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Use of Control Charts and Regression Analysis in Cement Manufacturing in South Africa

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Abstract: Continued monitoring of the mean strength of cement in manufacturing is essential. Cement strength is best measured after 7 and 28 days and has to meet the minimum standards as outlined in the South African Bureau of Standards. Early detection of low cement strength is important as continued production would result in large quantities of unusable cement and wastage to the environment. It is not known whether an $\bar{x}$-Shewart or Cumulative Sum (CUSUM) control chart will be feasible for cement manufacturing in South Africa. It is also not known from a South African context how 28 days mean strength could be predicted from variables associated with 7 days mean strength. Accurate predictions of this nature could safeguard against waiting for 28 days. Data was obtained from a cement factory in the North-West Province of South Africa from 17 Sept., 2015 to 31 May, 2016. This time-frame provided a data-set of 117 data points. Ethical approval was obtained from the North West University Ethical Committee (NWU-00433-16-S9). Data was analysed for normality and as descriptive statistics were calculated. Data was further assessed with x-Shewart and CUSUM control charts. Pearson correlation analysis was then applied on all variables (physical, chemical and strength). Stepwise linear regression analysis was used for the prediction model. A $p<0.05$ was considered statistically significant. All data was normally distributed with no missing values. The results of the current study demonstrated that it is feasible to use the $\bar{x}$-Shewart and CUSUM control charts. Out-of-control data points were readily detected by both $\bar{x}$-Shewart and CUSUM control charts. The two control charts reported similar findings. It is also shown that the process meets certain requirements or specifications as set out by the manufacturer. Lastly, 7 days strength and TiO_2 were the two independent variables that significantly predict 28 days with a coefficient of determination $R^2 = 0.35$ and SEE of 6.5 kPa ($p<0.05$). Effective use of control charts can lower the amount of chemical waste. The results of the current study demonstrated that it is feasible to use the $\bar{x}$-Shewart and CUSUM control chart to monitor and detect out-of-control values for cement strength (7 and 28 days) in cement manufacturing in South Africa. This would enable process engineers to timeously implement the necessary remedial actions plans to avoid waste which will eventually reach the environment. Moreover, 28 days mean strength can be significantly detected by early strength (7 days strength) and TiO_2 to provide an additional "warning system" for the early detection of a process running out-of-control.

Key words: Shewart, CUSUM, cement, deleterious material, process capability, control

INTRODUCTION

Since, the inception of industrial manufacturing, statistical process control has provided the necessary platform to ensure that production lines run effectively and efficiently (Gibbs and Harrison, 2010). The use of statistical process control has gained popularity in industrial processes that continuously provide manufactured material in large quantities. The use thereof has resulted in an increase in profit margins, driven down production costs and enhanced employee morale (Rao, 2010).

The pioneering researcher in statistical process control was Walter Shewart in 1924 (Ahmad *et al*., 2013; Montgomery, 2013). He realized that there are natural deviations in any statistical data set but attempted to control larger deviations caused by external influences in manufacturing processes. Consequently he introduced what is now known as control charts to continuously monitor pertinent variables related to production in manufacturing processes (Montgomery, 2012). A control chart consists of a mean value with upper and lower limits (Miah, 2016). The upper and lower limits are usually calculated using three standard deviations from

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the mean. The mean and standard deviation are calculated when the process is in control (Montgomery, 2012).

Shewart's notion of control charts is clearly applicable in the manufacturing of cement as there are many causes of variations in the production of cement (Gibbs and Harrison, 2010). Some of these causes could be due to the incorrect recipe of raw materials, faulty machinery, measuring scales losing accuracy, inaccurate testing equipment, contamination of raw materials and many more (Gibbs and Harrison, 2010). Control charts in cement manufacturing can be applied to monitor a range of variables such as consistence, water to cement ratio, cube/cylinder strength, raw materials or batching accuracy. However, the variable most applicable in cement manufacturing is the strength of the cement measured in Mega Pascal (MPa) (Gibbs and Harrison, 2010). Daily tests are performed at cement factories to determine the strength of the cement. There are tests at different days once the cement has been mixed in a standardized manner with water to form concrete. There is a 2, 7 and 28 days strength test (Gibbs and Harrison, 2013). The strength of the concrete is the strongest on the 28th day as the cement would have been allowed to set. However, it is not feasible for cement factories to wait 28 days before monitoring the quality of the cement because if the mean strength is below the lower permissible limit, 28 days of cement manufacturing will be faulty (Tsamatsoulis *et al*., 2012; Gibbs and Harrison, 2010). Consequently, the 2 and 7 days tests were also introduced. The downfall of these tests are that they are less accurate and more variable than the 28 days test. Subsequently, researchers have attempted to predict 28 days strength using variables related to the 2 and 7 days test (Tsamatsoulis *et al*., 2012; Kheder *et al*., 2003; Tsivilis and Parissakis, 1995).

Problem statement: Continued monitoring of the mean strength in cement manufacturing will indicate if a process is running out-of-control (Tsamatsoulis *et al*., 2012; Gibbs and Harrison, 2010). The early detection of such problems is clearly important as continued production would result in a large amount of cement being manufactured not in line with the South African Bureau of Standards (SABS). Continued production with an out of control process would ultimately lead to the company accruing large costs. It is not known whether a Shewart or Cumulative Sum (CUSUM) control chart will be feasible for cement manufacturing in South Africa.

Also, it is not known from a South African context how 28 days mean strength could be predicted from variables associated with 7 days mean strength. Accurate predictions of this nature could safeguard the optimal running of production lines with early detections.

Therefore, the research questions that arise is whether it is feasible to use control charts for statistical process control in cement manufacturing in the North-West Province of South Africa? Secondly, what type of control charts would be best suited to analyse the mean strength of cement manufacturing? Thirdly, how capable is the process to meet specific requirements or specifications specified by the manufacturer. Lastly is it possible to accurately predict the 28 days strength of concrete using variables associated with 7 days strength?

Literature review

Quality: There are many definitions for quality (Mitra, 2016). Most individuals would define quality as the characteristics that a certain product or brand possess. Although a conceptual definition is useful, a more specific and precise definition is needed (Mitra, 2016). Montgomery (2012) defined quality as being inversely proportional to variability. Furthermore, Montgomery (2012) provides a definition for the improvement of quality as "a reduction in the variability of the process or product". It is also often necessary to assess quality by analyzing factors such as performance, reliability, durability, serviceability, aesthetics, features, perceived quality and conformance to standards (Garvin, 1987).

