Control Charts and Models Predicting Cement Strength: A Strong Tool Improving Quality Control of Cement Production

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Abstract: - The present study aims to describe control charts techniques daily applied in the quality control of cement production and at the same time to develop mathematical models predicting the cement strength at 28 days based on early strength as well as on physical and chemical characteristics of the cement types investigated. As a result of both tools combination, a PI controller is constructed, regulating the 28 days strength around a target, moved always inside the limits prescribed in the existing cement standards. The models performance is investigated by analyzing the Type I and Type II errors. The implementation of these techniques in the daily quality control has been proved as an important factor of quality improvement by maintaining a low variance of typical strength.

Key-Words: - Strength, Control Chart, Model, Cement, Prediction, Clinker, Quality Control

1 Introduction
Control charts techniques constitute a widely applied and useful tool in investigating of different characteristics of various processes and products. Some of them have been standardized in ISO 8258:1991 standard. In the building materials sector and specifically for cement and concrete, several examples of implementation are referred [1, 2, 3, and 4].

As concerns quality data, control charts are frequently applied to the results of 28 days compressive strength and depending on their position; respective actions are taken so that the strength is maintained near to a desired target. A first disadvantage of this methodology is that the delay of 28 days of receiving results is enough long and likely the reasons causing strength divergence already have disappeared. A second drawback related with the delay of measuring process is that if the producer does not undertake any action during this period, cement outside of specifications will be probably produced. In case of absence of separate facilities to stock the uncontrolled cement quantities, a quality accident will happen. The following practices of avoiding low strength results are usually implemented: (1) conservative cement compositions and (2) empirical estimation of the 28 days strength according to the early strength results, based on the past experience. The first action results in a higher cement cost, while the second one in an increase of the strength variance due to the empirical approach.

An effective operation of quality control needs corrective action when a deviating trend occurs either by understanding and eliminating the cause of the disturbance or by taking compensatory action until the disturbance sources or the process changes would be fully understood. When a variable is to be measured after a relatively long time interval, as it happens with the 28 days strength measurement, the models predicting this variable are very useful in case their standard error is acceptable. Several studies describe numerous modeling techniques. Depending on the degree of complexity and data availability, the different models select as inputs, some of the subsequent physical, chemical and mechanical characteristics of the cement and clinker: Fineness, clinker mineral compounds, content of main oxides, cement composition and early cement strength. The modeling is based on linear or non-linear regression of existing data, fuzzy logic or neural networks. Odler [5] presented a review of the basic correlations between 28 days strength of cement and clinker mineral composition, cement fineness and sulfates content. Tsivilis et al. [6] developed a regression model for the prediction of Portland cement compressive strength after 2, 7 and 28 days where the importance of chemical, mineralogical and fineness factors was pointed out. Linear or non-linear regression models are described in [7, 8, 9, 10,11, 12, 13, 14, 15]. Another trend of modeling in the field of cement strength prediction is the usage of fuzzy logic and neural networks [16, 17, 18, 19, and 20]. The majority of these models
utilize results of cement produced in industrial or laboratory scale aiming to estimate the corresponding model parameters. The minimum distance between experimental and computed strength is used as optimization criterion.

A disadvantage of some models is the requirement of additional analyses that usually are not made on daily basis in the industrial production. Implementation of such models in the daily quality control of cement plants is hardly found in the published literature. The predictions are accurate inside their field of application, i.e. for the given cement types, physical and chemical properties of cement and clinker and raw materials used. Therefore there are not “universal” equations deriving sufficient predictions for any cement and clinker quality. Taking into account the above restrictions, the predictive models constitute extremely useful tools. The objective of the present study is to combine the control chart technique with strength prediction models. Afterwards, based on this combination, a PI controller is constructed, regulating the 28 days strength around a target. The resulting tool is constantly applied in Halyps cement plant in long term. The data of each cement mill (CM) are treated separately. In the present paper CM6 is chosen producing two cement types conforming to the norm EN 197-1:2008: CEM A-L 42.5 and CEM II B-M (P-L) 32.5. In the subsequent sections, the results of six continuous years are analyzed. Based on these results an evaluation of implementation is performed and opportunities for improvement are investigated.

