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CONTROL CHARTS MONITORING FOR QUALITY CONCRETE PAVEMENTS

Summary. In this article, Control charts are employed to analyse the strength quality control of ready-mixed concrete for rigid pavement. The results of the study support that CUSUM statistical analysis is more sensitive than the Shewhart control chart. The CUSUM chart can detect the continual changes in the concrete quality in a more accurate way. By combining the CUSUM control chart and the Shewhart control chart, higher accuracy of quality control analysis could be achieved, in order words, for quality control performance when in built/pouring the ready-mix concrete as rigid pavement.

Keywords: pavements, quality, monitoring, CUSUM charts, Shewhart charts

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1. INTRODUCTION

The intent of a statistical control chart of the quality of concrete pavements is to provide practitioners in the field with clear and concise information that will give them guidance on steps that they can take to construct a durable concrete pavement. Moreover, this also motivates the exploration of various reliability and durability related studies [1-7,16-21,26,28-30]. In keeping with this objective, the recommendations provided in code EN 206 [9] and the use of control charts in concrete production are key references. Publicly funded construction of transportation facilities in Poland is a multi-billion zlotys industry, which entrusts taxpayer funds to state transportation agencies (GDDKiA) and private contractors to provide durability and reliability of public roads. Currently, the roads are expected to have assured quality.

Early implementation of quality control charts in the transportation arena is a more comprehensive approach to consider quality control as an element of quality assurance. As taxpayers, we expect our investment to yield a long-lasting transportation system. Improved quality reduces the costs associated with re-work. These cost savings from improved quality have benefits for contractors and agencies. Although quality control functions are commonly contractually delegated to subcontractors, producers, fabricators and manufacturers, the prime contractor must take the lead role in monitoring the effectiveness of quality control at all levels during the construction process. Good quality can only be achieved by a trained labour force utilising materials that conform to specifications, and which are supported by a QC staff and program that provide timely feedback. Continuous process improvement and prevention of defects should be the aim of the contractor and material supply chain. It is far better to prevent defects rather than become proficient at finding the cause of defects after the fact. Open and timely communication between all parties is vital to an effective quality control program based on, for example, quality control chart Acceptance testing should be based upon samples, which have been obtained in a random manner to remove any potential bias. Random sampling is also applicable to contractor testing which will be evaluated using statistical process control (SPC) techniques. Random samples should be obtained in accordance with EN 206 [9] or other code procedures. The variability observed in concrete paving projects is attributable to four sources: material, process, sampling, and testing (Figure 1). It is important to note that every test result we examined includes these sources of variability [10-12,14,22-25].

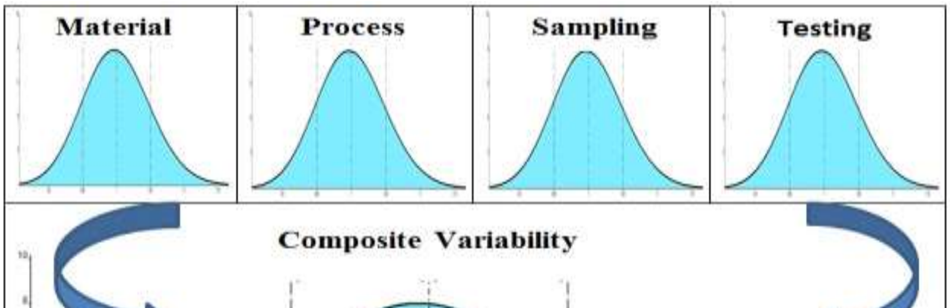

Fig. 1. Sources of construction variability

Understanding the materials, precision and bias of each test procedure is critical to proper interpretation of quality control testing and acceptance testing. The term process control is often used synonymously with quality control. Reducing variability in materials and in processes is a focus of quality control efforts. Reduced variability indicates a higher level of control. The same is true in sampling and testing activities. We should strive to reduce the variability of our QC testing activities:

- utilising the same technician, especially within payment lots,
- all technicians should be properly trained and certified,
- follow strict adherence to testing procedures,
- testing equipment should be calibrated and certified as necessary [10-12,14,22-25].

