# A framework for monitoring asphalt mix temperature during construction using Statistical Process Control charts

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***Abstract*—Current quality control mechanisms tend to focus on the end-result and not on elements of the asphalt construction process that may lead to an asphalt layer not lasting for its intended life. Specifications tend to focus on quality characteristics, some of which are the percentage voids, the final density and layer thickness of the compacted mix. Statistical testing in its current form provides vital indications of whether the contractor has complied with the quality requirements set by the client. While statistical testing is relevant and important, it does not provide significant insight into the overall risk of failure because of "processes gone wrong." The missing link is a focus on the process, and whether there is variability in the construction process. This paper presents a framework for monitoring asphalt mix temperature during construction using Statistical Process Control (SPC) techniques. The techniques are applied to more than 40 asphalt construction projects in the Netherlands where new technologies including Differential GPS, infrared cameras and laser linescanners are used to monitor and make the construction process explicit. Most projects show evidence of extensive temperature homogeneity with large temperature differentials due to assignable causes of variability at the asphalt plant, during transport or on the construction site. These operational problems are in the main, causing the construction process to be "out of control" and possibly could have been avoided with better planning. Overall, this research shows that acceptance testing, on its own, does not holistically capture the extent of variability encountered in the asphalt process. The absence of a record of the process is a significant gap in fully understanding the most important process parameters.**

***Keywords*—asphalt; construction; process control; quality control; quality assurance***

## I. ASPAHLT QUALITY ASSURANCE AND QUALITY CONTROL

Quality Assurance (QA) is defined as "a set of activities intended to establish confidence that quality requirements will be met whilst Quality control (QC) is defined as "a set of activities intended to ensure that quality requirements are actually being met" [1]. Currently, QA specifications are an important component of an organization's commitment to overall quality management, and consist of several activities, including: process control, acceptance control, and sometimes, independent assurance of a product [2]. Specifications generally recognized for the construction of asphalt pavements are classified into product specifications, method-related specifications (MRS), end-result specifications (ERS), performance-related specifications (PRS), and QC/QA specifications. The next section provides a brief description of each specification.

### *A. Product specification*

In construction, a product specification is used when a generic description of a desired product or process cannot be easily formulated. It usually contains an "or equivalent" clause to allow for some measure of competition in providing the product. However, it is generally acknowledged that such a specification severely limits competition, which increases costs. Also, it provides very little latitude for innovation, and in the context of road construction, creates substantial risk for road authorities [3].

### *B. Method-related specification*

Materials and method-related specifications, also called method specifications, recipe specifications or prescriptive specifications, are specifications that direct the contractor to use specified materials in definite proportions and to use specific types of equipment and methods to place the materials [4]. The resulting construction quality is thus dependent on the methods, materials and equipment described in the specifications. Under these specifications, the low-bid contractor has little incentive to use better methods or materials that will result in a higher quality than that corresponding to the specified methods and materials [5]. In essence, the road authority bears full responsibility for the performance of the constructed layer and contractor innovation is severely restricted. The burden of quality control and inspection, both labour-intensive activities, is the responsibility of the road authority [6].

### *C. End-result specifications*

End-result specifications (ERS) are the opposite of methods and materials specifications. An end-result specification is one in which the characteristics of the product are stipulated, and the contractor is given considerable freedom in achieving those characteristics. ERS are based on properties indicative of potential pavement performance, which place the responsibility for the quality of construction on the contractor and should ideally offer the contractor the complete freedom in the methods used to arrive at the required "as-built" quality levels [2]. This type of specification allows the contractor to experiment with new construction methods and the contractors will normally do so if it possibly offers a competitive advantage. The overall result is, theoretically, a high-quality product that meets design expectations [6]. The road authority's responsibility is to accept or reject the final product or to apply a penalty system for the degree of non-compliance with the specification. The road authority would normally use statistical techniques in employing ERS. In well-written specifications, statistical techniques account for sources of variability (sampling and testing) when placing limits on the material variability.

### *D. Performance related specifications*

Performance related specifications (PRS) are those in which the product payment is directly dependent upon its actual performance. Typical of these specifications are warranty and design-build-operate contracts. Contractors are held responsible for the product performance within the context of what they have control over. The contractor is given a great deal of freedom in providing the product, as long as it performs according to the established guidelines [3]. In this case, the contractor assumes considerable risk for the level of service the product provides by paying for or providing any necessary maintenance or repair within the warranty period. According to [2], performance-related specifications are difficult to develop, but offer the ultimate means of compensation for a delivered product in that variable payment (incentive/disincentive) can be assigned based upon expected performance and an increase or reduction in life cycle value of the product relative to the design life cycle worth. The development of a PRS involves having links between quality characteristics (asphalt content, gradation, density, etc.), engineering properties (modulus, tensile strength, etc.), and performance (distress, serviceability level).