2 Building the Control Charts

To create a control chart, not only the central line (CL) is necessary, based on the established target, but also the lower and upper control limits, LCL and UCL respectively. The calculation of these two limits needs the knowledge of the “natural” standard deviation of the process. Its value is computed from the whole population after the subtraction of the outliers. This latter subpopulation consists of highly diverging points where the source of deviation is unknown or known but abnormal. In case the source of abnormality is known, quality department must take action to eliminate this source.

Natural deviation, σ, is computed as described in section 2.1 from the absolute differences, R, between two consecutive values, according to ISO 8258:1991 [21]. To investigate the trend of the average values, the exponentially weighted moving average (EWMA) is considered as developed by Newubauer [22] and Pan [23].

2.1 R-Charts and Natural Deviation

As natural deviation, σ, of a quality or process variable the standard deviation is considered of a small subgroup of the total population, which means that it is intrinsic characteristic of the variable. As long as more and of bigger intensity are the disturbances in which concrete causes can be attributed, so much bigger is the difference between natural and overall standard deviation. In case there are not multiple measurements during a short time period, then σ is calculated by the absolute difference R, between two successive values, assuming that disturbances in a narrow time interval are of low intensity. The quality data of a cement type produced in the same CM are investigated. As time interval the difference between two consecutive production days is taken, which usually is one day. According to ISO 8258:1991 the subsequent procedure is followed for a variable X:

(i) For the day i, \( R(i) \) is computed from formula (1):

\[
R_i = |X_i - X_{i-1}|
\]  

(ii) The average difference \( R_{\text{Aver}} \) is calculated over all the inspection period.

(iii) \( R_i \) values which are higher than a permissible maximum difference, \( R_{\text{Max}} \), given by equation (2) are characterized as outliers and excluded from further calculations.

\[
R_{\text{Max}} = 3.267 \cdot R_{\text{Aver}}
\]  

(iv) After the outliers exclusion a new \( R_{\text{Aver}} \) is determined and the steps (ii)-(iii) are repeated up to the outliers are disappeared.

(v) The natural deviation of the variable is calculated by formula (3). This value represents the current natural limits of the quality or process variable.

\[
\sigma = 0.8865 \cdot R_{\text{Aver}}
\]  

As an example of application, the R-chart for several quality characteristics of CEM B-M (P-L) 32.5 produced in CM6 during one year is shown in Figure 1. The following variables are processed: (1) %sulfates content, %SO3; (2) %clinker content, %clinker; (3) %residue at 40 microns sieve, R40; (4) 1 day compressive strength, str_1 (Mpa); (5) 7 days
compressive strength, \( \text{str}_7 \) (Mpa); (6) 28 days compressive strength, \( \text{str}_{28} \) (Mpa). The natural deviation and the standard one are connected with equation (4), where \( s_{\text{Other}} \) is the standard deviation due to other sources not inherent in the process. When these sources are discovered and progressively eliminated, then \( \sigma \) and \( s \) are approaching. It shall be mentioned that the laboratory repeatability and short term reproducibility are included in the natural deviation.

\[
s^2 = \sigma^2 + s_{\text{Other}}^2
\]  

(4)

Figure 1. Typical R-chart for cement quality characteristics.

2.2 Control Charts of Moving Average
Processing of the average values trends is performed via EWMA control charts, because this kind of statistics can detect small trends of variation. For a variable \( X \) these charts are built according to the following procedure:

(i) For time \( i=0 \) the initial moving average \( Y(0) \) is expressed by the relation (5):

\[
Y(0) = X(0)
\]  

(5)

(ii) For a parameter \( \lambda \), where \( 0 < \lambda \leq 1 \), the statistic \( Y(i) \) is computed by the recursive formula (6):

\[
Y(i) = \lambda \cdot X(i) + (1 - \lambda) \cdot Y(i - 1)
\]  

(6)

(iii) If \( \lambda=1 \), the moving average values become equal to the current ones. As long as smaller \( \lambda \) value is, the rate of change becomes lower and trends of higher duration can be revealed.

(iv) The central line of the chart is equal to the target, \( X_T \).