Quality control: Quality control involves steps taken by the process engineer to ensure that the quality of the end product is maintained and assured to the clients (Miah, 2016; Montgomery, 2012). Technological developments in the construction industry are very active and ongoing. These technological advances will not be complete without also technological improvements in the manufacturing of the cement that is used.

Statistical process control: Statistical Process Control (SPC) is an effective method to continuously monitor the control of process in the manufacturing industry (Mitra, 2012; Annalakshmi *et al*., 2013; Montgomery; 2013; Shao and Lin, 2013; Zhang *et al*., 2014; Ou *et al*., 2012). It is a statement about the quality of processes in an efficient way by analysing a sample of items (Kern, 2014). It is a method used by process control engineers to detect out-of-control processes as early as possible and locate the fault (s) on the production line (Psarakis *et al*., 2014; Phaladiganon *et al*., 2013). Montgomery (2012) specifically defines statistical process control as "a powerful collection of problem-solving tools useful in achieving process stability and improving capability through the reduction of variability. SPC is based on sound principles which analyze large complicated data sets in a simplified manner through easy-to-understand charts and diagrams. Some of these include a histogram, stem-and-leave plot, Pareto chart, cause-and-effect diagram, scatter diagram and control charts (Montgomery, 2012).

Control charts: A control chart is one the most appropriate techniques used to assess statistical process control (Mitra, 2016; Montgomery, 2012). A control chart provides a simplified picture using data sets (some of which are very large), so that, the significance of the data can be understood (Rao, 2010; Carson and Yeh, 2008). Rao (2010) defined a control chart as "a chronological (hour-by-hour, day-by-day) graphical comparison of actual product quality characteristics with limits reflecting the ability to produce as shown by past experience on the product characteristic". A control charts exhibits properties to monitor the process (Mitra, 2016). If the process is in control, sources of variability are within the allocated limits of allotments. However, if the process is running out of control larger sources of variability will be present (Montgomery, 2012). In such a case, the process engineer is alerted and should take action to locate the fault in production. The use of an effective use of a control chart is a prominent method to reduce variability. Two types of control charts are discussed briefly.

Shewart control charts: Shewart control charts are probably one of the most technically sophisticated charts (Montgomery, 2012). Shewart control charts are very useful to indicate large assignable shifts that occur in the process mean (Montgomery, 2012). They are also very useful to bring disorderly processes into control as the trends of these charts provide guidance to the assignable causes.

Shewart control charts can be a mean value (x) with carefully calculated control limits (upper control limit and lower control limit) (Mitra, 2016; Carson and Yeh, 2008). Often warning limits are also added to alert the process engineer (Carson and Yeh, 2008). Corrective action is needed if values deviate beyond the control limits. The mean and upper and lower control limits are set when it is known that the process is in control (Carson and Yeh, 2008).

CUSUM control chart: CUSUM (Cumulative Sum) control charts were first used in the 1950's (Gibbs and Harrison 2010). These charts are also used in the manufacturing process to determine quality (Mitra, 2016). An advantage of the CUSUM c\hart is that information obtained in past observations is used and therefore it is sensitive to smaller shifts in the process mean (Chang *et al*., 2013; Montgomery, 2013). This makes the CUSUM chart very appropriate when the process is running in-control with reliable estimates of the process mean and standard deviation (Montgomery, 2012). CUSUM control charts are often referred to as time-weighted control charts (Montgomery, 2012).

Use of control charts in the manufacturing of cement: Cement factories produce large amounts of cement. They continuously produce cement 24 h during a day, 7 days a week. It is of no surprise then that process engineers have to continuously monitor cement production in order to safeguard large amounts of cement being produced which do not conform to SABS standards (Gibbs and Harrison, 2010). Control charts have widespread use in the manufacturing of concrete and is used widely to monitor product characteristics such as the consistency or strength of the cement (Chang *et al*., 2013; Tsamatsoulis, 2012; Gibbs and Harrison, 2010; Carson and Yeh, 2008).

Mean strength of cement: The most commonly measured variables in determining the quality of cement is the mean strength of thereof (measured in MPa (Gibbs and Harrison, 2010). It is standard practice to measure mean strength of cement at 2, 7 and 28 days with specialised equipment (Gibbs and Harrison, 2010). However, in most cases, control systems monitor cement strength at 7 days as the risk of waiting 28 days is unacceptable to both the producer and consumer (Gibbs and Harrison, 2010). Testing at 2 days will induce greater variability than testing at 7 days as the time-to-set have a greater impact on early testing (Gibbs and Harrison 2010). The use of 7 or 28 days is therefore generally preferred. Researchers have attempted to predict the 28 days strength of cement using early testing strength as well as the physical (fineness) and chemical characteristics (clinker mineral compounds, oxides and cement composition) of the cement type (Tsamatsoulis, 2012; Garcia-Casillas *et al*., 2007; Kheder *et al*., 2003; Tsivilis and Parissakis, 1995).

Out-of-control action plan: When a process is running out of control and the fault cannot be identified it can be very difficult (Mullins, 2003). The researcher suggest that process engineers should continuously take notes on the chart regarding process observations and actions. In many cases the control limits need to be reset in order to monitor the stability of the process accurately (Mullins, 2003). In other cases, outliers could be responsible for an out of control process without any assignable cause and consequently removed from the data set (Mullins, 2003). In such instances a false alarm is created and can negatively impact the manufacturing efficiency (Shao and Lin, 2013).

Process capability: The Shewart $\bar{x}$ control chart provides the process engineer with the information regarding the performance or process capability of the cement factory. The control chart data is used to describe the capability of the process to meet certain requirements or specifications as set out by the manufacturer (Miah, 2016; Mitra, 2016; Montgomery, 2012; Ahmad *et al*., 2013). Another metho to express the process Capability (C_p) is to determine the process capability ratio using both the Upper Specification Limit (USL) and Lower Specification Limit (LSL). The ratio is calculated using $C_p = (USL-LSL)/6\sigma$ (Montgomery, 2012).

Deleterious material: Deleterious Materials (DM) are materials that are environmentally damaging. These materials come from chemical waste during cement manufacturing. Cement waste will always find its way to the environment. The lower the cement waste the lower the environmental damage. In this case control charts are used to efficiently monitor the cement production process.

MATERIALS AND METHODS

Aims and objectives:

- The main objective is to determine whether it is feasible to use the $\bar{x}$-Shewart control chart in statistical process control for the mean strength of cement at 7 and 28 days
- To determine the effect of using the $\bar{x}$-Shewart control chart versus the tabular CUSUM control chart at 7 and 28 days
- To determine whether the process meets certain requirements or specifications as set out by the manufacturer?
- To determine which variables associated with 7 days strength can be used to accurately predict 28 days mean strength?