2. STATISTICAL PROCESS CONTROL

Control charts are useful tools which when combined with some well-proven rules can assist contractors in identifying changes in their materials and processes. The primary purpose of using Statistical Process Control (SPC), specifically control charts, is to identify change. Their function is not to indicate whether a test result passes or fails the acceptance criteria, but rather to indicate if the test result was unusual. Control charts are an effective means for identifying the impact of assignable causes on the materials and/or construction processes. Some agencies/contractors use moving average instead of individual test results as a tool for trend evaluation. Once identified, the materials and/or processes can be adjusted to account for the influence of the assignable cause [10-12,14,22-25]. For example, a sharp reduction in air content may indicate that the carbon content of the fly ash has changed, requiring an increased dosage of air-entraining admixture [8,13]. Simply put, a control chart provides a visual indication of whether a process is in control (Figure 2).

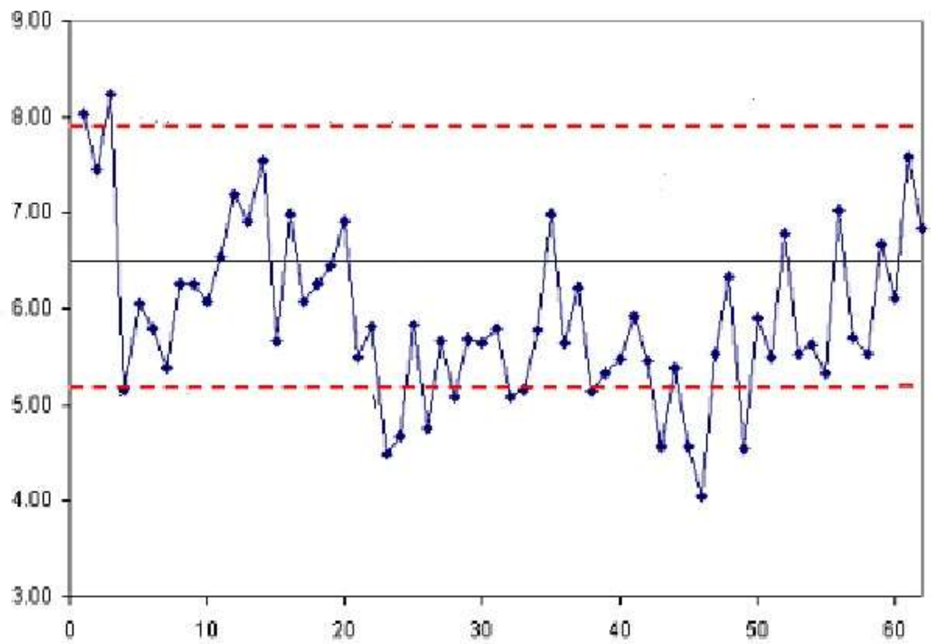

Fig. 2. Control chart for the average air void content according to [24]

3. THE CUSUM CONTROL CHART

Cumulative Sum (CUSUM) charts are proven techniques for improving productivity, effective in defect prevention, prevent unnecessary process adjustments, provide diagnostic information and provide information about process capability. CUSUM control charts are amongst some of the most important management control tools. CUSUM control charts directly incorporate all the information in the sequence of sample values by plotting the cumulative sums of the deviations of the sample values from a target value. The CUSUM chart presents the cumulative sum and they combine information from several samples, thus, CUSUM charts are more effective than Shewhart charts for detecting small process shifts. If the process remains in control at the target mean value - μ_0, the CUSUM defined in the above equation should vary randomly about zero. However, if the mean shifts upward to some value $\mu_1 > \mu_0$, then an upward or positive drift will develop in the cumulative sum (CUSUM). Conversely, if the mean shifts downward to some value $\mu_2 < \mu_0$, then a downward or negative drift in CUSUM will develop [8,11-14,25,28].

