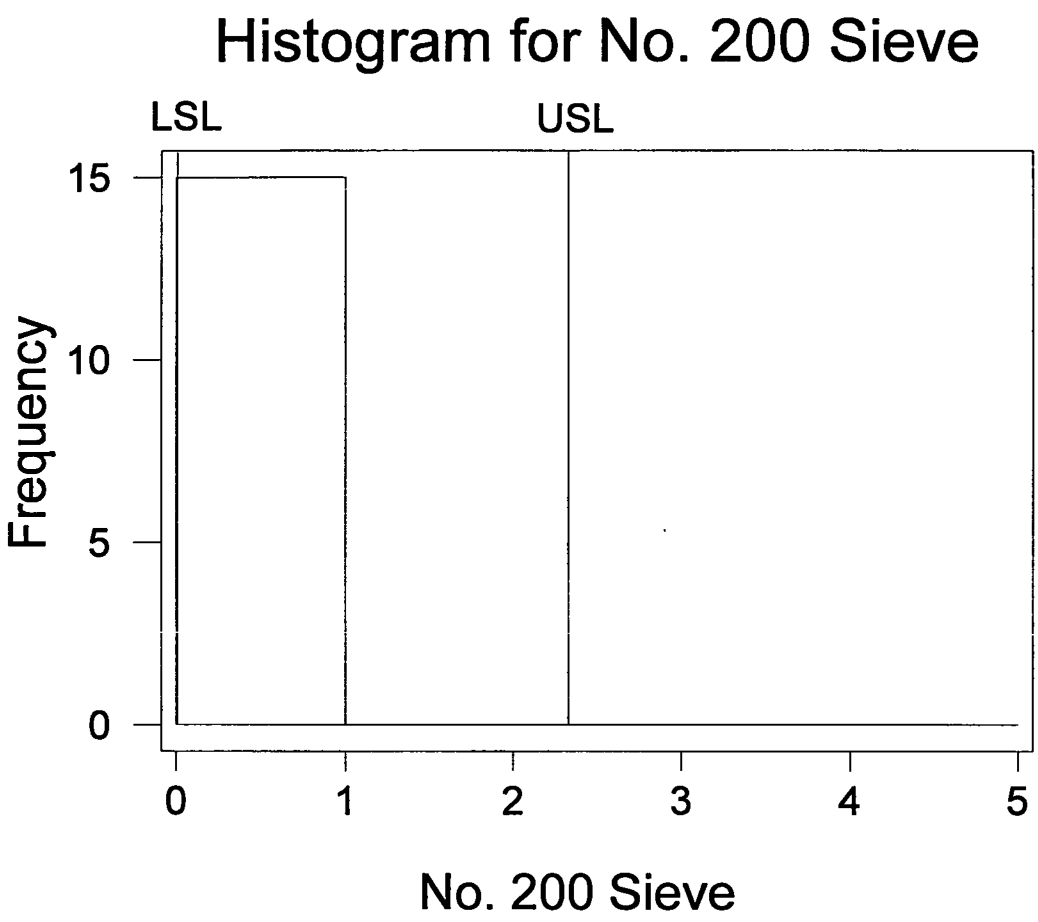
I and MR Chart for No. 100 Sieve



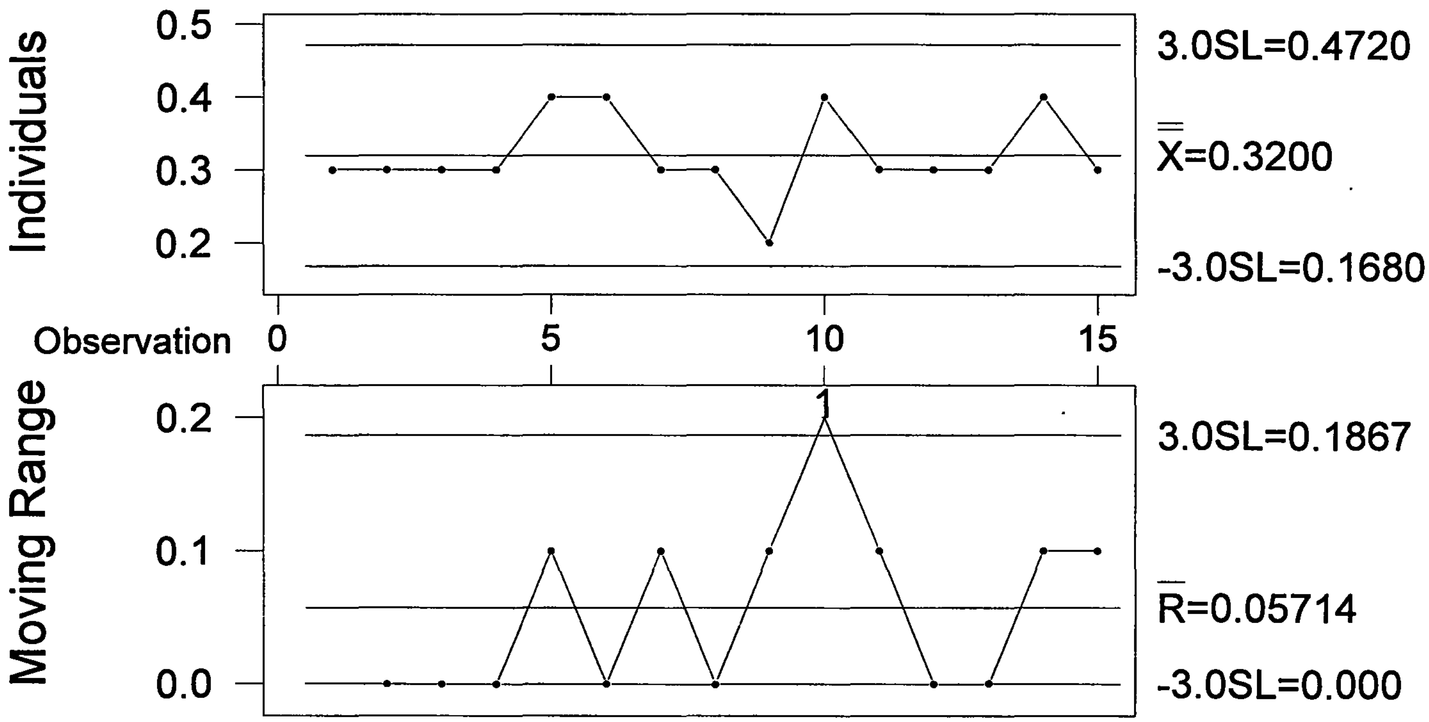
Process Capability Analysis for No. 100 Sieve



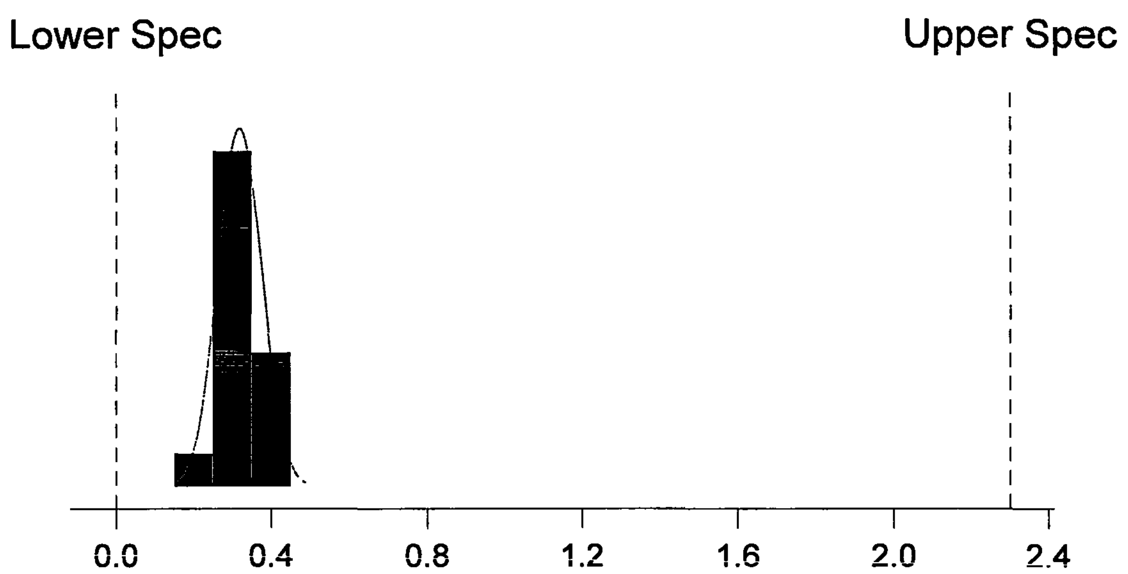
Pp	1.02	Targ	3.2000	Mean	3.73333	%>USL Exp	1.27	PPM>USL Exp	12736
PPU	0.74	USL	5.2000	Mean+3s	5.70274	Obs	0.00	Obs	0
PPL	1.29	LSL	1.2000	Mean-3s	1.76392	%<LSL Exp	0.01	PPM<LSL Exp	57
Ppk	0.74	k	0.2667	s	0.65647	Obs	0.00	Obs	0
Cpm	0.78	n	15.0000						