Data: Data regarding the mean strength (7 and 28 days strength) of cement of all-purpose cement for the period 17 Sept., 2015 to 31 May, 2016 was obtained from a cement factory in the North West Province of South Africa. The manufacturer also provided data regarding the physical and chemical composition of the cement for analysis.

Analysis of the data: Data was analyzed with the Statistical Package for the Social Sciences (SPSS 23.0, SPSS Chicago, IL, USA) and Microsoft Excel in 2013. The distribution of the variables and normality was assessed with the Kolmogorov-Smirnov test, histogram, stem and leave plot and the box and Whisker plot. The process engineer at the cement factory provided a reliable and valid mean and SD for a period when the process was well in-control.

Shewart and CUSUM control charts: The Shewart and CUSUM control charts were constructed in Microsoft Excel. The control charts were assessed for 7 and 28 days strength separately for the period mentioned.

The Shewart-control chart: Two standard deviations above the mean was used to determine the upper control limit and two standard deviations below the mean was used to calculate the lower control limit. The central line indicated the mean when the process was in control. Two SD were used instead of three as cement factories have to conform to strict SABS requirements.

CUSUM control chart: A tabular CUSUM control chart was set up. The tabular CUSUM regards value from previous observations into each individually plotted value, increasing the sensitivity of detecting small shifts in the process mean (Carson and Yeh, 2008). Calculations for the CUSUM control chart is shown in the next paragraph. These are done separately for 7 and 28 days strength. The value of 5 was used for small h. "K" was calculated as 0.5× SD. Mean and SD when the process is in-control was be used:

$$\begin{aligned} K &= 0.5\times SD \\ H &= 5\times SD \end{aligned} \quad (1)$$

The μ_0 value is the mean strength of cement when the process is in control which is also the mean strength of the cement at 7 and 28 days, respectively:

$$Ci+ = \text{Corresponding value}-(\mu_0+K)+Ci\ (\text{previous})$$

$$Ci- = (-)\ \text{Corresponding value}+(\mu_0-K)+Ci\ (\text{previous})$$

Regression analysis: A model predicting 28 days strength based on early strength as well as physical and chemical characteristics of the cement type was conducted with stepwise forward multiple regression analysis. A stepwise forward multiple regression analysis was chosen as the number of independent variables entered and the order of entry were determined by statistical criteria generated by the stepwise procedure. The stepwise forward multiple regression analyses was performed in SPSS.

The Levene's test was used to assess the homogeneity of variances of the dependent variable. Multicollinearity was assessed with the bivariate correlations so that strong correlations between independent variables are excluded. The dependent variable was 28 days mean strength. Possible independent variables included could be 7 days strength, Non-Deleterious Material (NDM), particle size, SiO_2, Al_2O_3, Fe_2O_3, Mn_2O_3, TiO_2, CaO, MgO, P_2O_5, Cl, SO_3, K_2O, Na_2O, CO_2 and XRF Sum. Variables that demonstrated significant relationships with 28 days mean strength in the bivariate correlational analyses ($p<0.05$) was entered as independent variables (provided that the assumption of multicollinearity is not violated).

The coefficient of determination will be reported together with the parameter estimates, standard error, t-value, p-value and standardized estimates of each variable.

Ethical considerations: Ethical approval was obtained from the North West University (Mafikeng Campus) Ethical Committee. The ethical approval number for this study is: NWU-00433-16-S9.

RESULTS AND DISCUSSION

Descriptive statistics and normality for 7 and 28 days mean strength: Descriptive statistics for the 7 and 28 days mean strength of cement are depicted in Table 1 and Fig. 1. Normality for 7 and 28 days mean strength of cement was assessed with inferential statistics (Kolmogorov-Smirnov test in Table 2) and visually with a histogram (Fig. 2) and the box and Whisker plot (Fig. 3). From the information provided in this Table 2 and Fig. 2 and 3, we can report that the assumption of normality has not been violated. The p-value for the Kolmogorov-Smirnov test is larger than 0.05 (Table 2). A few outliers are shown in the box and Whisker plot (Fig. 3) but should not be deleted or replaced with mean values as instructed by the process engineer. They were correctly entered and are valid data points. However, the few outliers did not skew the data, due to the large number of observations (n = 117 data points). No missing values were reported in the data set.

Descriptive statistics and normality for all other variables: Table 3 provides descriptive statistics and normality for all other variables.

Mean and SD for 7 and 28 days strength of cement when process was in-control: The process engineer at the cement manufacturing firm provided data and he and his team of quality control specialists assured that the process was well in-control (Carson and Yeh, 2008). The mean and SD was provided to us from the period of 1st Jan., 2015 to 31st May, 2015 when the cement plant and the processes thereof was running effectively and efficiently. No mishaps or problems occurred during this period. The mean and SD for 7 and 28 days mean strength during this period is provided in Table 4.