(v) The standard deviation \( \sigma_{\text{EW}} \) of the statistic \( Y \) is computed from the natural deviation of variable \( X \) according to the formula (7):

\[
\sigma_{\text{EW}} = \sigma \cdot \sqrt{\frac{\lambda}{2 - \lambda}}
\]  

(7)

(vi) The central line, upper and lower control limits are determined from equations (8):

\[
\begin{align*}
CL &= X_T \\
LCL &= X_T - 3 \cdot \sigma_{\text{EW}} \\
UCL &= X_T + 3 \cdot \sigma_{\text{EW}}
\end{align*}
\]  

(8)

2.3 Application of Natural Deviation Principle
To investigate the differences under natural and standard deviation of the 28 days strength, six year results are considered, divided in periods of one year for both cement types. The values of \( s \), \( \sigma \) and \( s_{\text{Other}} \) are shown in Table 1.

Table 1. Natural and standard deviation results

<table>
<thead>
<tr>
<th>Year</th>
<th>( s )</th>
<th>( \sigma )</th>
<th>( s_{\text{Other}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM B-M (P-L) 32.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>1.69</td>
<td>1.23</td>
<td>1.16</td>
</tr>
<tr>
<td>2007</td>
<td>1.86</td>
<td>1.29</td>
<td>1.34</td>
</tr>
<tr>
<td>2008</td>
<td>1.72</td>
<td>1.31</td>
<td>1.11</td>
</tr>
<tr>
<td>2009</td>
<td>2.18</td>
<td>1.46</td>
<td>1.62</td>
</tr>
<tr>
<td>2010</td>
<td>1.97</td>
<td>1.10</td>
<td>1.63</td>
</tr>
<tr>
<td>2011</td>
<td>1.88</td>
<td>1.11</td>
<td>1.52</td>
</tr>
<tr>
<td>CEM A-L 42.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>2.38</td>
<td>1.68</td>
<td>1.69</td>
</tr>
<tr>
<td>2007</td>
<td>2.72</td>
<td>2.12</td>
<td>1.70</td>
</tr>
<tr>
<td>2008</td>
<td>2.36</td>
<td>1.96</td>
<td>1.31</td>
</tr>
<tr>
<td>2009</td>
<td>2.40</td>
<td>1.87</td>
<td>1.50</td>
</tr>
<tr>
<td>2010</td>
<td>2.35</td>
<td>1.63</td>
<td>1.69</td>
</tr>
<tr>
<td>2011</td>
<td>2.01</td>
<td>1.58</td>
<td>1.24</td>
</tr>
</tbody>
</table>

Natural deviation represents the ability of the Quality Control:

(i) to achieve a low short term reproducibility as regards strength measurement

(ii) to keep the main factors affecting the cement strength as clinker and SO3 content, fineness, clinker quality, near to the decided targets. The size of the remaining variance, \( s_{\text{Other}} \), provides to the quality department the margins of improvement under the current conditions of Process Control. By searching, detecting and eliminating the sources of \( s_{\text{Other}} \) the overall deviation and the natural one are reduced.
### 3 Mathematical Models Predicting Strength

The modeling of 28 days cement strength is based exclusively on industrial data of cement produced in CM6 of Halyps cement plant during six years. Two cement types of different composition and strength are considered, conforming to the norm EN 197-1:2008: CEM A-L 42.5 and CEM II B-M (P-L) 32.5. The first type, except clinker and gypsum, contains also limestone, while the second one pozzolane and limestone, as main components. More than 1700 data sets of cement fineness, composition and strength were utilized for this purpose. The main cement constituents are calculated one from first or second model, M = number of experimental sets, k = number of independent variables for the first or second model. The full set of data involves all results of the two mentioned cement types from 2006 to 2011. This set is divided in five subgroups of data in a progressive way: Data of (a) 2006-07; (b) 2006-08; (c) 2006-09; (d) 2006-10; (e) 2006-11. To calculate the parameters of the first subgroup the subsequent procedure is followed:

(i) Initial values of the model parameters are determined using multiple regression for subset (a).
(ii) With t-test and 95% probability, the non significant variables are excluded.
(iii) Steps (i) and (ii) are repeated iteratively until all coefficients of the resulting model become statistically significant.
(iv) Except the residual error, $s_{res}$, the total variance of the experimental data is computed, $s_{tot}^2$ and the variance captured by the model, $s_{mod}^2$, given by formula (11).

$$s_{Mod}^2 = s_{tot}^2 - s_{res}^2$$

(v) The model regression coefficient, $R_M$, is computed by equation (12).

$$R_M = \frac{s_{Mod}}{s_{Tot}}$$

(vi) For the parameters ($A_i$, $A_{ii}$, $A_{ij}$) computed for the subgroup (a), multiple regression and steps (iv), (v) are repeated for the next subgroups (b), (c), (d), (e).

