TEST METHOD T 194

ESTABLISHING AND MAINTAINING CONTROL CHARTS FOR CONCRETE PAVEMENT SURFACE HEIGHTS

REVISION SUMMARY

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TEST METHOD T 194

ESTABLISHING AND MAINTAINING CONTROL CHARTS FOR CONCRETE PAVEMENT SURFACE HEIGHTS

1.0 SCOPE

This Test Method describes the procedures for:

- establishing ***acceptance*** control charts;
- determining the process control limits for ***process*** control charts;
- re-calibrating the ***process*** control charts and;
- the actions arising from control analysis,

for surface heights of concrete pavements placed by paving machine or by hand in accordance with RTA model contract specifications for controlling concrete pavement surface heights and base course thickness.

2.0 PURPOSE

The purpose of the control charts is to measure and control the variance of the constructed concrete pavements surface heights relative to their design heights. The process control charts also enable estimation of the capability of the construction process to construct the pavement surface within specified tolerances of its design height.

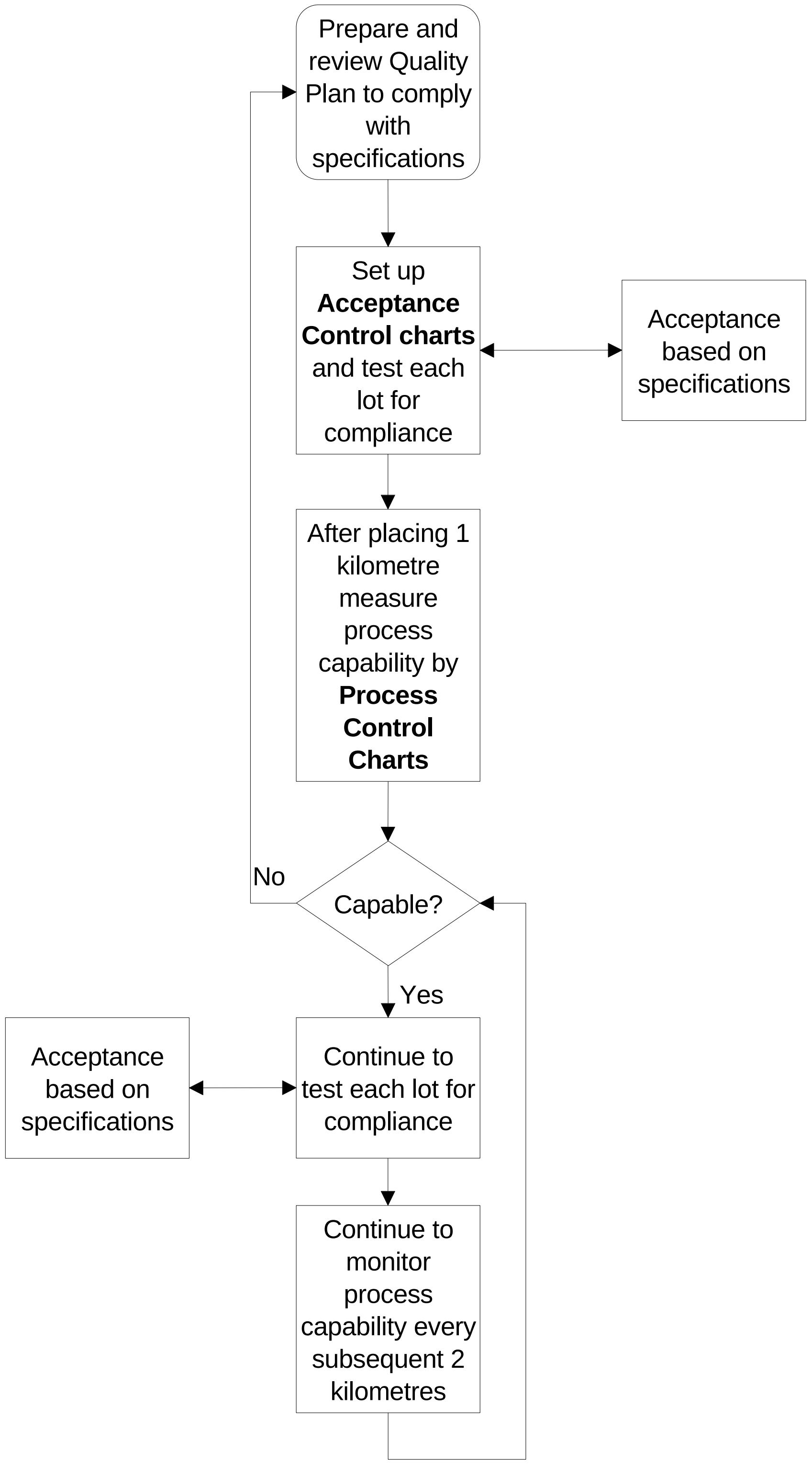
3.0 OVERVIEW

Measurement of the pavement surface heights is by survey, as defined in specification RTA Q. The control charts analyse results of conformance verification surveys of pavement surface heights that follow the sampling plan described in Test Method T195. The control charts provide a trend analysis of the sample mean and standard deviation of the surface level departures measured for each lot. A surface level departure is defined as the difference in height between the as constructed pavement surface and its equivalent design height. The decision lines of the process control charts provide guidance as to when intervention of the process is warranted.

Apart from the effect of data correlation on the standard deviation of the sample mean, Australian Standard, AS 3942, "Quality Control – Variables Charts – Guide", gives background information on the preparation of control charts for this Test Method. This Test Method will highlight where its methods for estimating statistical parameters differ from AS 3942.

Diagram 1

Flow Chart showing the role of acceptance control charts and process control charts to controlling pavement surface heights.



4.0 DEFINITIONS

The definitions contained in RTA model specification clauses for construction of concrete pavements also apply to this Test Method.

Clause 5.1 of Test Method T195 contains the definitions for full and residue lots.

5.0 APPARATUS

To assist electronic data transfer, control charts should be plotted electronically by computer software such as spreadsheet or dedicated statistical packages.

6.0 PROCEDURE

The acceptance limits and process control limits, defined by this Test Method, require compliance with the sampling plan given in Test Method T 195.

This Test Method samples the pavement on a lot by lot basis, with each lot defined as 100 lineal metres of pavement of a day's homogeneous work. However, due to various factors it is not possible to assume that an even multiple of 100 metres of pavement will be placed each day. Test Method TM 195 describes the method of sampling the residue portion of the pavement from the end of the last even 100 lineal metres of pavement to the end of the day's pour. Tables 2, for Acceptance Limits, and Table 4, for Process Control Charts, provide parameters for residue lots.

In addition, trial pavements, equipment breakdown and inclement weather, may lead to less than 80 lineal metres of pavement being placed during a day's work. Where one day's work consists of less than 80 metres of pavement, then sample the pavement as one lot in accordance with Test Method T195. For the subbase surface all surface level departures must lie within the range of zero to –20mm. For the base surface all surface level departures must lie within the range of zero to +20mm. Lots representing one day's homogeneous work that is less than 80 metres in length are excluded from control charting requirements described in this Test Method.

6.1 ESTABLISHING ACCEPTANCE CONTROL CHARTS

This Test Method shows the acceptance limits for concrete pavements placed by a paving machine only. The acceptance limits for hand placed concrete pours are contained in the RTA specification clauses for construction of concrete pavements.

6.1.1 The Acceptance Limits

The acceptance limits of the sample mean, $\bar{x}$**,** are set equispaced about the target height, as shown in Table 1 for full lots and Table 2 for residue lots. The acceptance limit for the sample standard deviation, s_x, for each lot is also shown in Table 1 for full lots and Table 2 for residue lots.

Table 1 – Acceptance Limits for Full Lots

Acceptance Limits for $\bar{x}$ (mm)	**Acceptance Limits for s_x**
Target for surface level departures $\pm$ 8.7	$\leq$7.5 mm.

Notes:

1. Target for surface level departures for the subbase surface is –10 mm.
2. Target for surface level departures for the base surface is +10 mm.

Table 2 – Acceptance Limits for Residue Lots

Lot Type	Lot Length (m)	AL Width for $\bar{x}$, Target (+/-) mm	AL for s_x mm
Residue Lot	80	9.6	7.6
Residue Lot	85	9.4	7.6
Residue Lot	90	9.2	7.6
Residue Lot	95	8.9	7.6
Full Lot	100	8.7	7.6
Residue Lot	105	8.6	7.6
Residue Lot	110	8.5	7.6
Residue Lot	115	8.3	7.6
Residue Lot	120	8.2	7.6
Residue Lot	125	8.0	7.6
Residue Lot	130	7.9	7.5
Residue Lot	135	7.8	7.5
Residue Lot	140	7.7	7.5
Residue Lot	145	7.5	7.5
Residue Lot	150	7.7	7.5
Residue Lot	155	7.3	7.5
Residue Lot	160	7.2	7.5
Residue Lot	165	7.1	7.5
Residue Lot	170	7.0	7.5
Residue Lot	175	6.9	7.5

6.1.2 Preparing the Acceptance Control Charts

Prior to surveying subbase concrete, establish acceptance control charts for both the sample mean ($\bar{x}$) and the sample standard deviation (s_x).