Histogram for No. 200 Sieve
LSL
USL
15
10
5
0
Frequency
0
1
2
3
4
5
No. 200 Sieve

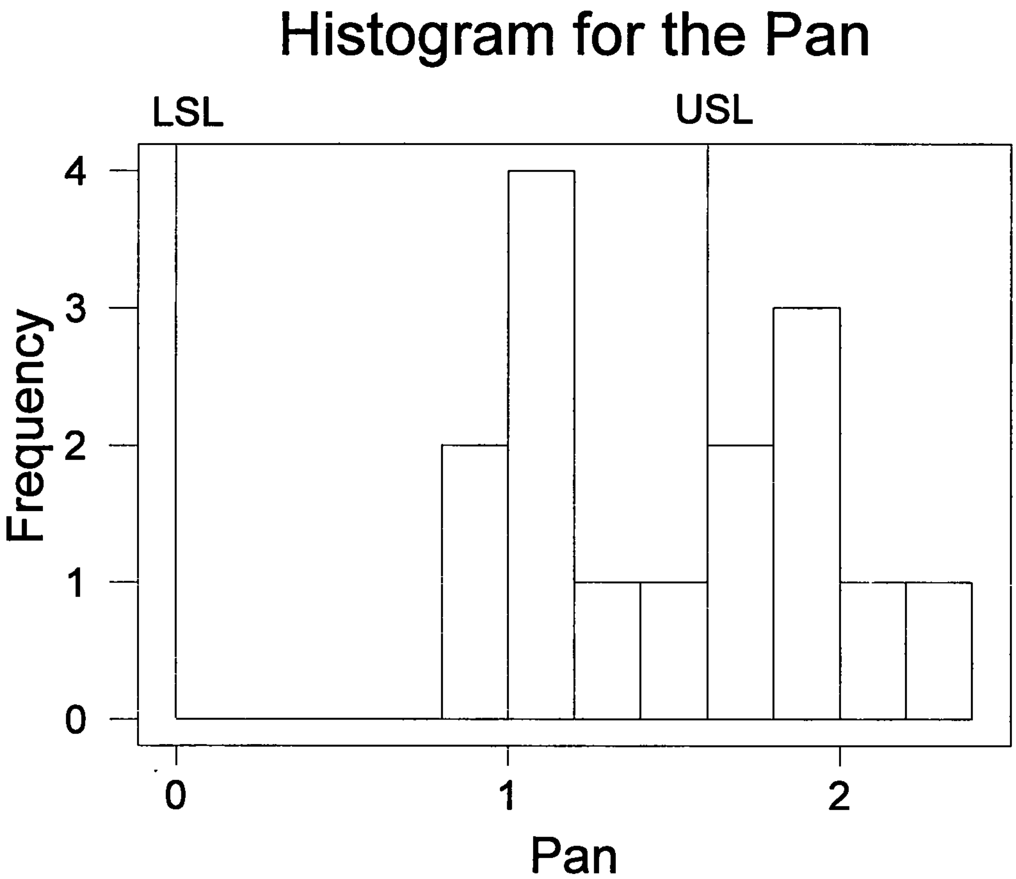
I and MR Chart for No. 200 Sieve



Process Capability Analysis for No. 200 Sieve



Pp	6.84	Targ	0.3000	Mean	0.320000	%>USL Exp	0.00	PPM>USL Exp	0
PPU	11.77	USL	2.3000	Mean+3s	0.488184	Obs	0.00	Obs	0
PPL	1.90	LSL	0.0000	Mean-3s	0.151816	%<LSL Exp	0.00	PPM<LSL Exp	0
Ppk	1.90	k	0.7217	s	0.056061	Obs	0.00	Obs	0
Cpm	6.41	n	15.0000						


Histogram for the Pan
LSL
USL
Frequency
0
1
2
3
4
0
1
2
Pan

I and MR Chart for the Pan