### *E. QC/QA specifications*

QC/QA specifications are a combination of ERS and MRS. The contractor is fully responsible for controlling the quality of the work and the road authority's responsibility is to ensure that the quality achieved is adequate to meet the specifications. The promise of QC/QA is that better quality can be achieved by allowing the contractor more direct control over his or her operation. In theory, control of work is more efficient when the control function is fully integrated into the contractor's operation [4]. However, QC/QA specifications only address who is responsible for the quality of construction and in a way they are vague [6]. The result is there are many variations of quality assurance programs using QC/QA specification. These variations usually come in the form of how the quality is to be controlled and how the quality of the final product is to be measured and weighted. Authorities using QC/QA specifications will use different methods for controlling quality and measuring the quality in the final product. Nevertheless, a quality assurance program that utilizes a QC/QA specification emphasizes two distinct elements, quality control and quality acceptance. In a typical QC/QA specification the contractor is fully responsible for controlling the quality of the work and the road authority's responsibility is to ensure that the quality achieved is adequate to meet the specifications. Hence, the rather separate, definitive QC role for the contractor and the QA role for the road authority.

### *F. Preliminary discussion*

Statistical specifications are intended to limit the variability inherent in construction materials and construction methods. However, in the case of asphalt construction, the variability of material is intertwined with the variability associated with sampling and testing the material. Common threads in all specifications are the focus on material properties, the need to limit variability in the final product, and the use of statistical techniques to account for variability in the final product. The use of statistics is appropriate given the variability inherent in any product and in the case of asphalt, the variability associated with sampling and testing activities.

So where does this leave the contractor who has to deal with extensive specifications calling for quality, quality and more quality? This is probably quite challenging given the extent of variability that could arise during the sourcing of aggregates, asphalt production, and most importantly, during construction. Also, having to concentrate on extensive field and laboratory testing that firstly, determines the overall performance of the "as-built" product and secondly, determines whether penalties are applied for not meeting the specifications. This raises the need for contractors to have tight control of the asphalt process if they are to meet specifications. The elements of a QC plan vary and may include testing frequency, sampling, personnel and corrective action. In essence, process control requires that contractors statistically monitor the quality of a product through production with frequent testing and control charts given the variability inherent in any product and the variability associated with sampling and testing activities. For the asphalt process, this means that the contractor has to sample and test asphalt at the source, plant and during construction to show that the process in "in control." This sampling is important for determining key asphalt properties mentioned earlier and for confirmation that the asphalt layer "as-built" meets the specification.

A question arises: what process is controlled through this elaborate testing of the asphalt? This research points to a possible gap in process control during asphalt construction. Sampling is undertaken at the plant, the truck and behind the paver. Nuclear density tests are carried out during construction and finally, cores are drilled to ascertain final density. Admittedly, each process associated with the production and placement of asphalt has an inherent variability that is due to variations in material, equipment, and procedure. The goal of the specification and subsequent testing is supposed to limit the variability of materials and construction operations to the extent that this affects the performance and economics of the pavement [3]. Herein lays the confusion. Statistical specifications and QC procedures in its current form focuses on materials and not directly on construction operations. Several authors speak to the variability encountered in construction and the need for monitoring the process [7, 8, 9]. At no point during current QC procedures is there a direct focus on the variability inherent in the transport, the paving and the compaction phases of the asphalt process. Therefore, the overall conclusion is that there is a gap in the quality control process. The missing link is a focus on the process, and whether there is variability in the construction process.

## II. The Process Quality improvement (PQi) methodology and measuring asphalt temperature

In the next section, a project monitored using the PQi methodology developed by [10], is used to show how Statistical Process Control (SPC) can be used to highlight variability and to improve asphalt construction quality. Thereafter, the techniques are applied to 40 monitored projects. During PQi monitoring exercises, new generation sensors are used to monitor the asphalt construction process during "live" projects. Two types of highly precise sensors are used to exactly document the temperature distribution behind the paver and accurately track the paver movements. A Raytek MP150 laser line scanner is used to measure the asphalt surface temperature. It uploads 1024 discrete temperature values per line with a 150 Hz update rate. Differential GPS (DGPS) receivers, configured to receive correction signals from a Trimble RTK Bridge and both GPS and GLONASS navigation satellites, is located on the paver next to the line scanner (see Fig. 1 below). A total of 40 asphalt construction projects (base and surfacing layers) were monitored using the developed methodology over an 8-year period resulting in more than 350 hours of lay-down surface temperature measurements taken directly behind the paver screed. The lane widths monitored varied between 2.5m and 7m. The reader is referred to [10, 11] for more detailed descriptions of the monitored projects.

## III. SPC and the asphalt construction process

According to [12] "It is impossible to inspect or test quality into a product; the product must be built right the first time." This implies that the manufacturing process must be stable and that all individuals involved with the process must continuously seek to improve process performance and reduce variability in key parameters. Statistical Process Control (SPC) is a primary tool for achieving this objective. In any production process, regardless of how well designed or carefully maintained it is, a certain amount of inherent or natural variability will always exist. This natural variability or "background noise" is the cumulative effect of many small, essentially unavoidable causes. In the framework of statistical quality control, this natural variability is often referred to as a "stable system of chance causes." A process that is operating with only chance causes of variation present is said to be in statistical control where the chance causes are an inherent part of the process. Other kinds of variability may occasionally be present in a process. This variability in key quality characteristics usually arises from three sources: improperly adjusted machines, operator errors or defective raw materials. Such variability is generally large when compared to the background noise, and it normally represents an unacceptable level of process performance. The sources of variability not part of the "chance causes" are referred to as "assignable causes." If the process is unstable there are supposed to be special causes of variation that are not process inherent; this