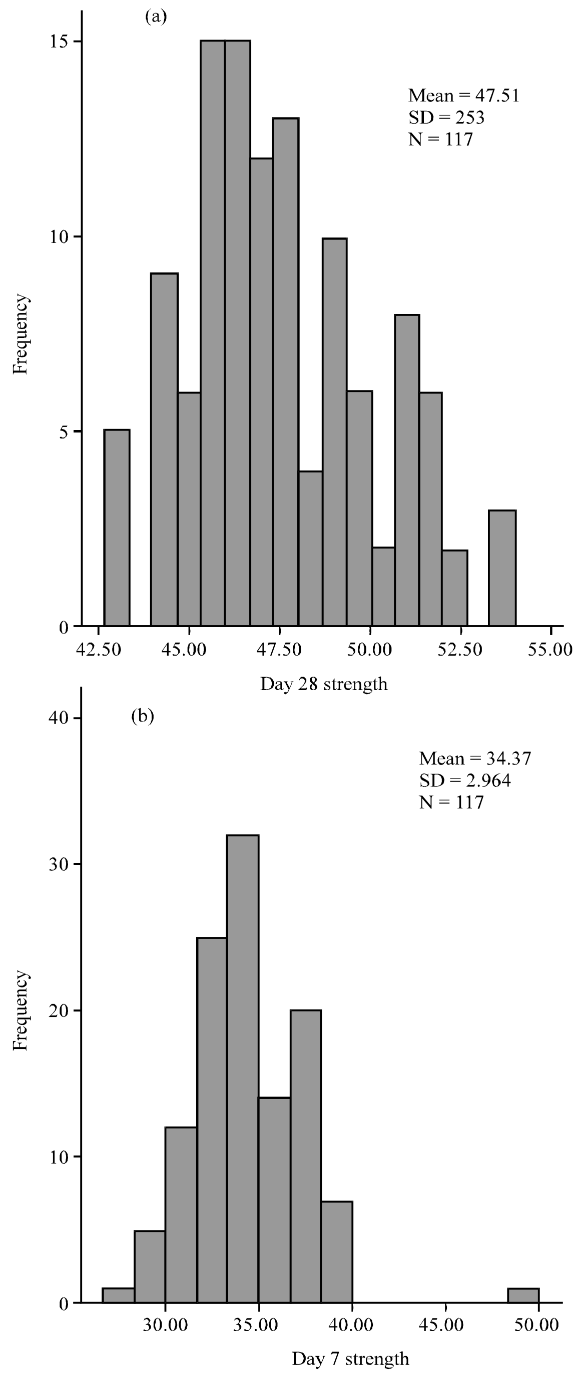

Fig. 1: Histogram for 28 and 7 days mean strength of cement. The x-axis is the day strength while the y-axis is the count of frequency

Table 1: Descriptive statistics for 7 and 28 days mean strength of cement

Days	N	Minimum	Maximum	Mean	SD
Day 28 strength	117	42.83	53.64	47.5091	2.53050
Day 7 strength	117	26.79	49.90	34.3724	2.96379
Valid N (listwise)	117				

Table 2: Normality (Kolmogorov-Smirnov test) for 7 and 28 day mean strength of cement

	Kolmogorov-Smirnov[a]		
	Statistic	df	Sig.
Day 28 strength	0.068	117	0.200
Day 7 strength	0.074	117	0.168

[a]stands for Kolmogorov-Smirnov test for normality

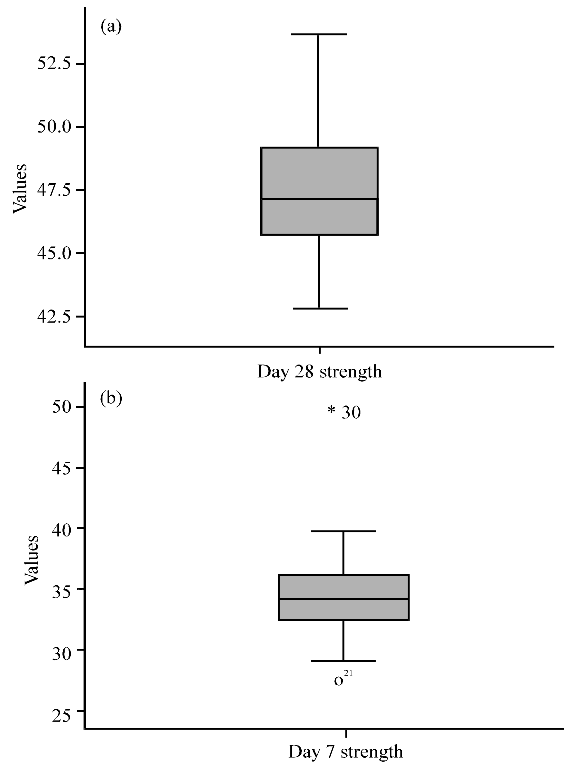

Fig. 2: a, b) Box-and-Whisker plots for 28 and 7 days mean strength of cement. For the 28 days strength the parameters maximum, third quartile, median, first quartile and minimum are not close to each other. Unlike 28 days cement the 7 days strength cement, the parameters are close to each other

The 28 days mean strength of the cement is stronger as the cement would have set for a longer period of time. The mean value of 28 days mean strength is much higher than the permissible value of 42.5 kPa for this type of cement. Such high values, safeguard the factory against minimum-allowed values determined by the Bureau of Standards of South Africa (SABS., 2013). In fact, the

Table 3: Descriptive statistics and normality (Kolmogorov-Smirnov test) for all other variables

Variables	N	Minimum	Maximum	Mean	SD	Kolmogorov Smirnov P
Particle size (µm)	117	6.84	12.08	9.54	1.06	0.20
SiO_2	117	18.11	20.37	19.03	0.44	0.20
Al_2O_3	117	2.90	3.81	3.37	0.17	0.20
Fe_2O_3	117	2.47	3.48	2.84	0.18	0.15
TiO_2	117	0.25	0.42	0.30	0.03	0.11
Cl	117	13.00	95.00	42.01	12.61	0.08
SO_3	117	1.06	1.75	1.37	0.13	0.20
CO_2	117	3.50	8.86	6.73	0.86	0.07

Table 4: Mean and SD for 7 and 28 days strength of cement when the process was in-control

Day of cement strength	Mean (kPa)	SD
7 days strength	34.2	2.6
28 days strength	47.5	2.4

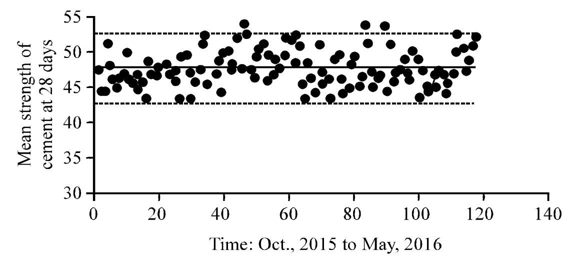

Fig. 3: Shewart-$\bar{x}$ control chart for 28 days mean strength. The x-axis represents the time points from 17 Sept., 2015 to 31 May, 2016. The y-axis depicts the strength of the cement. The central line indicates the mean strength of the cement when the process was in control. The dotted lines indicate upper and lower limits

cement factory has an internal bench mark of 43.8 kPa to further safeguard against failure to meet minimum standards. As expected, the 7 days strength of cement is slightly more variable as the cement would have not been allowed to set fully. More factors could influence the time-to-set at 7 days.

$\bar{x}$-Shewart control chart: The two Figs below (Fig. 3 and 4) depict the $\bar{x}$-Shewart control charts for 7 and 28 days mean strength of cement. The x-axis provide the time periods from 17 Sept., 2015 to 31 May, 2016. The y-axis in Fig. 3 and 4 provides an indication of the mean strength of cement. The central bolded line in each figure illustrates the mean strength of cement when the process was in-control. The upper and lower control limits in each figure is also depicted with bolded dotted lines. The SD was used to calculate two SD's above for upper control limits and two SD's below for lower control limits.