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\text{Str}_{28_7}$</th>
<th>$\text{Str}_{28_1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>35.54</td>
<td>4.171</td>
</tr>
<tr>
<td>%Clinker</td>
<td>-0.313</td>
<td>-0.313</td>
</tr>
<tr>
<td>Sb/10$^4$</td>
<td>32.0</td>
<td>20.75</td>
</tr>
<tr>
<td>R40</td>
<td>1.075</td>
<td>-0.067</td>
</tr>
<tr>
<td>STR 1</td>
<td>0.914</td>
<td></td>
</tr>
<tr>
<td>%Clinker*Sb/10$^4$</td>
<td>-0.420</td>
<td></td>
</tr>
<tr>
<td>%Clinker*R40</td>
<td>-0.014</td>
<td></td>
</tr>
<tr>
<td>%Clinker*STR 1</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>Sb*R40/10$^4$</td>
<td>2.164</td>
<td>-0.026</td>
</tr>
<tr>
<td>STR 1*STR 7</td>
<td>-0.013</td>
<td></td>
</tr>
<tr>
<td>%Clinker$^2$</td>
<td>5.49*10$^{-3}$</td>
<td>3.05*10$^{-3}$</td>
</tr>
<tr>
<td>STR 1$^2$</td>
<td>-0.060</td>
<td>0.036</td>
</tr>
<tr>
<td>$s_{res}$</td>
<td>1.843</td>
<td>1.451</td>
</tr>
<tr>
<td>$R_M$</td>
<td>0.962</td>
<td>0.977</td>
</tr>
</tbody>
</table>

The parameters values and the corresponding variances for the full set of data are shown in Table
3. The following non-linear variables passing the t-test are found: \%Clink-Sb/10^4, \%Clink-R40, \%Clink-Str_1, Sb-R40/10^4, Str_1-Str_7, \%Clink^2, Str_1^2. The parity plots of the two models are demonstrated in Figures 2 and 3.

Figure 2. Calculated vs. actual 28 days strength for the first model

Figure 3. Calculated vs. actual 28 days strength for the second model

4 Design of Strength Controller

The combined action of control charts and of models predicting strength, analyzed in sections 2 and 3, offers the possibility to build a controller regulating the 28 days strength around a predefined target. A proportional – integral controller (PI) is designed. The moving average of the result of first model - Str_28_1=F(\%Clinker,Sb,R40,Str_1) - constitutes the controller input. This variable, named EW_Str, is the process variable of the feedback loop. Clinker content, \%Clink, is the control variable. The moving average function, calculated from equation (6), can be considered as a filter of the Str_28_1 variable.

A block diagram of the transfer functions constituting the closed loop is given in Figure 4.

Transfer function \( G_{Meas} \), involves the measurement of the physical, chemical and mechanical cement properties. The corresponding delays, expressed in days, appear in Laplace form. The control strategy is to regulate EW_Str variable in order to achieve a Str_28 of minimum variance around the target Str_T. The digital implementation of the controller equation is given by the set of equations (13).

\[
Cl_{Instr}(I + 1) = Cl_{Instr}(I) + k_p \cdot [e(I) - e(I - 1)] + k_i \cdot e(I)
\]

\[
e(I) = Str_T - EW_Str(I)
\]

(13)

Where the last production date is I and the next one is I+1. \( Cl_{Instr}(I) = \% \text{clinker of the nominal composition of the day } I \). If I and I+1 are successive dates (for example 3 July and 4 July), str_1(I) has not been yet measured at date I+1. In this case J=I-1 and Str_28_1(I-1) is calculated using equation (9) and values of \%Clinker(I-1), R40(I-1), Sb(I-1), Str_1(I-1). On the contrary if dates I, I+1 are discontinuous, then Str_1(I) exists and prediction Str_28_1(I) is determined from the corresponding physical, chemical and mechanical data. The proportional and integral coefficients of the controller are \( k_p, k_i \), respectively. The values of these two coefficients have been calculated with trial and error by simulating the controller operation using data of older years. A small dead band has been also added to the PI controller. Thus, when the proposed actions are very small are neglected. Moreover the regulator includes permissible zone of control variable, i.e. minimum and maximum limits of clinker content, so that the percentage of clinker is found permanently inside the limits provided by the cement standard.