The $\bar{x}$ acceptance control chart is to consist of:

1. A horizontal scale to show the lots in order of construction.
2. A vertical scale to show the $\bar{x}$ values for each lot in millimetres.
3. Draw the following three additional horizontal lines:
   - one horizontal line to show the target value for $\bar{x}$ of the surface level departures in accordance with the specifications and
   - two horizontal lines showing the upper and lower acceptance limits of the sample mean in accordance with Clause 6.1.1 of this Test Method.

The *s* acceptance control chart is to consist of:

1. A horizontal scale to show the lots in order of construction. Maintain the same reduction ratio as the horizontal scale of the $\bar{x}$ chart.
2. A vertical scale to show the s_x value for each lot in millimetres.
3. A horizontal line to show the acceptance limit for the sample standard deviation in accordance with Clause 6.1.1 of this Test Method.

In addition, prepare a Lot Schedule that includes,

- a unique identifier of each lot,
- delineation of the pavement course,
- date of construction,
- delineation of a full or residue lot,
- sample standard deviation,
- sample mean,
- sample size *n* and
- the acceptance limits for both the sample mean and standard deviation for each lot.

RTA model Contracts Specification Clauses for controlling concrete pavement surface heights and base course thickness contain the formulae for calculating $\bar{x}$ and s_x for each lot, which follow accepted statistical theory. Plot the sample mean ($\bar{x}$) and sample standard deviation (s_x) of each lot on the $\bar{x}$ and s_x control charts, respective. After plotting a point, draw a straight line to the previously plotted point to show the process trend.

Plot the $\bar{x}$ acceptance control chart above the s_x acceptance control chart with the same horizontal reduction ratio. This will aid analysis of the results by clearly showing the relationship between trends in the sample mean and standard deviation.

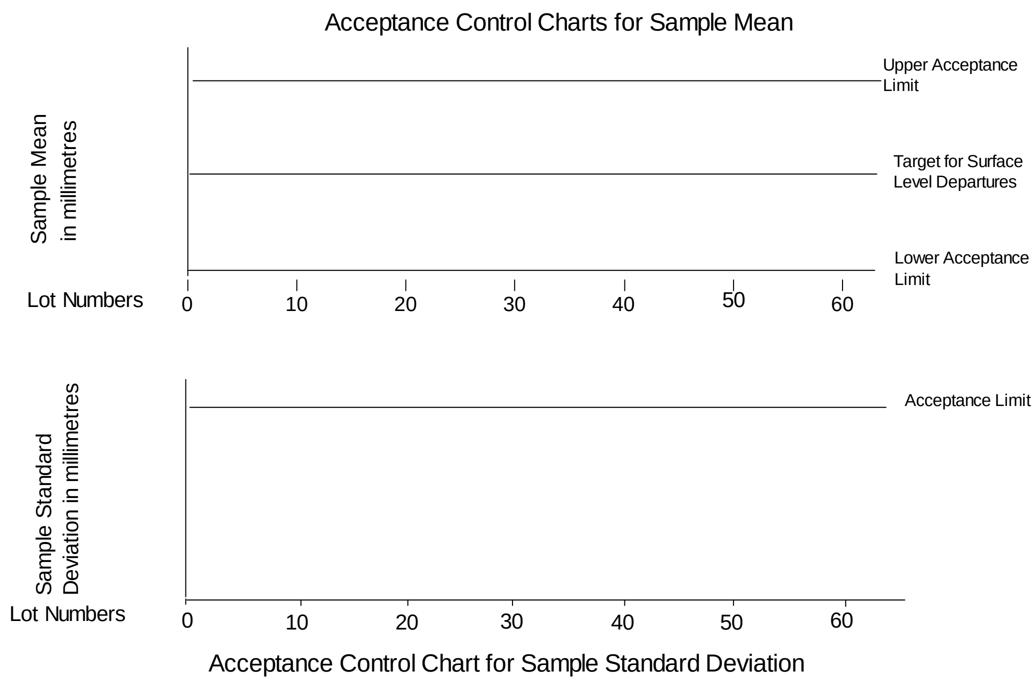


Figure 1
Acceptance Control Charts Set Up for Paving

6.1.3 Uniquely Define Each Lot

Lots may be formed with the same chainage but with different offset from the road centreline. This will occur when more than one concrete pour places the full pavement width of the road. The unique identification of each lot, required for the lot schedule above, may also need to include an offset from the road centreline or some other method, to uniquely define the lot.

6.1.4 Plotting Results on the Acceptance Control Charts

Plot the results of the conformance verification survey as soon as practicable but no later than 48 hours after placement of concrete.

6.1.5 Order of Plotting Survey Results

Plot surveys results, first in date order and then in time order of placement of concrete. This will track the construction process and assist in detecting any problems in the process controls that may arise.

6.1.6 Separate Control Charts for Subbase and Base Surfaces

Establish separate acceptance control charts for both the subbase and base surfaces. The acceptance limits for both surfaces are given in Tables 1 and 2.

6.2 ESTABLISHING PROCESS CONTROL CHARTS

Due to data correlation, different pour widths do not influence the control limits for both acceptance control charts, nor do they influence the process control limits for the process control charts for the sample mean. However, they do influence the process control limits for the sample standard deviation, due to the variable sample sizes created by variable pour widths, as described in Test Method T195. This is shown in Tables 3 and 4, which show different pour widths as well as variable lot lengths.

6.2.1 Plotting Process Control Lines on Acceptance Control Charts

Calculate and plot process control lines on the Acceptance Control Charts after surveying one kilometre of pavement. Include all lots surveyed in the first kilometre for calculating process control lines.

The following lines are the process control lines that define the $\bar{x}$ and *s* Process Control Charts:

1. a horizontal line, $\bar{\bar{x}}$, plotted on the $\bar{x}$ acceptance control chart showing the overall mean value of the surface level departures, also known as **the process mean**;
2. two horizontal lines plotted on the $\bar{x}$ acceptance control chart for the **upper and lower process control limits**;
3. a horizontal line on the *s* acceptance control chart showing the pooled estimate of **the process standard deviation**;
4. two horizontal line on the s acceptance control chart showing the **upper and lower process control limits of the sample standard deviation**.
5. Insert additional columns for the process control lines to the lot schedule described in Clause 6.1.2 and add the values of the process control lines. The process control lines are;
    - the process mean,
    - the upper and lower process control limits of the sample mean,
    - the pooled variance estimate of the process standard deviation and
    - the upper and lower process control limits of the sample standard deviation.

6.2.2 Calculation of the Process Control Lines

The process mean, $\bar{\bar{x}}$, is the overall mean of the surface level departures measured at the time of setting the process control lines and is given as:

$$\bar{\bar{x}} = \frac{\sum_{i=1}^{m} n_i \bar{x}_i}{\sum_{i=1}^{m} n_i} \qquad (1)$$

where, $\bar{x}_i = \frac{\sum_{i=1}^{n} x_i}{n}$ *is the sample mean of the i th lot, which has* n_i *sample measurements and there have been m lots surveyed since the previous calibration.*

The pooled estimate of the process standard deviation, $s_{x\,pooled}$, estimates the average variability within each lot since the previous calibration and is given as:

$$s_{x\,pooled} = \sqrt{\frac{\sum_{i=1}^{m} (n_i - 1) s_i^2}{\sum_{i=1}^{m} n_i - m}} \qquad (2)$$

where m and n_i *are given in equation (1) and* s_i *is the sample standard deviation of the ith lot which is defined as:*

$$s_i = \sqrt{\frac{\sum_{i=1}^{n_i} \left(x_i - \bar{x}_i\right)^2}{n_i - 1}} \qquad (3)$$

where x_i *is the ith sample of the ith lot, which has a sample mean of* $\bar{x}_i$.

Equations (1) and (2) give the same estimates of the **process mean** and **standard deviation** as AS 3942, if all lots have the same number of sample measurements. However, variable pour widths and residue lots make it unlikely that all lots will have of equal sample sizes.