As depicted in the respective figures, the process was well in-control for 28 days mean strength

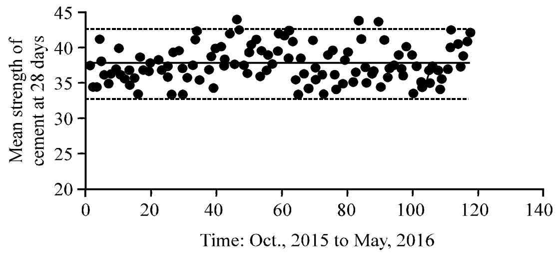

Fig. 4: Shewart-$\bar{x}$ control chart for 7 days mean strength. The x-axis represents the time points from 17 Sept., 2015 to 31 May, 2016. The Y-axis depicts the strength of the cement. The central line indicates the mean strength of the cement when the process was in control. The dotted lines indicate upper and lower limits. The dot indicates the mean strength of cement at a given time

(all observations fall within the lower-control limits). There are two or three borderline observations for lower limits but the mean strength of subsequent observations were well within limits again. The process engineers did identify lower mean strength over these periods and corrected this by mixing the cement finer to obtain stronger subsequent values.

There are three observations that fall outside the upper control limits. High values for mean strength does not indicate failure of the system but is representative of strong cement mixtures.

Regarding 7 days mean strength, one observation "fell" below the lower permissible limits of agreement. However, subsequent observations were again well within the allotted limits of agreement. Seven or more consecutive points on the lower-side of the target mean were seen from data point 6-16 and 101-112 (these points coincide with 28 days mean strength). The process engineers did identify lower mean strength over these periods and corrected this by mixing the cement finer to obtain stronger subsequent values. From point 17 and 113 onwards, the weaker strength was rectified. Seven or more consecutive points on the upper-side of the target mean were observed from points 50-62.

Tabular CUSUM control chart: Results in this study provides the reader with information pertaining to tabular CUSUM control charts for 7 and 28 days mean strength of cement. Tabular CUSUM control charts are used to detect when smaller shifts in the process mean transpired.

Calculations for 28 days mean strength: Mean is 47.5 and SD is 2.4:

$$\begin{aligned} K &= 0.5\times SD = 0.5\times 2.4 = 1.2 \\ H &= 5\times SD = 5\times 2.4 = 12 \end{aligned} \quad (2)$$

The μ_0 value is 47.5 which is also the mean strength of the cement at 28 days. The equations presented herein are provided by Montgomery (2012):

Ci+ = Corresponding value-(μ_0 +K)+Ci (previous)

Ci+ = Corresponding value-(48.7)+Ci (previous)

Ci- = (-) Corresponding value+(μ_0-K)+Ci (previous)

Ci- = (-) Corresponding value+(46.3)+Ci (previous)

Under the column C_i (representing lower control limits) the process was in-control for all 117 data points. On the other hand, C_i + was greater than H (12) at data point 60. However, caution is not warranted as strong values of cement strength is more than optimal. In the following section the results for 7 days CUSUM will be presented.

Calculations for 7 days mean strength: Mean is 34.2 and SD is 2.6:

$$\begin{aligned} K &= 0.5\times SD = 0.5\times 2.6 = 1.3 \\ H &= 5\times SD = 5\times 2.6 = 13 \end{aligned} \quad (3)$$

The μ_0 value is 34.2 which is also the mean strength of the cement at 7 days:

Ci+ = Corresponding value-(μ_0 +K)+Ci (previous)

Ci+ = Corresponding value-(35.5)+Ci (previous)

Ci- = (-) Corresponding value+(μ_0-K)+Ci (previous)

Ci- = (-) Corresponding value+(32.9)+Ci (previous)

Calculations for 7-day mean strength: Mean is 34.2 and SD is 2.6:

$$\begin{aligned} K &= 0.5\times SD = 0.5\times 2.6 = 1.3 \\ H &= 5\times SD = 5\times 2.6 = 13 \end{aligned} \quad (4)$$

The μ_0 value is 34.2 which is also the mean strength of the cement at 7 days:

Ci+ = Corresponding value-(μ_0 +K)+Ci (previous)

Ci+ = Corresponding value-(35.5)+Ci (previous)

Ci- = (-) Corresponding value+(μ_0-K)+Ci (previous)

Ci- = (-) Corresponding value+(32.9)+Ci (previous)

Table 5: CUSUM for 28 day mean strength of cement

Time point	28 days strength	xi-1	x-xi-1	|xi-Xi-1|	ci+	ci-	N+	N-
1	47.34	N/A	N/A	N/A				
2	44.15	47.34	-3.19	3.19	0.00	2.15	0	1
3	44.18	44.15	0.03	0.03	0.00	4.27	0	2
4	50.9	44.18	6.72	6.72	2.20	0.00	1	0
				…				
114	47.33	50.12	-2.79	2.79	4.73	0.00	1	0
115	48.5	47.33	1.17	1.17	4.53	0.00	2	0
116	50.72	48.5	2.22	2.22	6.55	0.00	3	0
117	51.68	50.72	0.96	0.96	9.53	0.00	4	0

Table 6: Tabular CUSUM for 7-day mean strength of cement

Time point	7 daya strength	xi-1	x - xi-1	|xi-Xi-1|	ci+	ci-	N+	N-
1	35.53	N/A	N/A	N/A				
2	30.27	35.53	-5.26	5.26	0	2.63	0	1
3	34.8	30.27	4.53	4.53	0	0.73	0	2
				…				
114	34.9	34.9	0	0	0	9.75	0	9
115	34.87	34.9	-0.03	0.03	0	7.78	0	10
116	36.21	34.87	1.34	1.34	0.71	4.47	1	11
117	30.55	36.21	-5.66	5.66	0	6.82	0	12

The CUSUM charts are presented in Table 5 and 6.

Process capability

28 days mean strength: The process capability is calculated for 28 days strength. The upper specification limit was set to 57 kPa. The stronger the cement, the better it is. The lower specification limit was 42.5 kPa which is the lowest limit set according to the SABS standards (SABS., 2013).

$$Cp = USL\text{-}LSL/6\times SD = 57\text{-}42.5/14.4 = 1.007$$

Note that, the value is greater than 1.

7 days mean strength: The process capability is also calculated for 7 days strength. The process capability of 7 days is not deemed necessary as it does not reflect the strength of the final cement product. The calculation however is shown below.