Therefore, if a trend develops in the plotted points – either upward or downward, we should consider this as evidence that the process mean has shifted, and a search for some assignable cause should be initiated. For determining whether the process is out of control, a formal decision procedure can be laid down in the form of a truncated V-shaped mask popularly known as V-mask [10,22,23].

CUSUM charts are more effective than Shewhart charts in detecting small and moderate-sized sustained shifts in the parameters of the probability distribution of a quality characteristic. Though in some cases, CUSUM charts are very useful, they are not meant to replace the Shewhart chart, which can be used to detect a wider assortment of effects due to assignable causes. It is, therefore, frequently recommended that Shewhart control lines be used in conjunction with CUSUM charts. In Statistical Process Control (SPC) methods, the control charts are major tools used for monitoring and improving manufacturing processes [10-12,14,22-25].

4. THE APPLICATION OF CUSUM CONTROL CHART

This study shows the Shewhart control chart and the CUSUM chart applied to analyse contrete compressive strength for monitoring the changes and variation factors of the trend of quality concrete intended for building a road. In practical application, the concrete strength quality will be accepted on the basis of each individual lot and is established according to the requirements specified in the EN 206 [9] as well, in which, the Shewhart control chart and CUSUM control chart is recommended as the basis of quality statistical acceptance.

The Shewhart control chart and the Tabular CUSUM chart can be independently applied in the Acceptance control chart. However, distinctive characteristics exist between the CUSUM and Shewhart control chart. In this respect, the Shewhart control chart does not take into account the changes in the average value of continuous compressive strength under the same construction project and the same mixing ration parameter required for designing the concrete strength, instead, quality control and analysis are executed for the total lot count of the current concrete displacement.

Unlike the Shewhart control chart, the CUSUM statistic analysis method has its own serial and cyclic features, meaning that CUSUM will make reference to the cumulative variation amount of the average deviation target value obtained from previous samples. In this way, it will be accumulated to current-term average sample count for overall consideration in order to effectively evaluate the supplier’s concrete quality control and stability in the material used in the same construction site, the same strength mixing ratio, and the same design strength.