Process variability, $s_{x\,process}$**,** measures the variability of the process about the process mean and is given as;

$$s_{x\,process} = \sqrt{\frac{\sum_{j=1}^{N} \left(x_j - \bar{\bar{x}}\right)^2}{N - 1}} \qquad (4)$$

where N is the total number of surface level departures measured at the time of calculating the control lines since the previous calibration, x_j *is the jth surface level departure and* $\bar{\bar{x}}$ *is given by equation (1).*

Process variability is the standard deviation of all the surface level departures, from all lots, measured at the time of calculating the control lines since the previous calibration.

For this Test Method this will usually differ from $s_{x\ pooled}$ as given by equation (2), due to the effect of data correlation.

The upper and lower process control limits for the $\bar{x}$ control chart are set equispaced about $\bar{\bar{x}}$ and their positions are given as:

$$\bar{\bar{x}} \pm 3 s_{x\ process} F_x \qquad (5)$$

where F_x is 0.525 for full lots, as shown in Table3. Table 4 contains F_x values for lots between 80 and 175 metres in length. Verify the state of process control for individual residue lots that plot close to the process control limits by calculating their process control limits using Table 4.

The positions of the upper and lower process control limits for the s_x control chart are given as:

Lower process limit = $S_1 s_{x\ pooled}$

Upper process limit = $S_4 s_{x\ pooled}$ (6)

where S_1 and S_4 are given in Table 3 for full lots of different pour widths. Select the appropriate S_1 and S_4 values for full lots for the next planned pavement width for construction. Verify the state of process control for individual lots that plot close to the process control limits by calculating their process control limits using Tables 3 and 4

NB: Use $s_{x\ process}$, as defined by equation (4) for the $\bar{x}$ chart and $s_{x\ pooled}$, as given by equation (2) for the s chart for surface level departures.

TABLE 3

Parameters for Process Control Charts for Full Lots

Pour Width W (metres)	Number of Strings	Sample Size n	F_x	S_1	S_4
W ≤ 1.5	1	20	0.525	0.50	1.47
1.5 < W ≤ 6.0	2	40	0.525	0.66	1.33
6.0 < W ≤ 11.0	3	60	0.525	0.72	1.27
11.0 <W ≤ 14.0	4	80	0.525	0.76	1.23

TABLE 4
Parameters for Process Control Charts for Residue Lots

Lot Type	Lot Length (m)	Pour Widths W ≤ 1.5 m				Pour Widths 1.5 m < W ≤ 6.0 m				Pour Widths 6.0 m < W ≤ 11.0 m				Pour Widths 11.0 m < W ≤ 14.0 m			
		n	S_1	S_4	F_x	n	S_1	S_4	F_X	n	S_1	S_4	F_x	n	S_1	S_4	F_x
Residue Lot	80	16	0.44	1.52	0.575	32	0.61	1.37	0.575	48	0.69	1.30	0.575	64	0.73	1.26	0.575
Residue Lot	85	17	0.46	1.51	0.560	34	0.63	1.36	0.560	51	0.7	1.29	0.560	68	0.74	1.25	0.560
Residue Lot	90	18	0.48	1.49	0.550	36	0.64	1.35	0.550	54	0.7	1.29	0.550	72	0.75	1.25	0.550
Residue Lot	95	19	0.49	1.48	0.535	38	0.65	1.34	0.535	57	0.71	1.28	0.535	76	0.75	1.24	0.535
Full Lot	**100**	**20**	**0.51**	**1.47**	**0.525**	**40**	**0.66**	**1.33**	**0.525**	**60**	**0.72**	**1.27**	**0.525**	**80**	**0.76**	**1.23**	**0.525**
Residue Lot	105	21	0.52	1.46	0.515	42	0.66	1.32	0.515	63	0.73	1.26	0.515	84	0.76	1.23	0.515
Residue Lot	110	22	0.53	1.45	0.505	44	0.67	1.32	0.505	66	0.73	1.26	0.505	88	0.77	1.22	0.505
Residue Lot	115	23	0.54	1.44	0.495	46	0.68	1.31	0.495	69	0.74	1.25	0.495	92	0.78	1.22	0.495
Residue Lot	120	24	0.55	1.43	0.490	48	0.69	1.30	0.490	72	0.75	1.25	0.490	96	0.78	1.21	0.490
Residue Lot	125	25	0.56	1.42	0.480	50	0.69	1.30	0.480	75	0.75	1.24	0.480	100	0.78	1.21	0.480
Residue Lot	130	26	0.57	1.41	0.475	52	0.70	1.29	0.475	78	0.76	1.24	0.475	104	0.79	1.21	0.475
Residue Lot	135	27	0.58	1.4	0.465	54	0.70	1.29	0.465	81	0.76	1.23	0.465	108	0.79	1.20	0.465
Residue Lot	140	28	0.59	1.4	0.460	56	0.71	1.28	0.460	84	0.76	1.23	0.460	112	0.8	1.20	0.460
Residue Lot	145	29	0.59	1.39	0.455	58	0.72	1.28	0.455	87	0.77	1.23	0.455	116	0.8	1.20	0.455
Residue Lot	150	30	0.6	1.38	0.445	60	0.72	1.27	0.445	90	0.77	1.22	0.445	120	0.8	1.19	0.445
Residue Lot	155	31	0.61	1.38	0.440	62	0.73	1.27	0.440	93	0.78	1.22	0.440	124	0.81	1.19	0.440
Residue Lot	160	32	0.61	1.37	0.435	64	0.73	1.26	0.435	96	0.78	1.21	0.435	128	0.81	1.19	0.435
Residue Lot	165	33	0.62	1.37	0.425	66	0.73	1.26	0.425	99	0.78	1.21	0.425	132	0.81	1.18	0.425
Residue Lot	170	34	0.63	1.36	0.420	68	0.74	1.25	0.420	102	0.79	1.21	0.420	136	0.82	1.18	0.420
Residue Lot	175	35	0.63	1.35	0.415	70	0.74	1.25	0.415	105	0.79	1.21	0.415	140	0.82	1.18	0.415

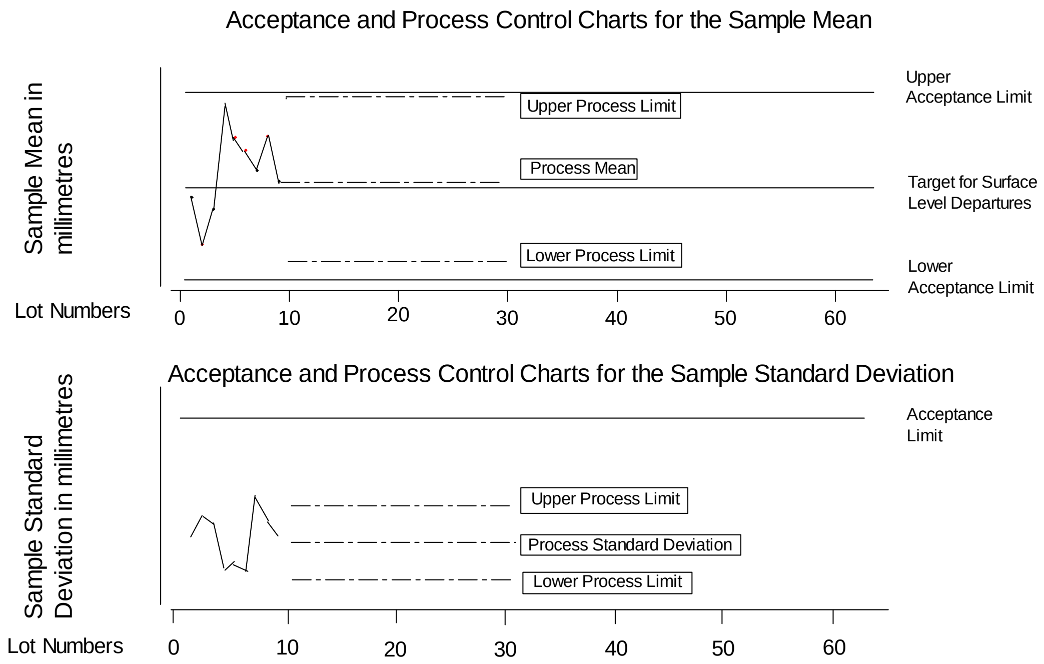


Figure 2
Process Control Lines Plotted on Acceptance Control Chart after 1 Kilometre
(Process lines plotted as dashed lines for clarity only)

Due to the effect of data correlation on the sample mean, factor F_x in equation (5) differs from Clause 4.3 of AS 3942, which uses $1/\sqrt{n}$ for determining the position of the process control limits. Factors S_1 and S_4, in equation (6), are calculated by the same formula that calculates factors S_1 and S_4 for Table 1 of AS 3942.

The producer's risks for the $\bar{x}$ and *s* process control charts are set at 0.0027. This infers that when the process is under control, one lot in 370 lots may signal a false alarm by wrongly indicating that the process is out of control.