The upper specification limit was set to 42 kPa. The stronger the cement, the better it is. The lower specification limit was 32 kPa which is the lowest limit set according to the SABS standards (SABS, 2013).

$$Cp = USL\text{-}LSL/6\times SD = 42\text{-}32/15.6 = 0.64$$

The Cp value calculates is <1 thus indicating that the process is capable of producing cement that meets the required strength.

Regression analysis: Regression analysis was conducted to predict 28 days mean strength of cement using information based on earlier-strength (7 days) as well as other physical and chemical characteristics of the specific cement type. However, prior to the regression analysis a bivariate correlational analysis was conducted (Table 7-10) as to ascertain which independent variables are correlated with 28 days mean strength. In this way, variables demonstrating multicollinearity are excluded.

The table shows that NDM, particle size, FE_2O_3, TiO_2 and CO_2 is significantly correlated ($p<0.05$) to 28 days mean strength. The magnitude of significant correlations range from r = 0.26-r = 0.39. All correlations are positive except for particle size. In other words, the smaller the particles, the stronger the cement.

After using the data presented in Table 5, we conducted the stepwise forward multiple regression analysis. The dependent variables entered was 28 days mean strength. The independent variables are 5 days mean strength, NDM, particle size, Fe_2O_3 and TiO_2. Assumptions of regression analysis have been met (Coakes and Steed, 2003):

- Normality of all associated variables was assessed in study 4.1 and reported to be acceptable. Moreover, the sample size is sufficient (n = 117 observations)
- There are twenty times more cases (n = 117) than predictors (n = 5)
- There are no extreme outliers for the five independent variables and the dependent variable
- There is no multicolinearity between the independent variables

According to the Levene's test the assumption for homogeneity of variances was not violated. The p-value presented herein is >0.05 which mean we fail to reject the null hypotheses and the assumption for the homogeneity of variance holds.

The following Table 9 and 10 indicate the results of the stepwise forward multiple regression analyses. In Table 10, two models are depicted. In the first model, only 7 days mean strength is included but in the second model both 7 days mean strength and TiO_2 is included as significant predictors. In this table, the coefficient of determination (R^2), adjusted R^2 and significance of the model is reported. The p-value is smaller than 0.05 reflecting that the model is significant. In other words, there are significant predictor(s) predicting the model. Furthermore, 35.5% of the variance in the dependent variable in model 2 is predicted by the independent variables. This is not a very strong predictor as 65.5% of the variance in the dependent variable (28 days mean strength) remain unexplained. The adjusted R^2 value is not much smaller than the R^2 value, demonstrating that the amount of variables entered did not affect the model negatively. The next table will show us which independent variables are significant in the prediction.

Table 7: Bivariate correlational analysis between 28-day mean strength and other physical and chemical variables

Variables	7 days strength	NDM	Particle size	SiO_2	Al_2O_3	FE_2O_3	TiO_2	Cl	SO_3	CO_2
Pearson correlation	0.501**	-0.418**	-0.264**	0.118	0.125	0.299**	0.378**	0.009	0.156	0.393**
Sig. (2-tailed)	0.000	0.000	0.004	0.206	0.180	0.001	0.000	0.924	0.092	0.000
N	117	117	117	117	117	117	117	117	117	117

**Shows that value is significant

Table 8: Regression model summary

Models	R	R^2	Adjusted R^2	SE of the estimate	F-statistic	p-value
1	0.500[a]	0.250	0.243	2.20900	31.092	0.000
2	0.596[b]	0.355	0.344	2.05752		

[a]Stands for predictors: (constant), day 7 strength; [b]Stands for predictors: (constant), day 7 strength, TiO_2

Table 9: Model summary with independent variables

	Unstandardized coefficients (B)	SE	Standardized coefficients (β)	t-values	Sig.
Constant	24.229	2.997	-	8.085	0.000
Day 7 strength	0.3920	0.065	0.458	6.010	0.000
TiO_2	32.915	7.673	0.327	4.290	0.000

Table 10: Tests of normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual MR	0.076	117	0.094	0.983	117	0.141

[a]Stands for Kolmogorov-Smirnov test for normality

Table 10 shows the parameter estimates (β), standard errors, t-value, p-value and standardised coefficients for each independent variable and the intercept. As demonstrated in Table 10, 7 days mean strength and TiO_2 significantly contributes to the model as the $p<0.05$. The standardized weight of 7 days strength (Beta = 0.458) is more than TiO_2 (Beta = 0.327) and carries more weight in the prediction equation. The other variables (NDM, particle size, Fe_2O_3) do not contribute to the model and should be excluded.

Consequently, the process engineers can use the prediction equation developed from this analysis to predict 28 days mean strength with the equation:

$$\text{Y (hat)} = 24.229+[(X1)\times(0.392)]+[(X2)\times(32.915)] \quad (5)$$

Where:

Y = Prediction of 28 days mean strength
X1 = The 7 days mean strength
X2 = TiO_2

The SEE was calculated using the equation:

$$\text{SEE} = \sqrt{(\Sigma(Y-Y')2/(N-1))}$$

Where:

Y = Actual values
Y' = Predicted values

The calculated SEE is 6.5 kPa.

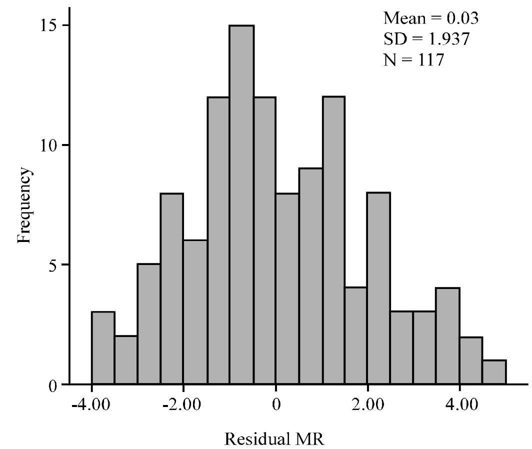

Fig. 5: Histogram the x-axis represents the residuals whiley-axis represents the frequency

Analysis of the residuals for the prediction equation: Furthermore, the difference between actual values and those of the prediction equation (i.e., the residuals) were examined for normality, linearity and homoscedasticity.

The residuals were normally distributed as assessed by a histogram (bell-shaped curve) and the Kolmogorov-Smirnov test with a p-value larger than 0.05 (Table 10 and Fig. 5). The residuals also demonstrated normality when observed with the QQ plot as all points lay close to the 45° line. Values were scattered linearly as demonstrated by a scatter plot between the obtained and predicted values. The correlation between obtained and predicted values is r = 65.1 ($p<0.05$) (Fig. 5-7).