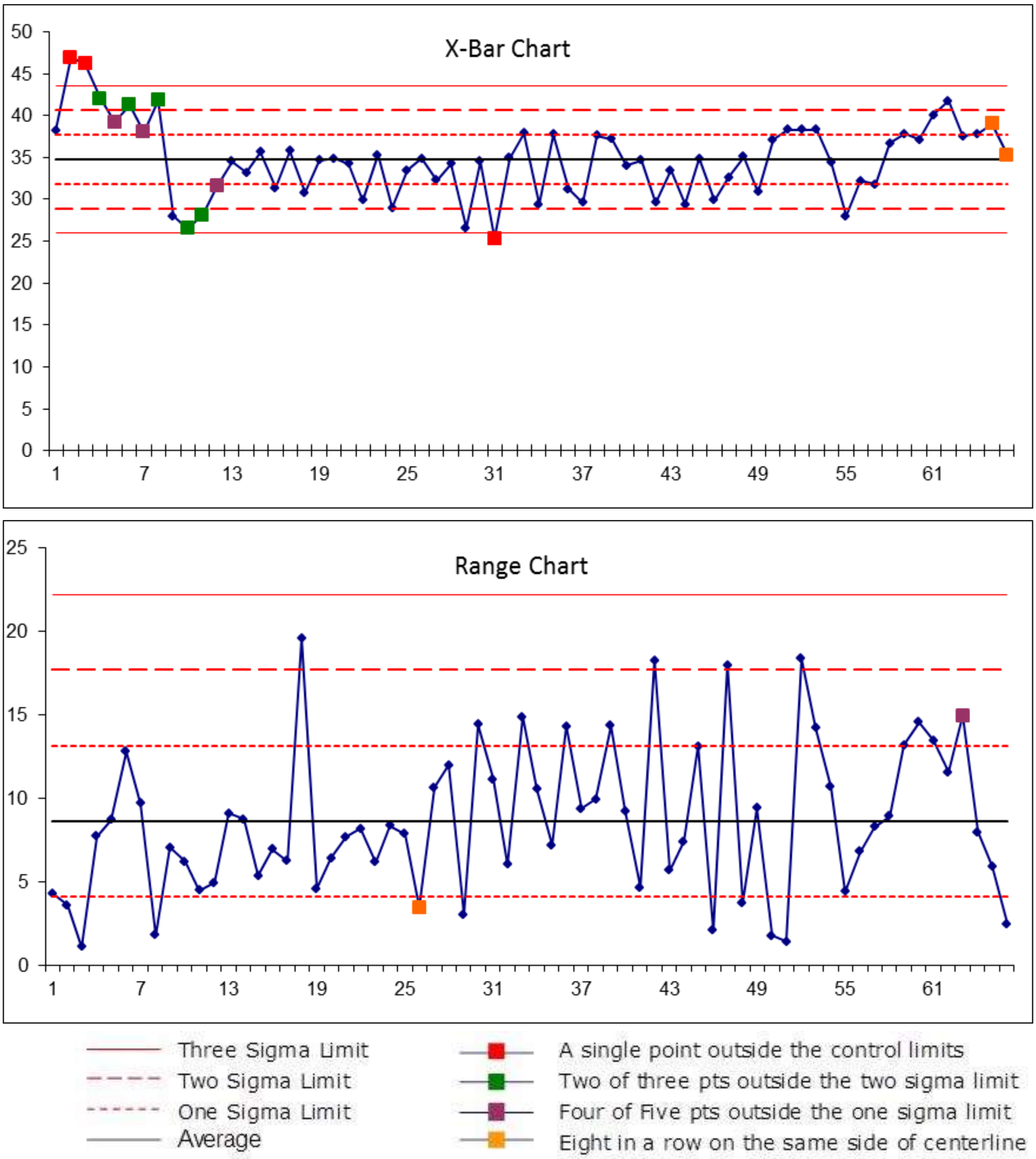

Fig. 3. Shewhart control chart: X-bar chart and range chart

The CUSUM quality control chart comprises all the information provided for the average compressive strength value of the concrete subject selected from the test batch in appropriate time, for which the previous mean compressive strength value is set asp,$_0$ for use as a referential or target value, and the mean compressive strength value of the respective batch subsequently poured is set as ^$_1$ in order to continuously detect the minor deviations between each batch. The result of relevant studies support that, with the quality subjected to normal distribution (p,o2) and using 3o as the control scope, the trend and deviation pre-alert of the cumulative and control charts are more sensitive than the Shewhart control chart. The development of the CUSUM method is to detect small shifts and fluctuations of variables for the mean value in order to provide judgment that is more sensitive when the mean compressive strength is beyond control.

In practice, the construction industry usually uses the X-bar-R chart as the concrete strength evaluation method for executing statistical quality control with the metering value of the pre-mixed concrete. The purpose of the X bar chart is to measure the stability of the mean concrete value, and the R-chart is to monitor the accuracy of the measuring equipment (Fig. 3). In comparison, the CUSUM chart is used to accumulate the deviation values between the average count of each sample group and the overall groups to present the development of the variation trend between the concrete lots. The change of the trend transition variation can be used to immediately detect minor changes in strength.

The Shewhart control chart does not take into account the changes in the average value of continuous compressive strength under the same construction project and the same mixing ration parameter required for designing the concrete strength; instead, quality control and analysis are executed for the total lot count of the current concrete displacement.