6.3 RE-CALIBRATION OF THE PROCESS CONTROL LINES

Re-calibrate the process control charts at the subsequent prescribed interval of two kilometres of pavement after the initial calibration where the process is found to conform. Only use measurements from the subsequence two kilometres of pavement to determine the positions of the process control lines during re-calibration

Re-calculate and re-plot the process lines by equations (1) to (6). The re-plotted process control lines commence from the first lot constructed after the two kilometres of pavement used for re-calibration. Do not remove or change process control lines from previous calibrations. The purpose of re-calibrating process control charts is to track any changes in the process. It may show an improvement, deterioration or consistency in quality control since the previous calibration.

Where calculation of the process control lines, at anytime, indicates that the process does not conform then the prescribed interval for the next calibration must be 1 kilometre, in accordance with the flowchart in 3.0.

6.4 HAND PLACED CONCRETE

Establish separate acceptance and process control charts for hand placed concrete for both the subbase and base surfaces, using the same formulae as concrete placed by a paving machine, as described in Clauses 6.1 to 6.3.

The Specifications contain values for Tables 1 to 4 for hand placed concrete.

7.0 REPORTING

7.1 ACCEPTANCE CONTROL CHARTS

Acceptance is on a lot by lot basis. Accept a lot as meeting the requirements for pavement surface heights if:

- its sample mean is greater than or equal to, the lower acceptance limit and less than or equal to, the upper acceptance limit for the sample mean

  and

- its sample standard deviation is less than or equal to, the acceptance limit for the sample standard deviation.

Both the sample mean and standard deviation must comply for acceptance of the lot.

7.2 PROCESS CONTROL CHARTS

The process of constructing the pavement surfaces to the correct height is considering as conforming when:

- The process control lines of the $\bar{x}$ Process Control Chart plot inside the acceptance limits of the $\bar{x}$ Acceptance Control Chart

  and

- The process control lines of the *s* Process Control Chart plot lower than the acceptance limit of the *s* Acceptance Control Chart.

7.2.1 Relationship between Acceptance Control Charts and Process Control Charts

The limits on acceptance control charts reflect RTA (customer) requirements as set out in the specifications. The process control limits on process control charts reflect the level of quality possible by the construction process (controlled by the supplier). The limit lines of the ***acceptance*** control chart and the limit lines of the ***process*** control chart are therefore independent. However, the supplier needs to ensure that quality controls reflect the product quality as defined by the acceptance limits in the specifications.

The relationship between the acceptance limits and process control limits graphically demonstrates the capability of the construction process. Process control limits that plot inside acceptance limits show that the process is capable of meeting specified requirements practically all of the time.

Process control limits that plot outside of the acceptance limits, on either the $\bar{x}$ or s_x process control charts, indicate a significant probability that the process will produce product that does not conform. This is true even though no lots may have yet been rejected. When process control lines plot outside acceptance lines, a review of process controls should be undertaken as a matter of urgency.

7.2.2 Assignable Causes

Investigate effectiveness of process controls when the process control charts suggest the presence of an assignable cause. Statistics plotted outside the process control limits are assumed to be the result of an assignable cause and not the result of the inherent variability of a controlled system. Assignable causes are the result of inadequate process control or a temporary breakdown in the system. When lots plot outside the process control limits the process is deemed to be uncontrolled during construction of that lot. Processes that remain uncontrolled increase the risk of lots being rejected as non-conforming in the future.

Investigate lots showing an assignable cause, even if the lot conforms, to ensure that all assignable causes are detected and removed from the system before causing non-conformity.

Types of assignable causes that break down control of concrete pavement surface heights may include:

- survey error in determining heights of trim pegs,
- error in setting string line off trim pegs,
- incorrect tension of string line,
- adjustments and wear of the paving machine,
- delivery of raw material to paving machine,
- quality of the concrete mix.

A sample standard deviation plotted lower than the lower process control limit may be due to an improvement in the process controls during construction of that lot. Investigation of the construction process during construction of the lot may identify improvements to the system that could be included in the project quality plan.

7.3 CONTROL CHART ANALYSIS

Calculation of process control lines (Clause 6.2) at any time may indicate that the process controls are not capable of meeting specified requirements. Alternative, it may indicate that the process controls are constructing the pavement surface with less than expected variability. In either instance this may lead to changes in the process controls to protect the base course thickness or to take advantage of improved process control to cut costs by reducing waste materials.

This Clause sets out the criteria for adjusting process controls and the magnitude of adjustments where the process does not conform. It also offers, where appropriate, guidelines for adjusting process controls to reduce the magnitude of waste materials where the process conforms.

Survey software for setting out pavement courses requires entry of the thickness of the pavement course or courses, above the surface being set out, as a design template. Adjustment of the design template in the survey software provides fine adjustment of the process mean and the process control limits. For example, to lower the process mean for the subbase surface by 5 mm, add 5 mm to the design template for the subbase surface. To raise the base process mean by 3 mm, where the base surface is the finished surface level, then enter a design template of 3 mm above the finished surface level.

7.3.1 Adjustments for Improved Quality

Reduced variability, as measured by the process standard deviation, is a measure of improved process control. Where calculation of the process control lines indicate a significantly higher level of quality control exist than that specified, then adjustments to the process controls may be appropriate to reduce wastage of raw materials. Adjusting the process mean closer to the design surface will achieve this outcome. However, this also increases the risk of lots plotting outside the acceptance limits of the $\bar{x}$ process control chart and therefore, lot rejection.

Table 5 shows process standard deviations and targets for the process means that have expected probabilities of 0.50% and 0.25% of lot rejection. This provides some guidance on the amount of adjustment that is possible for improved process control and associated risks.

Table 5 - Adjustment of the Process Mean Closer to the Design Surface and the Risk of Lot Rejection

	Target of the Process Mean (mm) with Probability of Lot Rejection	
Process Standard Deviation (mm)	**0.50%**	**0.25%**
4.0	6.7	7.1
3.5	6.0	6.4
3.0	5.3	5.7
2.5	4.6	4.9
2.0	4.0	4.2

NOTE: All values for the process mean are negative for the subbase surface and are positive for the base surface.

7.3.2 Actions Where the Process Does Not Conform

Where the process is found not to conform then the process control lines must be recalculated after placing 1 kilometre of pavement after completing actions required under this Clause.

Process control lines that plot outside the acceptance limits of the $\bar{x}$ control chart indicate that the process does not conform. Two scenarios may cause this to happen:

a) the process mean is too close to the upper/lower acceptance limit or
b) the variability within the process to too great to contain the sample mean within the acceptance limits.

Scenarios (a) and (b) may apply simultaneously. Therefore, when carrying out corrective action where the process does not conform, carry out actions required for scenario (a) before carrying actions required for scenario (b).

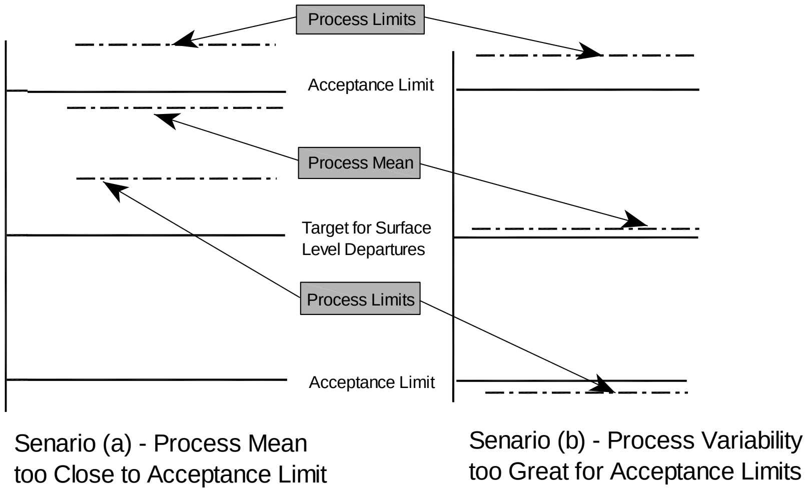


Figure 3
Scenarios Causing Process Control Limits to Plot Outside Acceptance Limits on $\bar{x}$ Acceptance Control Chart

Scenario (a) for $\bar{x}$ Control Chart: Where this Scenario exists then adjust the process controls to ensure that the process mean aligns with the Target for Surface Level Departures as given in Clause 6.1.1. The difference between the process mean and the Target for Surface Level Departures, as shown on the $\bar{x}$ Control Chart, defines the magnitude of the adjustment.

Scenario (b) for $\bar{x}$ Control Chart: Where this Scenario exists then adjust the process mean further away from the design surface than Target for Surface Level Departures as given in Clause 6.1.1. For the subbase surface this means lowering the process mean further and for the base surface this means raising the process mean further.