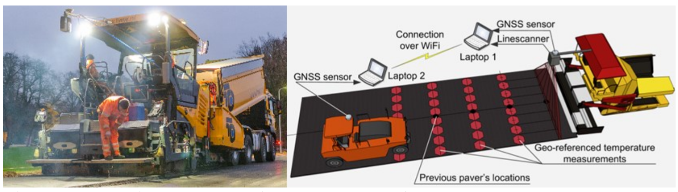


Fig. 1 Laser Linescanner and GPS set up on the paver

will be detected as an "out of control" condition [13]. A major objective of SPC is to quickly detect the occurrence of assignable causes of process shifts (where the process output does not meet the requirements), so that investigation of the process and corrective action may be undertaken before many nonconforming products are manufactured. The overall goal of SPC is the elimination of variability in the process. It may not be possible to completely eliminate variability, but the SPC chart is an effective tool in reducing variability as much as possible.

### *A. Applying the SPC charts for variables to assess temperature homogeneity*

A variable is a quality characteristic that can be measured on a numerical scale. For asphalt, the main process variables affecting overall quality are temperature and compaction. This section presents control charts for asphalt temperature homogeneity. When dealing with a quality characteristic that is a variable, it is usually necessary to monitor both the mean value of the quality characteristic and its variability [12]. Control of the process average or mean quality level is usually done with a control chart for means, or the $\bar{x}$ chart. Process variability is monitored with either a control chart of the standard deviation, called the s chart, or a control chart for the range, called an R chart. The functions of the two Shewhart charts are different [12]. The $\bar{x}$ chart monitors the average quality level in the process. The R chart measures the variability within the sample. Note that the control limits are driven by the natural variability of the process, measured by the process standard deviation σ, the natural tolerance limits of the process.

### *B. Statistical basis of the chart units*

Suppose that a quality characteristic is normally distributed with mean μ and standard deviation σ, where both μ and σ are known. The average of the sample could be calculated using:

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_n}{n}$$

However, μ and σ is not usually known in practice. They must be estimated from preliminary samples when the process is thought to be in control. These estimates should be based on at least 20 to 25 samples. If $\bar{x}_1$, $\bar{x}_2$, …, $\bar{x}_m$ is the average of each sample, then the best estimator of μ, the process average is an overall average $\bar{\bar{x}}$:

$$\bar{\bar{x}} = \frac{\bar{x}_1 + \bar{x}_2 + \cdots + x_m}{m}$$

Thus, $\bar{\bar{x}}$ would be used as the centre line on the $\bar{x}$ chart. To construct the control limits, an estimate of the standard deviation σ is needed. The estimate σ can be derived from the ranges of the m samples. The average range is calculated using:

$$\bar{R} = \frac{R_1 + R_2 + \cdots + R_m}{m}$$

The formulae for constructing the Upper Control Limit (UCL) and the Lower Control Limit (LCL) for the $\bar{x}$ chart are:

$$UCL = \bar{\bar{x}} + A_2\bar{R}$$

$$Centre\ line = \bar{\bar{x}}$$

$$LCL = \bar{\bar{x}} - A_2\bar{R}$$

Process variability can be monitored by plotting values of the sample range R on the control chart. The control limits for the R chart are given by:

$$UCL = D_4\bar{R}$$

$$Centre\ line = \bar{R}$$

$$LCL = D_3\bar{R}$$

Setting up the control charts is done in two phases. In Phase I, when preliminary samples are used to construct $\bar{x}$ and R control charts, it is customary to treat the control limits obtained from the above equations as trial control limits. A determination can then be made of whether the process was in control when the initial samples were selected by plotting the values of $\bar{x}$ and R on charts and analyzing them. A conclusion can then be drawn that the process was in control if all the points plot inside the control limits and the trial control limits are hence suitable for controlling current or future production.

### C. *Phase I application of the $\bar{x}$ and R control charts*

The Temperature Contour Plot (TCP) in Fig. 2 shows the extent of temperature homogeneity over the entire width and length of the road. Using this surface temperature data, a trial control chart using is set up for when the process is assumed to be in-control. Inspection of the TCP shows the first 270m to be fairly homogeneous in terms of temperature with μ =159.65°C, σ = 10.758 and the maximum temperature differential across the road width of 15°C.

This section of the asphalt layer is assumed to have been constructed whilst the paving process was in-control. Since the control limits on the $\bar{x}$ chart depends on the process variability and unless process variability is in control, the limits on the chart will have little meaning. Therefore, the R chart is first set up. The centre line for the R chart is given in the formula below where m is the number of samples chosen (between 20 and 25 temperature measurements considered):