The CUSUM Control Chart makes reference to the cumulative variation amount of the average deviation target value obtained from previous samples. It will be cumulated to current-term average sample count for overall consideration in order to effectively evaluate the supplier's concrete quality control and stability in the material used in the same construction site, the same strength mixing ratio and the same design strength.

The CUSUM quality control chart comprises of all the information provided for the average compressive strength value of the concrete subject selected from the test batch in appropriate time, for which the previous mean compressive strength value is set 35,04 MPa for use as a referential or target value, and the mean compressive strength value of the respective batch subsequently poured is set in order to continuously detect the minor deviations between each batch.

All data for reference class C30/37 was presented in Table 1. The basic analysis for formulating a CUSUM chart is as follows:

- Mean Sample (MS): 45,0 MPa,
- Standard Deviation (σ) : 5,02 MPa (Standard Deviation of compressive strength from the initial production),
- Target Mean Strength (TMS) = fck+2σ, according to [6], so: TMS = 37 + 2(5,02)= 47,04 MPa.

Data for the CUSUM plot are presented in Table 1. The column 1 of Table 1 represents concrete class, column 2 represents the 28-day cube compressive strength (xt) and in column 3 the deviations (both positive and negative) of TMS (47,04 MPa.) from x_t are calculated.

In general, upward slopes indicate an increase in mean strength and standard deviation, and downward slopes reflect a reduction. Minimum fluctuation of test strength of the target mean strength is desirable. As per Fig. 3, the trend of the graph for the Conventional CUSUM plot shows an increase in the strength trend up to sample no. 14, after which at sample no. 15 the strength falls below the specified strength of 35 MPa.

Tab. 1

Calculation of CUSUM charts

No. of samples	28-Day Compressive Strength [MPa]	xi-MS [MPa]	CUSUM Plot [MPa]	Cumulative sum [MPa]
1	40,9	0,9	0,9	6,4
2	37,2	-2,8	-1,9	9,1
3	36,6	-3,4	-5,3	11,2
4	48,6	8,6	3,3	25,3
5	47,2	7,2	10,5	38
6	45	5	15,5	48,5
7	45,5	5,5	21	59,5
8	46,4	6,4	27,4	71,4
9	46,6	6,6	34	83,5
10	44,8	4,8	38,8	93,8
11	44,1	4,1	42,9	103,4
12	37,1	-2,9	40	106
13	43,1	3,1	43,1	114,6
14	40,2	0,2	43,3	120,3
15	34,4	-5,6	37,7	120,2
16	35,1	-4,9	32,8	120,8
17	40,8	0,8	33,6	127,1
18	47,9	7,9	41,5	140,5
19	32,8	-7,2	34,3	138,8
20	38,8	-1,2	33,1	143,1
21	42,5	2,5	35,6	151,1
22	42,9	2,9	38,5	159,5
23	41,4	1,4	39,9	166,4
24	41,1	1,1	41	173
25	32,1	-7,9	33,1	170,6
26	29	-11	22,1	165,1
27	32,9	-7,1	15	163,5
28	40,8	0,8	15,8	169,8
29	39	-1	14,8	174,3
30	41,2	1,2	16	181
31	40,9	0,9	16,9	187,4

Though there is again a recovery of strength up to sample no. 17, the strength again falls below the specified strength at sample no. 18. Thereafter, the CUSUM plot shows a negative trend up to sample no. 30. This high degree of fluctuation of mean strength and standard deviation reveals the fact that the system of quality monitoring adopted by the RMC plant under study is inadequate. This also increases the probability of rejection of the concrete by the client.