The magnitude of the adjustment is the difference between the acceptance limit and process limit closer to the design surface, as shown on the $\bar{x}$ Control Chart. For the subbase surface this infers the difference between the upper acceptance and process limits; and for the base surface this infers the difference between the lower acceptance and process limits.

(c) The *s* control chart

Where process control lines of the $\bar{x}$ control chart plot inside the acceptance limits and the upper process control line of the *s* chart plots above the acceptance limit then carry out a review of the QUALITY PLAN.

Increased variability in the process, as measured by the process standard deviation, affects the limits of the $\bar{x}$ control charts. Therefore actions to address the effects of process control lines plotted outside the acceptance limits of the $\bar{x}$ Process Control Chart also address the effects of process control lines of the *s* Process Control Chart plotting outside the acceptance limit. Therefore, no further actions, than those described for the $\bar{x}$ control chart, are required where the upper process control limit of the *s* Process Control Chart is greater than its acceptance limit and the process limits of the $\bar{x}$ Process Control Chart plot outside the acceptance limits of the Acceptance Control Chart.

7.4 CONTROL CHARTS AS A MANAGEMENT TOOL

Control charts are a management tool that provides feedback to construction personnel on the quality of the processes to which they contribute. This feedback gives recognition to process improvement and looks for input from construction personnel when the process goes out of control or becomes incapable of meeting specified requirements. For this to be effective, project management may consider placing the control charts in prominent position on site, with all personnel involved in the process having access to view them.

ATTACHMENT

FIELD EXAMPLE OF CONTROL CHARTS

The following example is from a pilot study conducted by the RTA. The contract controlling the project specified construction of the subbase surface within the range of –0 to –20 millimetres of its design height and the base surface within the range of +0 to +20 millimetres of its design height. The following example contains the acceptance control charts and process control charts for the base surface.

									Standard Deviation - Limits				Mean - Limits				
Lot No.	Lot Location				Statistical Summaries			Full/ Res	Accepts.	Process Limits			Acceptance Limits		Process Limits		
	Start Ch.	Offset	Strgs	Const. Date	Stdev	Mean	*n*		Limits	Centre	LCL	UCL	L AL	U AL	Centre	LCL	UCL
1	48K 330	4L to 4R	3	30/10/1999	2.6	-1.0	58	F	7.5				1.3	18.7			
2	48K 230	4L to 4R	3	30/10/1999	3.5	-4.4	57	F	7.5				1.3	18.7			
3	48K 135	4L to 4R	3	1/11/1999	4.4	2.0	60	F	7.5				1.3	18.7			
4	48K 035	4L to 4R	3	1/11/1999	3.0	6.2	60	F	7.5				1.3	18.7			
5	47K 935	4L to 4R	3	1/11/1999	4.6	1.4	60	F	7.5				1.3	18.7			
6	47K 835	4L to 4R	3	1/11/1999	2.7	1.6	81	R	7.5				2.1	17.9			
7	47K 700	4L to 4R	3	4/11/1999	3.1	2.7	60	F	7.5				1.3	18.7			
8	47K 600	4L to 4R	3	4/11/1999	2.7	0.6	60	F	7.5				1.3	18.7			
9	47K 500	4L to 4R	3	4/11/1999	2.3	0.4	48	R	7.6				0.6	19.4			
10	47K 420	4L to 4R	3	5/11/1999	2.6	1.5	60	F	7.5				1.3	18.7			

TABLE A1 *- A lot Schedule in Accordance with Clause 6.1.2 for the Base Surface*
Lot Locations are in Metres, Control Limits are in Millimetres

Table A1 shows the survey conformance results for the first kilometre of the pavement, which are before calculation of the process control lines.

Column 1 contains the lot numbers in sequential order of construction.
Columns 2 and 3 contain the start chainage of each lot and offsets to both sides of the lot. This uniquely defines each lot on the base surface. Subtraction of the start chainages of consecutive lots gives the length of each lot. This project constructed the pavement in the direction of decreasing chainages.
Column 4 contains the number of strings across the lot for sampling the pavement.
Column 5 contains the construction date.

Columns 6, 7 and 8 contain the statistical summaries of each lot; the standard deviation, mean and sample size (*n*).
Column 9 identifies if it is a full or a residue lot.
Column 10 contains the acceptance limit for the sample standard deviation in accordance with Table 1 (See Note 1).
Columns 11, 12 and 13 are blank for the first kilometre of pavement construction until calculation of the process control lines for the s_x chart.
Columns 14 and 15 contain the upper and lower acceptance limits for the sample mean in accordance with Table 1. (Note 2)
Columns 16, 17 and 18 are blank for the first kilometre of pavement construction until calculation of the process control lines for the $\bar{x}$ chart.

Note: 1 Residue lots have different acceptance limits than full lots for the sample standard deviation, as shown by Table 2. Therefore, when plotting sample standard deviations of residue lots that fall outside the acceptance limit, use the appropriate acceptance limit, as given in Table 2, before rejecting the lot. As no lots in this example plotted outside the acceptance limits for the sample standard deviation, it was not necessary to verify the acceptance limits of residue lots.

Note: 2. Similarly, residue lots have different acceptance limits than full lots for the sample mean, as shown by Table 2. Therefore, when plotting sample means of residue lots that fall outside the acceptance limits, use the appropriate width acceptance limit, as given in Table 2, before rejecting the lot. This scenario applies to lot 9. However, the lower acceptance limit, as shown in column 14, is still greater than the sample mean, therefore reject the lot. Lot 6 is greater than the lower acceptance limit for full lots but is not lower for a residue lot of this size. Therefore, reject the lot.

Figures A1 and A2 are the acceptance control charts for the sample mean and sample standard deviation for data contained in Table A1. These charts show how the pavement surface heights compare to specified requirements. Figure A1 shows that the sample mean was less than the lower acceptance limit for 5 of the 10 lots constructed in the first kilometre of the pavement. However, as this project was being constructed to an earlier specification, no conclusion to the quality of work or compliance with requirements can be drawn.

Figure A2 demonstrates tight process control as the sample standard deviation was well under the acceptance limit for all lots.