$$\bar{R} = \frac{\sum_{i=1}^{19} R_i}{m} = \frac{204.4}{19} = 10.758$$

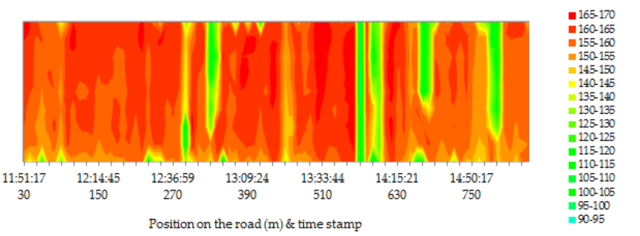


Fig. 2 Typical Temperature Contour Plot

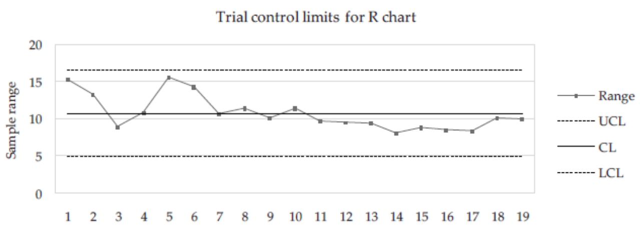


Fig. 3 Trial control limits for the R chart

A check of the Factors for Constructing Variables Control Charts shows that for n=5 (an appropriate subset of the 19 samples), the factors $D_3$ and $D_4$ are 0.459 and 1.541 respectively. Thus, the control limits for the R chart are:

$$UCL = D_4 * \bar{R} = 1.541 * 10.758 = 16.578$$

$$LCL = D_3 * \bar{R} = 0.459 * 10.758 = 4.938$$

The R chart in Fig. 3 shows that the process variability is in-control. The next focus is on the $\bar{x}$ chart where the centre line is given by:

$$\bar{\bar{x}} = \frac{\sum_{i=1}^{19} \bar{x}_i}{19} = \frac{3033.27}{19} = 159.65$$

The control limits on the $\bar{x}$ chart are:

$$UCL = \bar{\bar{x}} + A_2\bar{R} = 159.65 + (0.153 * 10.758) = 161.29$$

$$UCL = \bar{\bar{x}} - A_2\bar{R} = 159.65 - (0.153 * 10.758) = 158.00$$

Fig. 4 shows the $\bar{x}$ chart. The preliminary averages plotted on the $\bar{x}$ chart shows a process that is out-of-control. This is in contrast to the R chart, which shows that the process is in-control. The question now is whether to adopt the trial control limits and apply this to future production, or to eliminate those points outside the trial control limits? The elimination of data would mean reducing the sampling rate to around 15 points, somewhat below the recommended 20 to 25 points for preparing trial control limits. The alternative is to retain the points considering the trial control limits as appropriate for current control. If the point does represent an out-of control condition, the resulting control limits will be too wide. However, if there are only a few points, this should not distort the control chart significantly. In the case of the $\bar{x}$ chart shown in Fig. 4, eliminating the out-of-control points and recalculating $\bar{x}$ shows the UCL to shift slightly to 161.34 and the LCL to 157.97. This does not distort the chart significantly. The trail control limits for both the $\bar{x}$ and R charts can therefore be adopted.

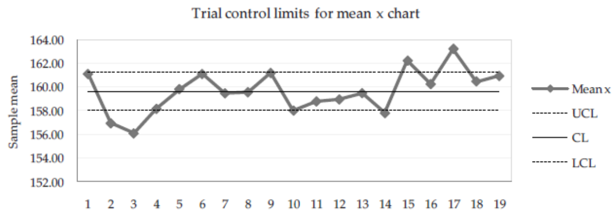


Fig. 4 Trial control limits for the mean x chart

### D. *Phase II application of the mean x and R control charts*

After a reliable set of trial control limits is established, a "full" control chart is constructed to study the rest of the paved lane. This is Phase II of control chart usage. The continuations of the $\bar{x}$ and R charts are shown in Fig. 5 and Fig. 6 respectively. The $\bar{x}$ control chart shows that the process is mostly in-control until the value from the 21st sample is plotted. After this point, a number of the out-of-control points, cyclic in appearance, plot below the LCL. Next, the event logs recorded during paving and the GPS data, are studied to look for assignable causes of variability. Interestingly, all significant points plotting below the LCL are those where the paver has stopped for a few minutes. The general pattern is that longer stops have resulted in the mean temperature dropping further and hence the process can be considered even more out-of-control. These stops have not taken place by chance. Rather, they are the result of the paver-shuttle buggy train having to wait while small bellmouths (intersections) are paved with a second paver. They are assignable causes of variability and should be eliminated through proper planning, the result of which is that the process should return to an in-control state. Also, a number of points plot above the UCL. First glance shows that these may not be significant since the delivered asphalt is above 160°C and would need to cool off somewhat before compaction is to take place. Herein lies a conundrum for the roller operators. Do they follow the paver closely given a specific temperature window for compaction or do they make adjustments in their operations given the increase or decrease in temperature behind the screed of the paver. What about the effects of small shifts in variability? Could this significantly influence their operations? Inspection of the R chart shows an almost mirror image of the out-of-control indicators encountered in the $\bar{x}$ chart. The paver stops have resulted in the highest temperature differentials across the width of the road.