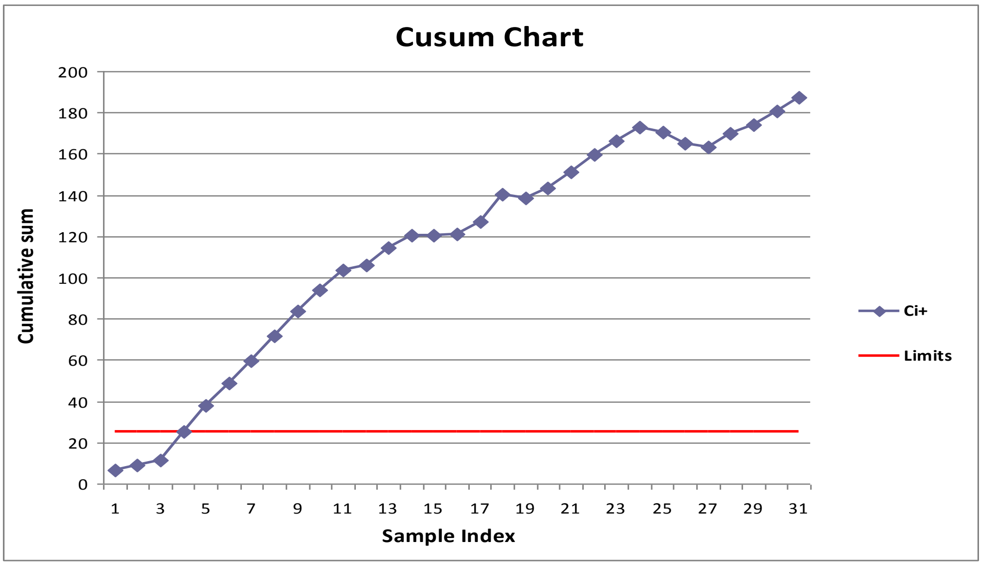

Fig.3. Conventional CUSUM chart for compressive strength

To confirm whether a significant change has occurred, a transparent mask, in the shape of a truncated “V” is placed over the last CUSUM plotted with the designated lead point shown in Fig. 2 superimposed over it. If the plot remains inside the boundaries of the mask, no significant change has occurred, that is, the concrete quality has not deviated from the desirable level significantly. The deviations that have occurred are acceptable and these are due to uncontrollable random factors. However, if the plot crosses a boundary, a significant trend can be detected and action is required. This mask is applied to the plot each time a new result is added and further check is made. The V mask is drawn joining three straight lines, namely, the base of the truncated V and the two inclined lines joining the base. The base is called the decision interval (DI) and its length is 8.1 σ. The gradient of the two symmetrically placed inclined lines is σ / 6 in the case of the mask meant for detecting a significant change in mean, a being the plant standard deviation. Application of V-Mask to CUSUM plot as a daily monitoring tool [9,13].

In Fig. 4, it is observed that by putting the lead point of the mask on sample no. 16, the CUSUM plot sample numbers 1 to 4 go beyond the boundary of the mask, which is a signal that a significant change has taken place in the compressive strength of concrete or a significant change of concrete class, sample no. 3 (36,6 MPa).

The result of relevant studies support that, with the quality subjected to normal distribution and using 3o as the control scope, the trend and deviation pre-alert of the cumulative and control charts are sensitive control chart. The development of the CUSUM method is to detect small shifts and fluctuations of variables for the mean value in order to provide more sensitive judgment when the mean compressive strength is beyond control.

In practice, the CUSUM chart is used to accumulate the deviation values between the average count of each sample group and the overall groups to present the development of variation trend between the concrete lots. The change of the trend transition variation can be used to immediately detect minor changes in strength.