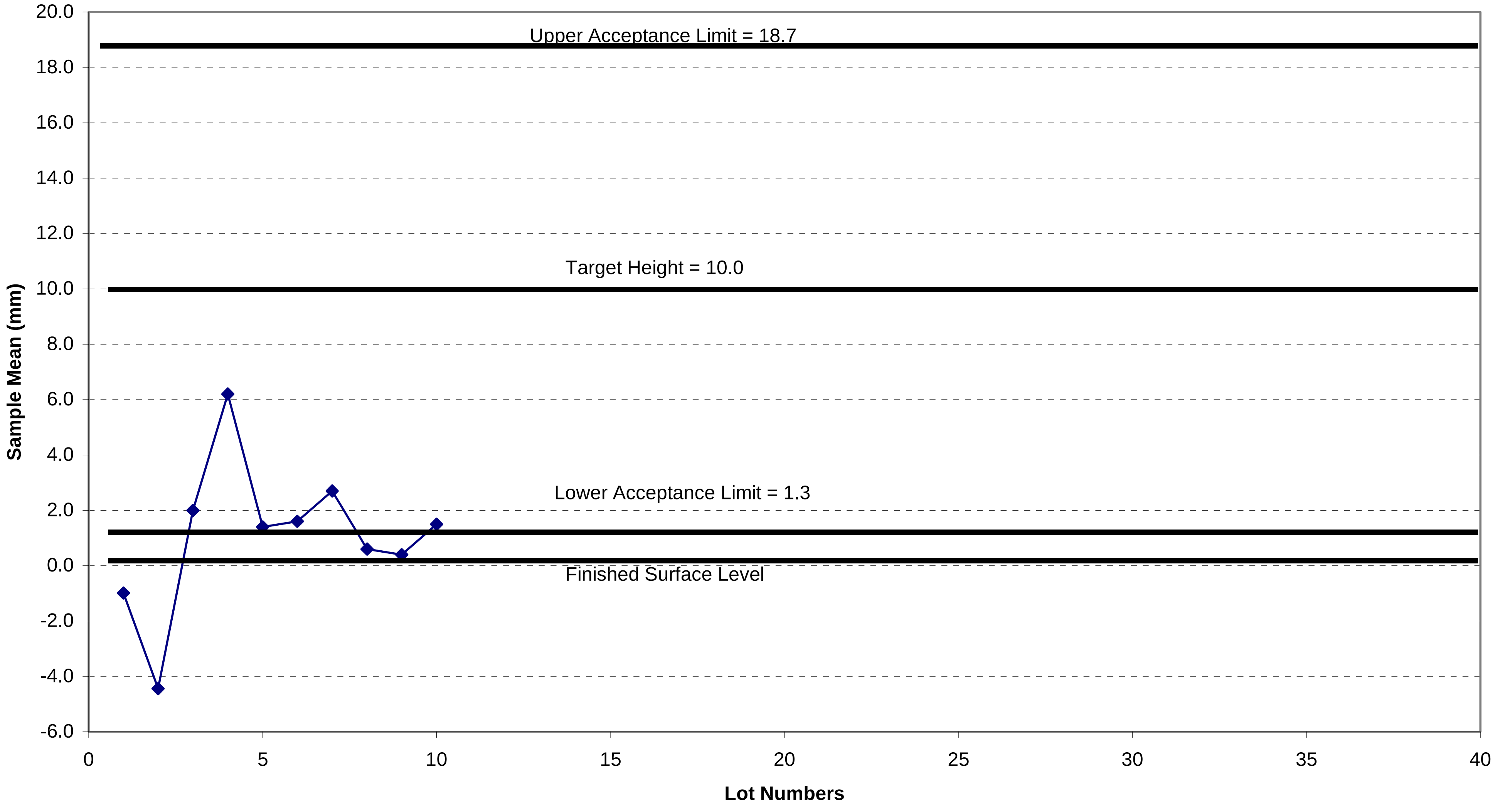


Figure A1 - $\bar{x}$ Acceptance Control Chart for the Base Surface

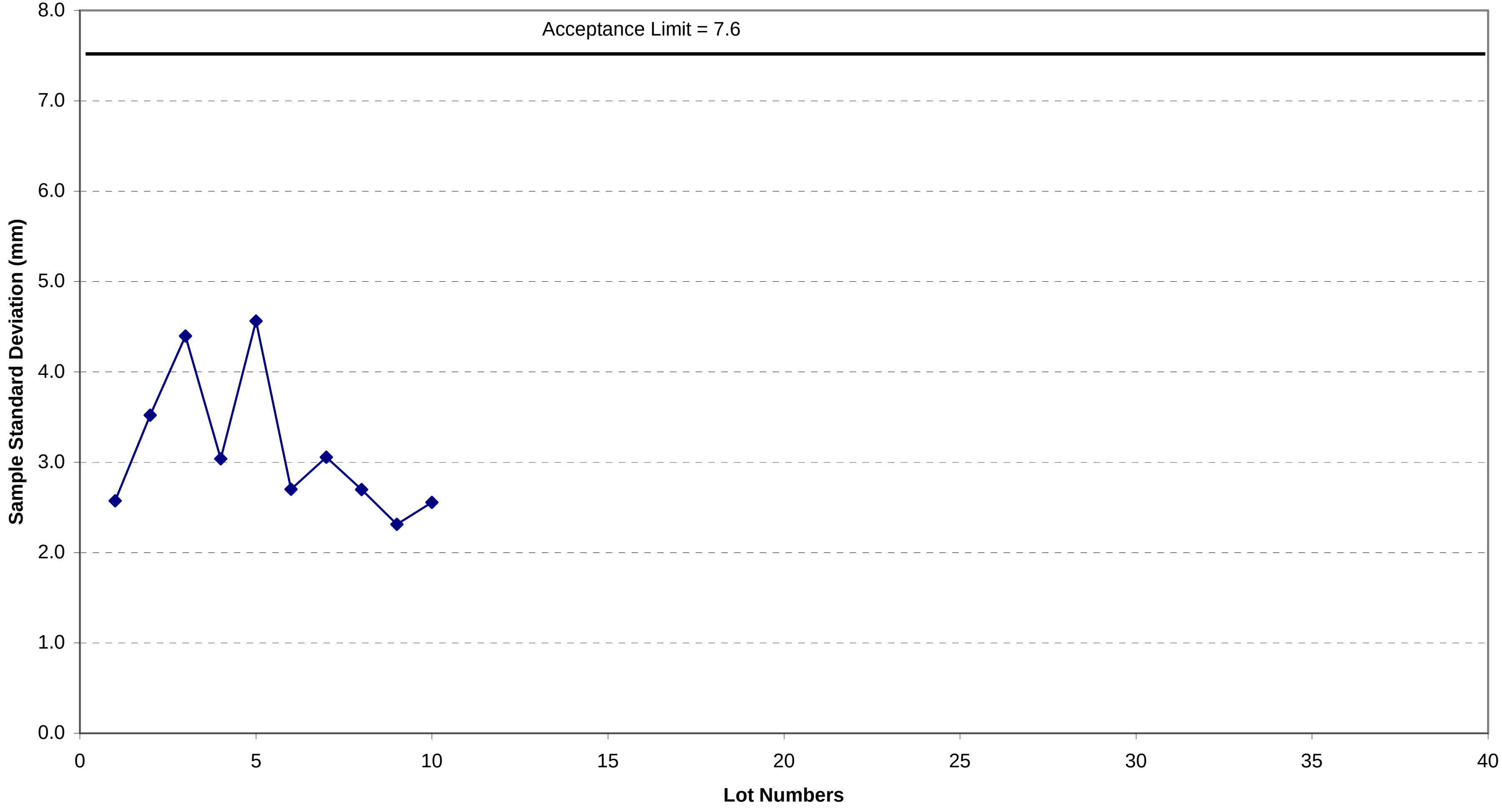


Figure A2 – s_x Acceptance Control Chart for the Base Surface

A1 Calculation of Process Control Lines

Figures A1 and A2 are the acceptance control charts, which show how the sample mean and standard deviation compare with tolerances given in RTA specification clauses for construction of concrete pavements. The next stage is to convert these to process control charts, which will estimate the state of process control and the capability of the process to meet specified requirements and assure base course thickness.

A1.1 The $\bar{x}$ Process Control Chart (The Sample Mean)

A1.1.1 The Process Mean

Equation (1) calculates the process mean for the first kilometre of the pavement.

$$\bar{\bar{x}} = \frac{\sum_{i=1}^{m} n_i \overline{x_i}}{\sum_{i=1}^{m} n_i} \qquad (1)$$

The Table A1 provides the data for solving equation (1). The $\overline{x_i}$ values are contained in column 7 and the n_i values are contained in column 8. The total of the multiplications of the sample size times the sample mean for each lot is the numerator of equation (1). The denominator is the sum total of column 8, which is the combined sample size of all the lots contained in the first kilometre of pavement.

The process mean by equation (1) for this example is 1.16 millimetres.

A1.1.2 The Process Control Limits

Equation (1) determines the centre line position for the $\bar{x}$ process control chart. The upper and lower process control limits are set equispaced about the centre line as given by equation (5), with the F_x values contained in Table 3 for full lots and Table 4 for residue lots.

The $s_{x\ process}$ value is determined by equation (4):

$$s_{x\ process} = \sqrt{\frac{\sum_{j=1}^{N}\left(x_j - \bar{\bar{x}}\right)^2}{N-1}} \qquad (4)$$

This calculation is <u>not</u> possible with the data provided in Table A1. It requires all the raw survey measurements taken on the first kilometre of pavement and for accuracy and efficiency, the use of a computer. The *N* value in equation (4) is same as the denominator of equation (1), which for this example is 604 measurements. The $s_{x\ process}$ for this example is 4.08 millimetres.

From Table 3 the F_x value for full lots with 3 strings (width between 6.0 and 11.0 metres) is 0.52. Therefore, the upper and lower process control limits are given as:

1.16 mm ± 3 x 4.08 mm x 0.52
1.16 mm ± 6.36 mm
Therefore, the upper process control limit = 7.5 mm and lower process control limit = -5.2 mm

RTA specification clauses for construction of concrete pavements require calculation of all sample means and standard deviations to the nearest 0.1 millimetres. This requires calculations with variables quoted to 0.01 millimetres and rounding of results to 0.1 millimetres, as shown in this example. The control lines commence from the next lot surveyed after their calculation.

The process mean, along with the upper and lower process control limits, may now be drawn on the acceptance control chart to convert it into a process control chart, as shown in Figure A3.

A1.1.3 Residue Lots

Residue lots have different F_x values from full lots, as shown in Table 4, which implies different process control limits for residues lots from the process control limits for full lots. Therefore, when plotting sample means of residue lots that fall outside the process control limits for full lots, use the appropriate F_x value in Table 4 with equation (5), before concluding whether the process shows an out of control state or not.

A1.2 S Process Control Chart (The Sample Standard Deviation)

A1.2.1 Pooled Estimate of the Process Standard Deviation

Equations (2) and (3) give the pooled estimate of the process standard deviation, $s_{x\ pooled}$. This calculation is possible from the data contained in Table A1. Equation (3) is the sample standard deviation for each lot as given in column 6 of Table A1. The n_i value is the sample size as given in Column 8 and m is the number of lots, which for this example is ten. The use of a computer and spreadsheet will simplify calculation of pooled variance estimate of the process standard deviation. For this example, $s_{x\ pooled}$ equals 3.22 millimetres.