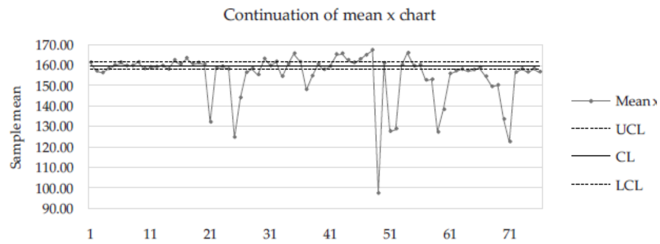


Fig. 5 Phase II continuation of mean x chart

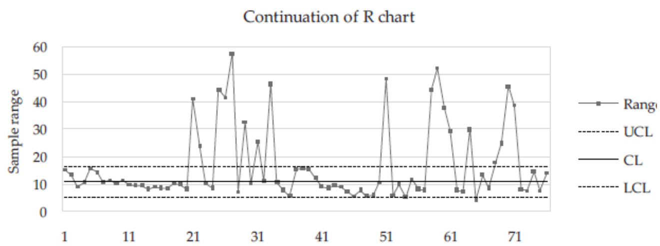


Fig. 6 Phase II continuation of R chart

### *E. Applying the Moving Average Control chart*

Temperature homogeneity is affected negatively on several occasions due mainly to paver stops, waiting for asphalt and alarmingly, the delivery of the wrong asphalt mix. The result is that temperature differentials occur ranging from the very small ($\Delta T < 10$°C) to the very large ($\Delta T > 30$°C). The basic SPC chart is useful in the diagnostic aspects of bringing an unruly process into statistical control, because the patterns on these charts often provide guidance regarding the nature of the assignable cause. However, a major disadvantage of a Shewhart control chart is that it uses only the information about the process contained in the last sample observation and it ignores any information given by the entire sequence of points. This feature makes the Shewhart control chart relatively insensitive to small process shifts [12]. The Moving Average control chart is more effective than the Shewhart chart in detecting small process shifts. It is based on a simple, unweighted moving average with the moving average of span w at time i defined as:

$$M_i = \frac{x_i + x_{i-1} + \cdots + x_{i-w+1}}{w}$$

At time period i, the oldest observation in the moving average set is dropped and the newest one added to the set. The variance of the moving average $M_i$ are:

$$V(M_i) = \frac{1}{w^2}\sum_{j=i-w+1}^{i} V(x_j) = \frac{1}{w^2}\sum_{j=i-w+1}^{i} \sigma^2 = \frac{\sigma^2}{w}$$

If $\mu_0$ denotes the target value of the mean used as the centre line of the control chart, then the three-sigma control limits for $M_i$ are:

$$UCL = \mu_0 + \frac{3\sigma}{\sqrt{w}}$$

And:

$$LCL = \mu_0 - \frac{3\sigma}{\sqrt{w}}$$

The Moving Average control chart is applied to the same data with w=5. The statistic plotted on the moving average control chart will be:

$$M_i = \frac{x_i + x_{i-1} + \cdots + x_{i-4}}{5}$$

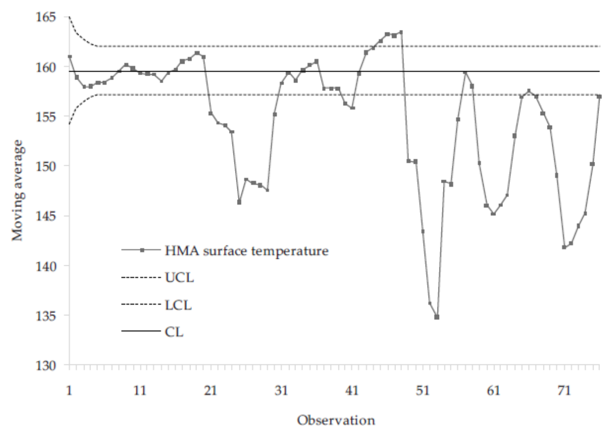


Fig. 7 Moving average control chart

The control limits for the moving average control chart are obtained from equations:

$$UCL = \mu_0 + \frac{3\sigma}{\sqrt{w}} = 159.65 + \frac{3 * 1.81}{\sqrt{5}} = 162.07$$

And:

$$LCL = \mu_0 - \frac{3\sigma}{\sqrt{w}} = 159.65 - \frac{3 * 1.81}{\sqrt{5}} = 157.22$$

Note that the control limits for $M_i$ apply for periods $i \geq 5$. For periods $0 < i < 5$, the control limits are given by $\mu\_0 \pm 3\sigma/\sqrt{i}$.

The moving average control chart is shown in Fig. 7. Once again, the process is shown to be out-of-control whenever the paver has stopped and the asphalt's surface temperature drops.

## IV. Assignable Causes of Variability

As mentioned earlier, the Moving Average Control chart is effective for detecting small process shifts. This makes it suitable for detecting changes in asphalt surface temperature resulting from changes in operational behaviour. It is therefore chosen as the preferred method to assess the extent of temperature homogeneity during paving operations and applied to projects monitored during this research. To date, more than 40 projects have been monitored and the Moving Average Control chart applied to all projects. The control chart shown in Fig. 8 is typical for a recently monitored project. The out-of-control points were compared with the event logs kept by the asphalt teams and researchers to make a distinction between assignable and chance causes of variability wherever possible. Because of space restrictions, only a brief overview of the analysis and results is reproduced here. Four projects are chosen for analysis in this paper, since they typically show evidence of extensive temperature variability. TABLE 1 summarises the lanes analysed and shows the average asphalt surface temperature, the number of points found outside of the control limits and their causes, the latter acquired from the event logs kept during each PQi exercise. The question then is whether the out of control points are due to assignable or chance causes of variability? Of the fifteen lanes studied, eleven show evidence of operational problems being the cause of the process being out of control and possibly could have been avoided with better planning. These operational problems can be classified into three main themes based primarily on their origin namely, whether the operational discontinuities occurred at the asphalt plant, during transport to the site or, at the construction site.