This study analyzed the use of the Shewart-$\bar{x}$ and CUSUM control charts and the process capability of producing cement at optimal strength for 7 and 28 days measurement. The study also predicted 28 days mean strength of cement by using variables associated with the physical and chemical composition of the cement and early cement strength.

First objective: The primary first aim of the current study is to determine whether it is feasible to use the Shewart-$\bar{x}$ control chart in statistical process control for the mean strength of cement at 7 and 28 days. As hypothesized, it is feasible to use the Shewart-$\bar{x}$ control chart. It is also explained by Gibbs and Harrison (2010), Carson and Yeh (2008) and Novokshchenov *et al.* (2006) that Shewart control charts have widespread use in the concrete industry as a tool for quality control. They explained that

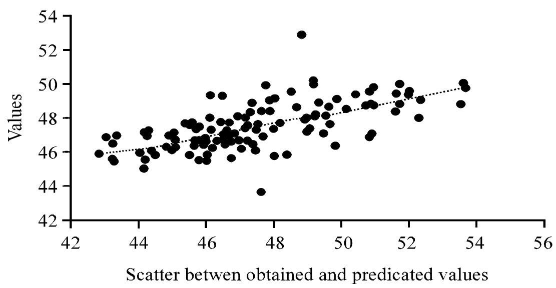

Fig. 6: QQ plot the x-axis represents the observed value while y-axis represents the expected normal

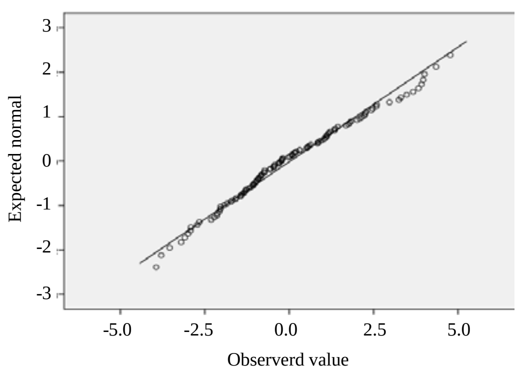

Fig. 7: Scatter plot x-axis represents the observed values and the y-axis represents the predicted values. The small dotted line is the regression line. The big dots are the plotted points and half of these points are on one side of the regression line

the continued monitoring of cement strength remains important. The reasons for this is that some of the possible causes thereof (incorrect recipe of raw materials, faulty machinery, weigh-scales loosing accuracy, a new-mill-batcher or -kiln, contamination of raw materials) could be detected so that early corrective action could be taken.

As depicted in Fig. 4, the process was well in-control for 28 days mean strength (all observations fall within and above the lower-control limits). There are two or three borderline observations for lower limits but the mean strength of subsequent observations were well within limits. Seven or more consecutive points on the lower-side of the target mean were seen from data point 101-110 (26 April to 15 May, 2016) for both 7 and 28 days mean strength. This finding reiterates the strong correlation obtained between 7 and 28 days mean strength ($r = 0.5$, $p<0.05$). The process engineer explained that a combination of a leaking gate above the silo and pressure equalising vents caused contamination with a different cement type. This led to higher residues and non-deleterious materials causing reduced strengths over this period. Seven or more consecutive points on the lower-side of the target mean were seen from data point 6-16 (28 September to 22 October, 2015) for 7 days strength. However, the process engineers could not identify the cause of lower mean strength over this period and corrected this by mixing the cement finer to obtain stronger subsequent values. Particle size decreased from 10.3-8.0 μm over these periods. From point 17 and 111 onwards, the weaker strength was rectified. There are three observations that fall outside the upper control limits (28 days mean strength). However, the mean strength of the cement was the variable of interest, values above the upper-control-limits were not representative of failure or out-of-control values but were there to guide the process engineer. Values above the upper-control-limit are representative of strong cement mixtures and meet SABS approved standards (SABS., 2013). Additionally, seven or more consecutive points on the upper-side of the target mean were observed from points 50-62 (7 days mean strength).

One observation "fell" below the lower permissible limits of agreement for 7 days mean strength. Since, there is only 0.3% probability that this resulted due to natural variation (Gibbs and Harrison, 2010; Carson and Yeh, 2008), it is likely that the reason presented by the process engineer resulted in the extreme value and subsequently immediate action was taken by the plant managers. The date of this observation was 31 October, 2015. The process engineer explained that at this date high MgO clinker was produced from a test stockpile. Normal clinker MgO is about 1.8 and this particular batch MgO was 3.8 which negatively affected the cement performance. After remedial action, subsequent observations were again well within the allotted limits of agreement.

To conclude, the $\bar{x}$-Shewart control charts provided information as to whether major shifts transpired in the data set. From, the information described above, no major noticeable shifts occurred for 7 and 28 days mean strength. However, lower mean strength values for data points 6-16 and 101-112 was identified and rectified. As such, it is feasible to use the $\bar{x}$-Shewart control chart in statistical process control for the mean strength of cement at 7 and 28 days.

Second objective: The secondary aim of this study was to determine the feasibility of using the tabular CUSUM control chart at 7 and 28 days. The CUSUM control chart as it provides a vivid illustration of any changes (Gibbs and Harrison, 2010). As hypothesized, it is feasible to use the CUSUM control chart. Positive and negative values presented in the tabular CUSUM for both 7 and 28 days strength were demonstrated randomly with these values cancelling each other out, (Gibbs and Harrison, 2010). Concerning 28 days mean strength and as studied in Table 5, column C_i which represents the lower control limits demonstrates that the process was in-control for all 117 data points. This is excellent news for the cement factory as their most stable and best-represented strength measure (28 days) reported values meeting lower-control-limits. This is probably due to good quality raw materials, good cement mixture, excellent clinker material, optimal and well-calibrated equipment and well-managed control processes. On the other hand, C_i+ (representing upper control limits) was greater than H (12) at data point 60. Also, C_i+ was greater than H (13) at data point 45 for 7 days strength. However, caution is not warranted as strong values of cement strength is indicative of excellent cement quality. It does however provide valuable feedback to the process engineer as it indicates small shifts of the mean. This finding merely alerts the process engineer that the cement does not have to be milled so finely.