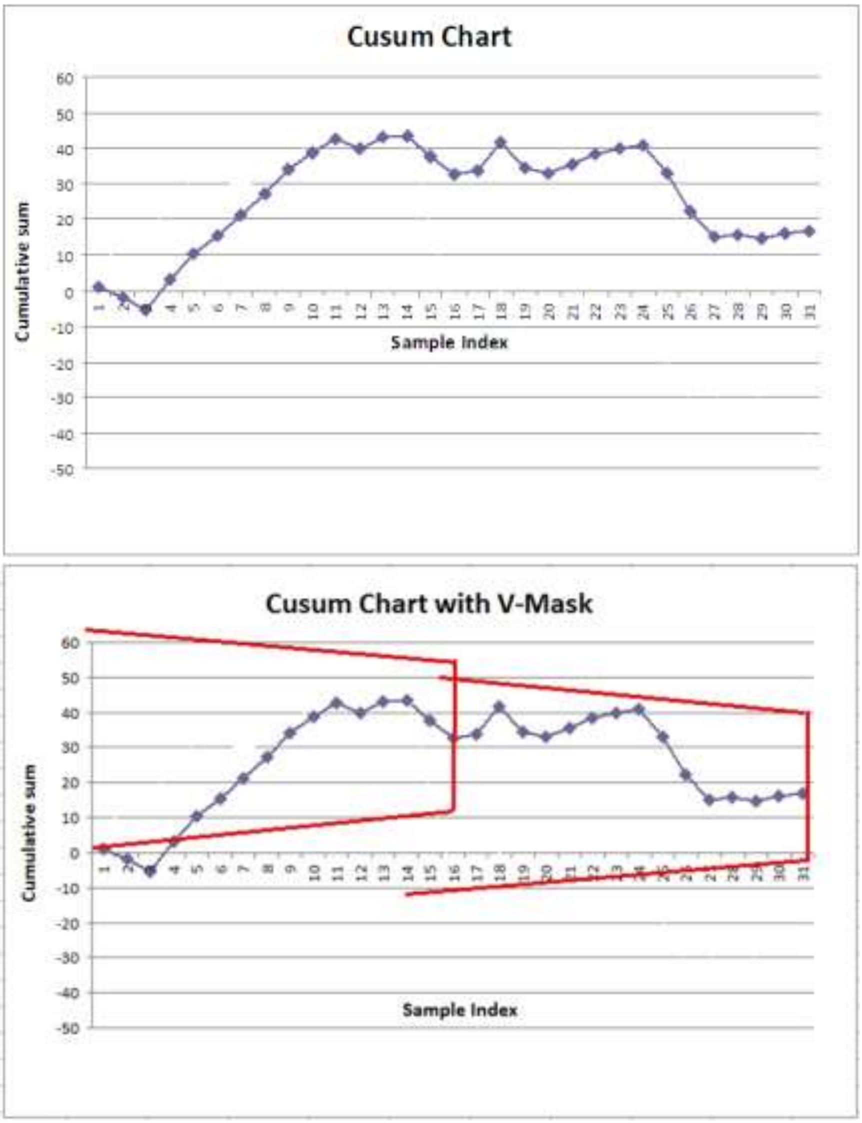

Fig. 4. CUSUM chart for compressive strength without and with V-Mask

5. CONCLUSIONS

Offering products and services of the highest quality is essential for durability, reliability and security of rehabilitated infrastructure investments, including roads. Ensuring the proper quality of production and services requires constant application of properly selected methods and tools enabling the analysis and evaluation of the processes carried out. Quality control should be active and not passive, therefore, it is extremely important to constantly monitor processes, analyse their variability and test their qualitative ability through the use of control charts.

The CUSUM chart uses a cumulative variation value, therefore, it should be suitable for application in the quality control of the concrete compressive strength. According to practical test application results, this study proposes that the CUSUM control chart should be used in order to objectively set the overall mean value as the average compressive strength of the concrete for accumulating to the current compressive strength deviation value. When a continuous deviation appears in the cumulative quantity of each group, it means that change has happened to the quality of the concrete compressive strength during the process and the acceptance and that the reasons must be sourced.

The CUSUM control chart is used to detect the existence of minor deviation in the target mean value, whereas, the conventional Shewhart control chart exhibits more significant changes when a greater deviation exists in the target mean value. Both have their advantages and weaknesses, and we suggest that they should be used together. To achieve the stabilised overall quality, the CUSUM allows for the use of the V-Mask for compliance control so that the causative reasons may be identified in advance in order to make appropriate process modification or adjustment.

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