Assignable causes originating at the asphalt plant and during transport: Sharp increases or decreases in the temperature of the asphalt delivered to site, as were the case on two occasions with Project 1, is evidence of possible operational problems at the asphalt plant. The average temperature of the asphalt delivered for Lane 1 on the first night's work, increased by approximately 10% (from an average of 145.7°C to 160°C) for the second half of the paved lane probably as a result of a number of loads being mixed at a much higher temperature than was required. A similar situation applies to Lane 2 on the second night with the average temperature of the delivered asphalt decreasing by 12% over the second half of the paved lane. With work being carried out at night, there was little chance that the supply trucks were caught in traffic and hence, the problem could be traced to the asphalt plant. On project 2, an asphalt plant breakdown resulted in a 72 minute wait for the paver unit and its personnel during the paving of the asphalt base layer. A rather unusual problem arose during the surfacing of the $AC_{LE}$ layer on Project 3. The average temperature of the $AC_{LE}$ is normally in the range of 95 to 105°C [14]. Yet, one truck load of asphalt destined for an $AC_{LE}$ lane had an average temperature of ±135°C, a clear indication that it was in fact a different mix to that specified for the lane and that the problem originated at the asphalt plant. A recurring problem initially brought to the attention of the research team in several interviews and workshops and reported on in [15] also becomes evident in Project 3. The paving team waits for asphalt to be delivered to the construction site on four occasions with the "wait" ranging in duration between 10 and 36 minutes. It's not clear whether this should be attributed to a delay at the asphalt plant or whether the delay was caused by traffic since the transport cycle was not monitored for this project. However, what is clear is that both delays are assignable causes given that they could have been avoided with better planning.

Assignable causes originating on the construction site: A problem shows up on several occasions namely, that of a cold start at the beginning of a paved lane. The temperature of the first asphalt load is somewhat lower than the average temperature of the rest of the paved lane. Lanes 2 and 3 of Project 1 both exhibit cold start ups on the first night. The mix temperature at the start is approximately 75˚C and increases to more than 140˚C over the first 20m. A similar occurrence is evident in Lane 3. In both cases, this cooler material at the start is probably as a result of the asphalt left in the paver hopper from the previous lane being remixed with a fresh load of asphalt at the start of the new lane. In Project 2, the control chart shows the process to be out of control on six occasions during paving of the SMA layer. Five are attributed to the paving unit stopping several times for between 6 and 14 minutes to wait for intersections to be paved with a smaller paver. This appears to be quite common with little or no thought given to proper planning. The intersections could possibly have been paved beforehand and the stops avoided on the main section to be paved. Long truck changes (>10 minutes) also results in the surface temperature dropping by between 10 and 20 ˚C during the paver stops. Working in confined areas and narrow widths also appears to be problematic with trucks either approaching the paver train from the wrong direction or not being able to pass each other. It is clear that cold starts, paver stops, waiting for asphalt and other operational discontinuities are avoidable and can therefore be eliminated from operational practices.

## V. Discussion and Conclusions

Regarding temperature homogeneity, the majority of the out of control points were encountered below the Lower Control Limits with less than 5% above the Upper Control Limits for the studied projects. One may assume that points above the UCL are not important given that the mix can cool off to the optimal compaction temperature before operators commence with breakdown rolling. This research shows that this is a dangerous assumption given that roller operators generally do not measure the temperature during compaction operations [16]. Compacting too early at the higher temperatures results in shoving of the mix [17]. Also, studies show that thermal differentials are more critical at low temperatures [18, 19]. Points below the LCL are thus perhaps more crucial given that roller operators would have less time available for compaction. In this case, compacting too late results in an under stressed condition, a condition occurring when the mixture is too cool with the result that the roller does not create shear forces sufficient to increase density. What is significant is that asphalt temperature outside the control limits indicates that the time available for compaction is different from the norm and requires a different approach to the compaction regime. In addition, shifts in the process mean may indicate an increase or decrease in temperature of the asphalt delivered to the site, an irregular supply of asphalt or a cooling of the asphalt whilst several trucks are waiting to deliver the asphalt.