As stated in Clause 6.2.2 of this Test Method, the standard deviation used to calculate the process control limits for the $\bar{x}$ process control chart differs from the standard deviation used for the process standard deviation of the s chart. For this example it is about 0.9 millimetres. If all of the surface level departures were completely independent of each other it would be expected that the standard deviations used on both process control charts would be the same. However, as there is high positive correlation between surface level departures taken on concrete pavement surfaces, this is negated.

A1.2.2 The Process Control Limits

Equation (6) gives the upper and lower process control limits for the s chart, with Table 3 giving the S_1 and S_4 values for full lots. For pavements with 3 strings (width 6.0 to 11.0 metres) S_1= 0.72 and S_4 = 1.27. For this example, equation (6) gave the following process control limits:

Lower process control limit	=	0.72 x 3.22 mm
	=	2.3 mm
Upper process control limit	=	1.27 x 3.22 mm
	=	4.1 mm

A1.2.3 Residue Lots

Residue lots have different S_1 and S_4 values from full lots, as shown in Tables 3 and 4, which implies different process control limits for residue lots from the process control limits for full lots. Therefore, when plotting sample standard deviations of residue lots that fall outside the process control limits, use the appropriate S_1 and S_4 value in Table 4 with equation (6), before concluding whether the process shows an out of control state or not.

A1.3 The Process Control Charts

Figures A3 and A4 show the process control lines plotted on the acceptance control charts in Figures A1 and A2 along with samples from the next two kilometres of the base surface.

Table A2 is the Lot Schedule contained in Table A1 with addition of the data from lots surveyed in the next two kilometres of the base surface.

									Lines For Standard Deviation, s_x				Lines For Mean, $\bar{x}$				
Lot No.	**Lot Location**				**Statistical Summaries**			**Full/ Res**	**Accept Limits**	**Process Lines**			**Acceptance Limits**		**Process Lines**		
	Start Ch.	**Offset**	**Stgs**	**Const. Date**	**Stdev**	**Mean**	***n***			**Centre**	**LCL**	**UCL**	**LAL**	**UAL**	**Centre**	**LCL**	**UCL**
1	48K 330	4L to 4R	3	30/10/1999	2.6	-1.0	58	F	7.5				1.2	18.8			
2	48K 230	4L to 4R	3	30/10/1999	3.5	-4.4	57	F	7.5				1.2	18.8			
3	48K 135	4L to 4R	3	1/11/1999	4.4	2.0	60	F	7.5				1.3	18.7			
4	48K 035	4L to 4R	3	1/11/1999	3.0	6.2	60	F	7.5				1.3	18.7			
5	47K 935	4L to 4R	3	1/11/1999	4.6	1.4	60	F	7.5				1.3	18.7			
6	47K 835	4L to 4R	3	1/11/1999	2.7	1.6	81	R	7.5				2.3	17.7			
7	47K 700	4L to 4R	3	4/11/1999	3.1	2.7	60	F	7.5				1.3	18.7			
8	47K 600	4L to 4R	3	4/11/1999	2.7	0.6	60	F	7.5				1.3	18.7			
9	47K 500	4L to 4R	3	4/11/1999	2.3	0.4	48	R	7.6				0.6	19.4			
10	47K 420	4L to 4R	3	5/11/1999	2.6	1.5	60	F	7.5				1.3	18.7			
11	47K 320	4L to 4R	3	5/11/1999	2.3	1.1	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
12	47K 220	4L to 4R	3	5/11/1999	2.1	0.2	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
13	47K 120	4L to 4R	3	5/11/1999	3.7	-4.0	58	F	7.5	3.2	2.3	4.1	1.2	18.8	1.2	-5.3	7.6
14	47K 020	4L to 4R	3	5/11/1999	2.7	-3.3	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
15	46K 920	4L to 4R	3	5/11/1999	3.7	-0.1	84	R	7.5	3.2	2.3	4.1	2.5	17.5	1.2	-5.2	7.5
16	46K 780	4L to 4R	3	8/11/1999	5.7	-1.3	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
17	46K 680	4L to 4R	3	8/11/1999	4.2	0.7	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
18	46K 580	4L to 4R	3	8/11/1999	2.5	7.0	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
19	46K 480	4L to 4R	3	8/11/1999	2.9	8.0	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
20	46K 380	4L to 4R	3	8/11/1999	2.1	6.0	63	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
21	46K 275	4L to 4R	3	10/11/1999	2.6	5.6	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
22	46K 175	4L to 4R	3	11/11/1999	2.6	4.5	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
23	46K 075	4L to 4R	3	11/11/1999	3.3	1.7	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
24	45K 975	4L to 4R	3	11/11/1999	2.8	1.4	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
25	45K 875	4L to 4R	3	11/11/1999	2.9	-0.6	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
26	45K 775	4L to 4R	3	11/11/1999	2.1	-2.0	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
27	45K 675	4L to 4R	3	11/11/1999	3.0	3.7	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
28	45K 575	4L to 4R	3	11/11/1999	2.2	2.2	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
29	45K 475	4L to 4R	3	12/11/1999	3.3	1.0	60	F	7.5	3.2	2.3	4.1	1.3	18.7	1.2	-5.2	7.5
30	45K 375	4L to 4R	3	12/11/1999	2.4	-1.4	75	R	7.5	3.2	2.3	4.1	2.1	17.9	1.2	-5.2	7.5

Table A2 - *Lot Schedule of the Base Surface*

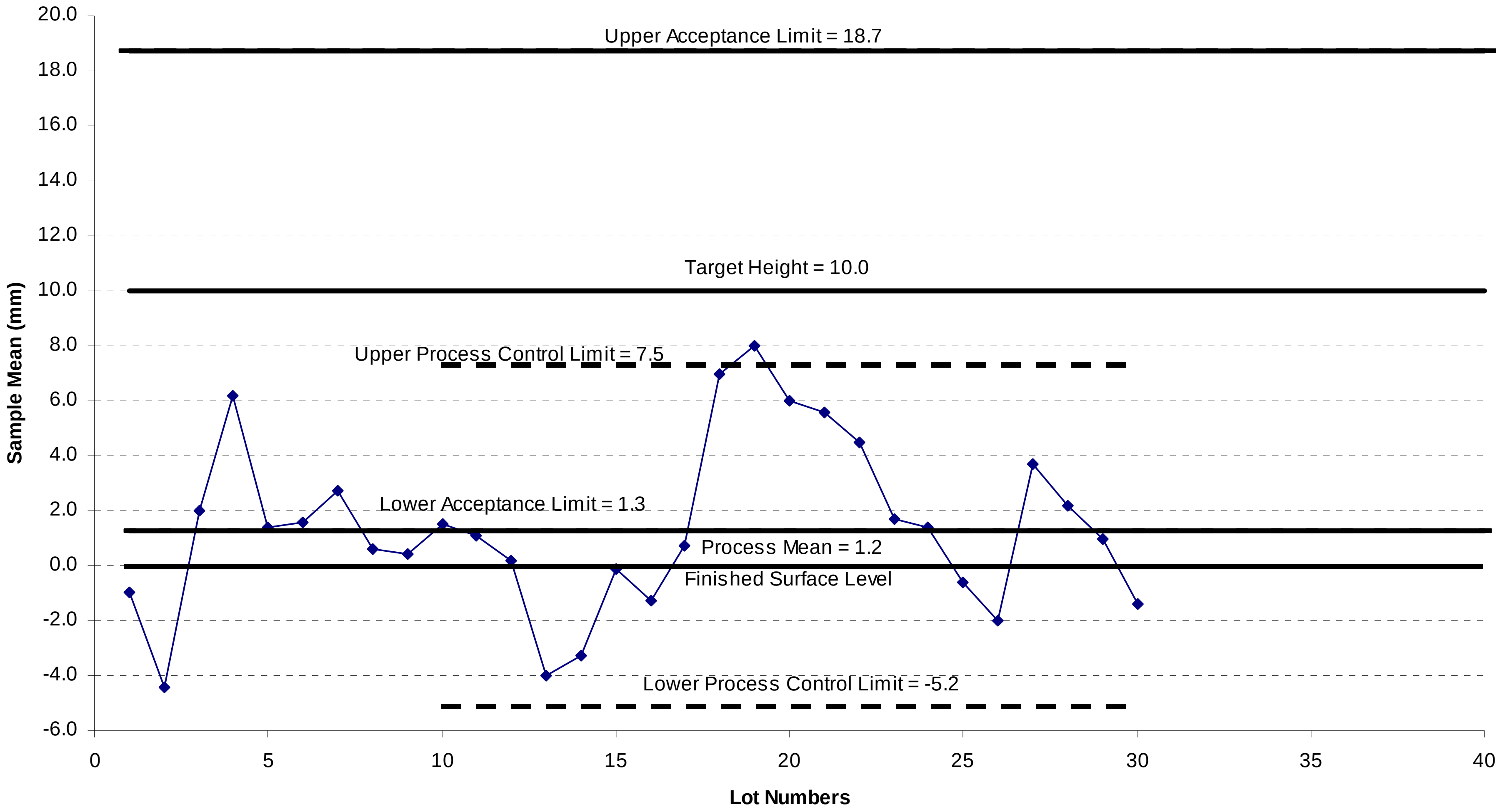


Figure A3 - $\bar{x}$ Acceptance Control Chart Converted to $\bar{x}$ Process Control Chart by the Addition of Process Control Lines