The only problem studied in the tabular CUSUM chart was located for lower strength values concerning 7 days strength. It is possible to determine at what point the process went out-of-control (Gibbs and Harrison, 2010). This finding does indicate a small shift in the process mean and immediate action should be taken by the process engineer to rectify the imbalance. This data point coincides with the findings from the $\bar{x}$-Shewart control at this same time-point (Fig. 6). Although, data points were well within permissible control limits, a sequence of 7 or more points below the mean strength of cement was identified as the problem. Corrective action according to the out-of-control action plan was taken, so that, cement strength values could return to previous values within permissible criteria. This was done by milling the cement finer as the second step “does the particle size of cement conform to the correct density?” in the out-of-control action plan was negatively affected. It is clear from the original data-set that values improved from data point 113 to 116 and were above the mean levels of strength.

Third objective: The third aim of the current study was to determine whether the process meets certain requirements or specifications as set out by the manufacturer. The hypothesis presented in Chapter 1 can be accepted for 28 days mean strength but not for 7 days mean strength.

The Cp value for mean 28 days cement strength is >1 reflecting that the natural tolerance limits are within the upper and lower specification limits with a small amount of non-conforming units (Montgomery, 2012). In this case, the process uses much less of the tolerance band. The process capability 7 days strength was also calculated but is not deemed necessary as it does not reflect the actual strength of the final cement product. However, the analysis was run and reported a Cp value of <1, demonstrating that the process uses more than 100% of the tolerance band and is yield-sensitive with a large amount of non-conforming units found (Montgomery, 2012). However, the process engineer at the cement-plant advised us to use this value as a guideline and that final assessment should result from the 28 days calculation. The calculation of 28-mean strength of cement is more robust compared to 7 days mean strength as the concrete allowed to “set” more optimally.

Fourth objective: Lastly, the fourth purpose of the current study was to determine which variables associated with 7 days strength can be used to accurately predict 28 days mean strength. The reason for this is that waiting 28 days (four weeks) to apply statistical quality control could have lasting repercussions (Novokshchenov *et al*., 1997). With the use of 7 days strength, adverse trends will be detected more rapidly rather than three weeks later with 28 days mean strength (Gibbs and Harrison, 2010). The 7 days strength rather than 2 days strength is preferred as 2 days strength introduces greater variability due to the initial temperature of the concrete (Dewar and Anderson, 2003). Also, predictions need to be developed separately for different types of cement as there are no “universal” equations (Novokshchenov *et al*., 1997). As far as we are aware, no predictions are available for the cement type “all-purpose” cement as analysed in the current study.

The hypothesis may be partially accepted. The hypothesis can be accepted as 7 days strength may be used to predict 28 days strength. However, the chemical variable, $Ti0_2$ also significantly contributed to the model. Together, these two variables (7 days strength and TiO_2) predicted 35.5% of the variance in the dependent variable with a SEE of 6.5 kPa. In the cement industry it is known that minor elements (like TiO_2) can enhance the strength of cement but it is very specific to the concentration and ratios with other elements and also the physical characteristics. There is evidence that TiO_2 between 0.2% and 1% can be beneficial to strength development in cement (Bhatty, 1995). Contradictory to this finding, another study found that TiO_2 induced setting time retardation and no significant impact on strength development (Kumar *et al*., 2014). Although, 7 days strength and TiO_2 predict 28 days mean strength with 35.5% accuracy, 65.5% of the variance remain unexplained. Consequently, the complexity and multidimensionality of cement manufacturing is appreciated (Gibbs and Harrison, 2010). However, the adjusted R^2 value is not much smaller than the R^2 value, demonstrating that the amount of variables entered did not affect the model negatively.

Previous studies have also conducted multiple linear regression analysis to predict cement strength. A study by Garcia-Casillas *et al.* (2007) demonstrated that the chemical-mineralogical synthesis of cement (%C3S, %C2s, %C3A, %C4Af) predicted Portland cement strength in Mexico. Unfortunately, the cement factory where our data was collected did not have the necessary equipment to analyse the chemical-mineralogical synthesis of the cement. Also, they did not include early cement strength (2 or 7 days) in their prediction models. Another study by Tsamatsoulis (2012) reported that cement fineness and early strength did significantly predict 28 days mean cement strength (R^2 values were not reported). The fact that cement fineness or particle size did not contribute to the regression model in the current study is unknown. It could possibly be explained by the fact that particle size showed a weak correlation with cement strength, although significant ($r = 0.26$; $p<0.05$). In another study by Kheder *et al.* (2003) carried out in Iraq, the importance of ultrasonic pulse and mortar density was reported to be useful in determining 28 days mean strength. They obtained high coefficients of determination ($R^2 = 0.90$) with low standard errors (1.89). Again, as previously stipulated the current study did not have access to sophisticated equipment such as the "non-destructive indicating tester" to assess "ultrasonic pulse at 150 kHz".

CONCLUSION

Although, our regression model was significant and did not violate the assumptions of linear regression analysis, the coefficient of determination was 35.5. As a consequence, the model can be used for predictions but should be done cautiously as 64.5% of the variance remains unexplained. The studied cement factory did not have sophisticated equipment to assess ultrasonic pulse, particle size and chemical-mineralogical synthesis of the cement.

LIMITATIONS

Equipment needed to measure ultrasonic pulse, particle size and chemical-mineralogical synthesis of the cement was not up-to-date or not of the latest technology and so affected the accuracy and strength of the prediction model. Also, using "in-control" data from a previous time-period may not be applicable to future time periods, although this method is globally used in statistically quality control. This is especially true in situations such as the cement industry where targets strengths remain unchanged.

RECOMMENDATIONS

Recommendations elicited from this study are provided in bullet points:

- $\bar{x}$-Shewart and CUSUM control charts are feasible to measure and monitor 7 and 28 days cement strength
- The monitoring of out-of-control data values was well detected with $\bar{x}$-Shewart and CUSUM control charts
- For this cement plant and for this cement type, the process does meet requirements and specifications as set out by the manufacturer
- The 7 days strength and TiO_2 significantly predict 28 days mean strength of cement with a coefficient of determination $R^2 = 0.35$ and SEE of 6.5 kPa
- Use of control charts lowers the amount of waste in cement manufacturing

SUGGESTIONS

A future study should run the analysis again when the studied cement plant obtains newer and more technologically advanced equipment and machinery to directly measure clinker quality and content. The measurement of variables associated with the clinker content will improve the prediction of the regression model. A future study should add the exponentially weighted moving average control chart to the analysis to determine the feasibility thereof in cement manufacturing. Future studies should also focus on other important variables analyzed in cement manufacturing such as the consistency of the cement. Lastly, future studies should also be performed to determine the feasibility of control charts with different types of cement. Especially, weaker cements which demonstrate more variability and lower mean strengths should be evaluated.

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