TABLE 1 SPC COMPARISONS FOR TEMPERATURE HOMGENEITY

| **Project** | | **HMA mix type** | **Lane length (m)** | **Lane width (m)** | **HMA surface temperature (°C)** | | **Total observations** | **Points outside control limits** | **Points with assignable causes** | **Reasons** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **µ** | **σ** | | | | |
| 1 – 1st night | Lane 1 | PA | 230 | 5 | 152.9 | 9.8 | 24 | 10 | 10 | Average temperature of last 110m increased from 145.7°C to 160°C |
| | Lane 2 | PA | 180 | 4 | 135.5 | 11.7 | 19 | 6 | 6 | Cold start up at the beginning of the lane – used last HMA from lane 1 for first 30m |
| | Lane 3 | PA | 180 | 3 | 138.0 | 10.9 | 19 | 6 | 6 | Cold start up at the beginning of the lane – used last HMA from lane 2 for first 40m |
| 1 – 2nd night | Lane 1 | PA | 210 | 5 | 140.8 | 12.3 | 22 | 5 | 1 | One 20min stop due to paver problem |
| | Lane 2 | PA | 210 | 4 | 135.3 | 15.4 | 22 | 12 | 12 | Average temperature of last 100m decreased from 144°C to 127.3°C |
| 2 | Layer 1 | AC | 350 | 7 | 158.3 | 9.96 | 35 | 8 | 8 | One major paver stop due to HMA plant breakdown (72 minutes) and several short stops waiting for small intersections to be paved |
| | Layer 2 | SMA | 770 | 7 | 154.7 | 13.8 | 76 | 34 | 34 | Five stops (ranging between 6 & 14 minutes) due to the main paver waiting for intersections to be paved with another smaller paver |
| 3 | Lane 1 | AC | 210 | 4 | 140.9 | 10.9 | 21 | 0 | 0 | Small fluctuations in moving average due to truck changeovers |
| | Lane 2 | AC | 210 | 4 | 110.9 | 26.0 | 55 | 41 | 32 | Two stops waiting for asphalt (34 and 36 minutes respectively) |
| | Lane 3 | AC | 210 | 4 | 131.1 | 15.6 | 22 | 8 | 8 | Cold start up and last material used in the hopper at the end of the lane |
| | Lane 4 | $AC_{LE}$ | 160 | 4 | 104.9 | 10.5 | 18 | 5 | 5 | One load AC placed in this $AC_{LE}$ lane |
| | Lane 5 | $AC_{LE}$ | 160 | 4.8 | 95.0 | 11.1 | 27 | 15 | 13 | Two stops (11 and 10 minutes respectively) |
| 4 | Lane 1 | AC | 86 | 4.2 | 145 | 17 | 13 | 8 | 7 | Cold start up at the start of the lane |
| | Lane 2 | AC | 86 | 4.5 | 145 | 20 | 16 | 10 | 10 | 10 minute period of heavy rain |
| | Lane 3 | AC | 86 | 5.2 | 144 | 13 | 25 | 5 | 5 | Light rain during paving |

PA= Porous asphalt

AC = Asphalt concrete base

SMA = Stone Mastic Asphalt

$AC_{LE}$ = Low Energy Asphalt Concrete

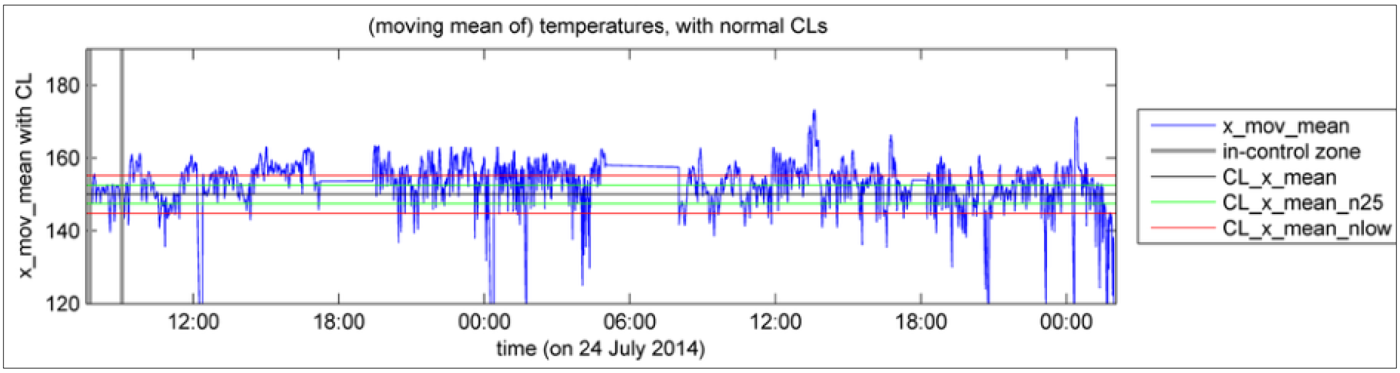


Fig. 8 Moving Average Control chart for a typical asphalt construction project

For contractors, the goal of quality control should be to limit the variability encountered during construction operations. This research shows that acceptance testing, on its own, does not holistically capture the extent of variability encountered in the asphalt process. The absence of a record of the process is a significant gap in fully understanding the most important process parameters. Regardless of the type of contract, a focus on key process parameters provides more control by indicating whether the process is in control or not.

### *A. Lessons for contractors*

In applying SPC techniques for monitoring key process parameters during construction, the contractor is able to set control limits for and reduce any variability within transport, paving and compaction. SPC should ideally, as suggested by [12] be used in an online setting to detect and correct assignable causes of variability as soon as possible to ensure that the process remains in as steady a state as is possible. The application of SPC techniques has several benefits for process control including: (a) intentionally identifying and studying operational deficiencies and strategies that are inappropriate (b) gradually eliminating assignable causes of variability over time (c) responding in time to resource wastage, and (d) dealing early enough with possible premature failure of the paved lane.