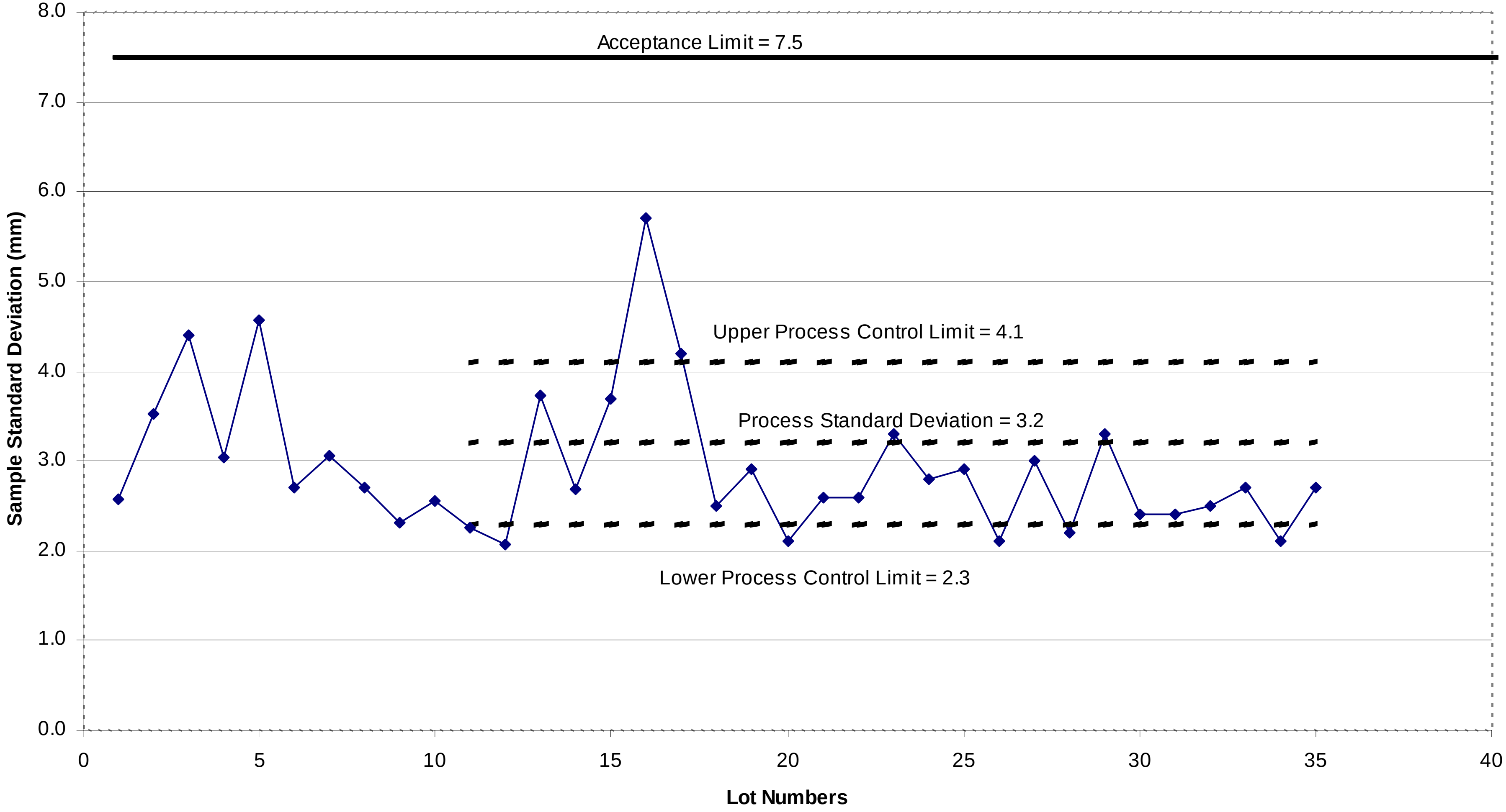


Figure A4 – *s* Acceptance Chart Converted to *s* Process Control Chart by the Addition of Process Control Lines

A2 Re-Calibration of Control Lines

The process control lines calculated in Section A1, set the expected limits of the outputs by the process for the next two kilometres of pavement. Re-calibration of the process control charts after construction of the next two kilometres of pavement will verify if the process has remained in control, has improved or has slipped.

Lots 11 to 30 inclusive, in Table A2, provide the data for next re-calibration of the lines of the control charts.

A2.1 The $\bar{x}$ Control Chart

Equations (1), (4) and (5) use the data from lots 11 to 30 to calculate the following values for the control lines for the $\bar{x}$ control chart:

$\bar{\bar{x}}$, the process mean	=	1.47 mm
Upper Control Limit	=	8.42 mm
Lower Control Limit	=	-5.47 mm

The process mean has only changed by only 0.31 mm, from 1.16 mm to 1.47 mm, which suggests that the process has remained similarly targeted for its three kilometres of construction

A2.2 The *s* Chart

Equations (2), (3) and (6) use the data from lots 12 to 32 to calculate the following control lines on the *s* control chart:

$s_{x\ process}$, the pooled estimate of the process standard deviation	=	3.07 mm
Upper Process Control Limit	=	3.90 mm
Lower Process Control Limit	=	2.21 mm

The pooled estimate of process standard deviation has improved slightly by 0.13 mm, from 3.22 mm to 3.09 mm. This suggests that the Contractor's process controls have been well monitored and effective in reducing variability.

A3 Control Chart Analysis

A3.1 The $\bar{x}$ Control Chart

The process is targeted too low to ensure construction of all the base surface such that the sample means will fall within the acceptance range. Compliance with this Test Method would have lead to rejection of five of the lots in the first kilometre of the pavement. It would have also rejected eleven lots in the next two kilometres of pavement, which the process also constructed too low. However, calculation of the process control lines, after the first kilometre, would have provided the Contractor with sufficient data to determine the amount of correction necessary to the target height to ensure compliance with this Test Method. This corrective action would have lead to acceptance of the eleven lots in the next two kilometres of pavement that were constructed below the lower acceptance limit.

The width of the process control limits suggests the Contractor could target the process mean lower than the nominated target height and still ensure that sample means falls within the acceptance limits. The half width of the process control limits is 6.4 mm. Adding this to the lower acceptance limit of 1.3 mm gives a target for the process mean of 7.7 mm. This would have provided a saving of 2.3 mm of base concrete to the Contractor, while still ensuring the RTA the specified base course thickness.

Only lot 21, which is too high, is outside the process control limits.

A3.2 The *s* Control Chart

The Contractor's process controls used on this project were effective in maintaining the variability well below the acceptance limit. This has meant that the specifications would not have rejected any lots due to the standard deviation (variability) being too high. However, lots 18 and 19 are above the upper process control limits, signalling an out of control state during construction of those two lots. Lot 18 is almost twice the standard deviation of the centre line of the *s* chart. This suggests the presence of an assignable cause as described in Clause 7.2.2 of this Test Method. RTA Specification Q requires investigation to determine the origin of assignable causes. For assignable causes of lots with standard deviations above the upper process control limit it may be necessary change the Project Quality Plan to ensure the probability of recurrence is diminished.

Investigation of assignable causes includes lots plotted below the lower process control limit such as lot 17. Lots plotted below the lower process control limit indicate an improvement in the process controls. Identification of the cause of the improvement for that lot may lead to its inclusion in the Project Quality Plan if it is considered economically viable. Lots 13, 22, 28, 30 and 32 are only marginally below the lower process control limit. Investigation of assignable causes for these lots may not prove economically viable, as any improvement would be only marginal.

Re-calibration of the process control lines shows only a slight reduction of the standard deviation, indicating that the process controls that affect variability are being well monitored.