Furthermore, it appears that current quality control practice does not control the "process." Rather, it mostly provides confirmation of an end-result. An assumption is made that the process is in-control if acceptance testing passes the necessary specification thresholds set for quality parameters like density, percentage voids, etc. This is perhaps a false assumption since this research shows the process could be out-of-control despite the contractor meeting the required specifications based on end-result testing. Also, [6] state that a QC plan must address actions needed, including the frequency of testing, to keep the process in control, quickly determine when the process has gone out of control, and to respond adequately to correct the situation(s) to bring the process back into control. Process control in this case, consists of statistically monitoring the quality of a product through production with frequent testing and control charts. There are two issues at stake here for asphalt construction. The first, the "frequency of testing" element is in conflict with the widespread belief that one cannot test quality into a product [12]. Also, testing is normally carried out post-construction to determine whether the relevant specifications have been met. This is too late given that remedial actions are not possible except having to replace the sections not meeting the specifications.

Therefore, this research points to firstly, a need for monitoring whether the process is "in-control" and secondly, for the acceptance testing to provide confirmation that the process is indeed "in-control." The establishment of "in-control" limits needs to be done with an understanding of the construction process and the factors affecting the process based on hard process data. The current business environment of working in lengthy guarantee periods (than what contractors are normally used to) highlights a need for process control. There is an incentive for contractors knowing that they have more control, can "tweak" process parameters during construction (in real time) and can justify the end-result so that there is as little variability as possible. Focusing on the process rather than the end-result enables contractors to identify poor operational practices that lead to premature failure including temperature segregation, poor construction joints, uneven compaction and density differentials. The benefits of using SPC techniques to contractors include:

- Process predictability should improve since control charts could be used to identify and eliminate assignable causes of variability,
- The percentage out of control runs should decrease. As assignable causes are eliminated, a higher percentage of plotted runs should be in control,
- Operators may feel empowered since they will be responsible for problem identification, resolution and possible elimination of assigned causes of variability,
- The importance of proper logistics planning will be understood, and
- Overall, the asphalt construction process will benefit from increased efficiency. Systematic elimination of assignable causes of variability should lead to greater efficiency.

### *B. Lessons for road authorities*

Having described the benefits of using SPC techniques for contractors, the next question is what lessons, if any, are there for road authorities? Could road authorities provide the stimulus for contractors to integrate the proposed SPC techniques into the asphalt process? What would motivate them to purchase new technologies and in so doing, monitor the paving process more closely?

In applying product and method specifications, the road authority is responsible for quality control and inspection and bears full responsibility for the asphalt pavement's performance. The contractor's payment is dependent on whether the end-result testing meets the statistical specifications. End-result specifications places the responsibility for the quality of construction on the contractor with the road agency's responsibility limited to accepting the final product based on statistical testing and then applying a penalty for non-compliance. Performance specifications, typically of the design-build-operate type, provide the contractor with a great deal of freedom in providing the product as long as it performs according to established guidelines. The specifications involve having links between quality characteristics, engineering properties and performance. In QC/QA specifications (a combination of end-result and method specifications), the contractor is fully responsible for controlling the quality of the work and the road authority's responsibility is to ensure that the quality achieved is adequate to meet the specifications. Two distinct elements are emphasized, the quality control and quality assurance of asphalt properties including bitumen content, aggregate gradation and mat density.

Regardless of the form of contract used, common to all is some element of statistical testing. It appears that the focus is, in one way or another, on testing if the "as built" end-result meets the specifications. Specifications generally tend to focus on quality characteristics such as the percentage voids, density and layer thickness. While these are important, they do not provide insight into the overall risk of failure as a result of “processes gone wrong during transport, paving and compaction." [20] demonstrated that random density measurements could not satisfactorily detect cyclic differential problems and recommended that these zones be identified and excluded from the final density measurements. This recommendation does not in any way, address the cyclic differential problem and the need to get to its cause before consciously eliminating it. Furthermore, predictions of premature failure are based on end-result sampling and testing and, not on elements of the process that may lead to premature failure. Limited statistical testing provides few insights into the construction process and whether failure and distress is as a result of poor operational practices and strategies. There is an absence of hard data to tie back to the process.

The question then is what role the road authority should play in encouraging process monitoring? Specifying that contractors monitor key process parameters has several advantages for the authority including that key process parameters are kept in control and that the authority is able to use permanently georeferenced data for the future monitoring of pavement distress and premature failure. Does this mean that statistical testing should be abolished or that more post-construction tests should be added? The answer to both questions is no. The end-result testing is an important part of the process in that the process elements are linked to the “as built” results and provides the basis for confirmation or rejection of operator behaviour namely, the process! Closely monitoring the process to study key process parameters may even lessen the number of tests needed. If during monitoring, the process is largely found to be "in control" then only a minimum number of tests would be needed to confirm the density results, mix constituents, etc. or to study problem areas e.g. insufficient density in the wheel paths.

### C. *An observation*

If as [21] suggests “The ultimate goal for the future of quality assurance in road construction is to achieve a state of enlightenment wherein statistical quality assurance practices are regarded as a logical and rational extension of engineering and mathematical knowledge”, then the starting point is knowing what is happening during the process. Therefore, a logical way forward is to focus on the construction process and measure those parameters that affect the process most. Overall, the conclusion is that the use of SPC techniques for monitoring asphalt temperature is useful for several reasons. Monitoring the process statistically provides opportunities for: (1) identifying whether the process is in control, (2) identifying the causes for it being out of control, and (3) responding immediately and systematically if the causes are due to operational deficiencies.

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