With the implemented regulation small changes in the composition are proposed- if they are required - so that two actions destructive for the product uniformity are avoided: (i) intervals of sluggishness followed by abrupt changes; (ii) continuous sudden changes. It must be noticed that the automatic control does not substitute but assists the daily experience and actions of the quality and process managers.
5 Results and Analysis

5.1 Implementation of the Strength Predicting Models

As mentioned in section 3 the entire set of data has been divided in five subgroups and the model parameters are estimated. The model parameters of each subgroup are applied in the next year. For example the parameters of the subgroup (a) – years 2006-2007 – are applied during 2008. The above procedure has been applied continuously from 2008 to 2011. In Tables 4 and 5 the following results are demonstrated for the first and second model correspondingly: (i) model parameters; (ii) residual error of each subset, $s_{res}$ and of each cement type, $s_{resBM}$, $s_{resAL}$; (iii) standard deviation of subset $s_{Tot}$ and of each cement type, $s_{TotBM}$, $s_{TotAL}$; (iv) model regression coefficient $R_M$; (v) residual error after the application during the next year, $s_{next}$ and regression coefficient $R_{next}$; (vi) The ratios $R_s=s_{next}/s_{res}$ and $R_R=R_{next}/R_M$. From the results of Tables 4, 5 the subsequent remarks can be made:

(a) For the first model the residual error for each cement type and for total data, $s_{res}$ are significantly lower than the corresponding standard deviation.

(b) The application of the first model to next year data results in a relative increase of $s_{next}$. The ratio $s_{next}/s_{res}$ is found within the zone [1.05, 1.22]. The corresponding ratio of regression...
coefficients belongs to the interval [0.938, 0.965]. These results can be considered as adequate in regulating the cement strength.

(c) The second model is much more accurate from the first one as it takes into account the actual 7 days strength. Its application to next year data derives ratios $R_s$ ranging from 0.96 to 1.08.

(d) Due to the much bigger delay time of this model compared with the first one, in general it cannot be utilized for direct control purposes. However, it can be used as additional information for the cement composition adjustment.

Table 5. Parameters of model str_28_7

<table>
<thead>
<tr>
<th></th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const</td>
<td>7.080</td>
<td>2.857</td>
<td>-1.693</td>
<td>2.630</td>
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<tr>
<td>Sb/10^4</td>
<td>24.74</td>
<td>46.75</td>
<td>54.10</td>
<td>30.98</td>
</tr>
<tr>
<td>Str_1</td>
<td>0.964</td>
<td>1.038</td>
<td>0.887</td>
<td>0.410</td>
</tr>
<tr>
<td>Str_7</td>
<td>0.276</td>
<td>0.313</td>
<td>0.508</td>
<td>0.641</td>
</tr>
<tr>
<td>Clink · Sb/10^4</td>
<td>-0.455</td>
<td>-0.787</td>
<td>-0.888</td>
<td>-0.528</td>
</tr>
<tr>
<td>Sb·R40/10^4</td>
<td>0.139</td>
<td>5.2·10^{-2}</td>
<td>0.143</td>
<td>7.2·10^{-2}</td>
</tr>
<tr>
<td>Str_1·Str_7</td>
<td>3.1·10^{-2}</td>
<td>3.4·10^{-2}</td>
<td>1.7·10^{-2}</td>
<td>8.2·10^{-3}</td>
</tr>
<tr>
<td>%Clink</td>
<td>3.5·10^{-4}</td>
<td>4.1·10^{-4}</td>
<td>4.5·10^{-4}</td>
<td>3.5·10^{-4}</td>
</tr>
<tr>
<td>Str_1^2</td>
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<td>-0.081</td>
<td>-0.048</td>
<td>-0.016</td>
</tr>
<tr>
<td>Sres</td>
<td>1.43</td>
<td>1.42</td>
<td>1.41</td>
<td>1.40</td>
</tr>
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<td>SresBM</td>
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<td>1.27</td>
</tr>
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<td>SresAL</td>
<td>1.72</td>
<td>1.68</td>
<td>1.69</td>
<td>1.64</td>
</tr>
<tr>
<td>sTot</td>
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<td>6.93</td>
<td>6.86</td>
<td>6.71</td>
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<td>sTotBM</td>
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<td>2.56</td>
<td>2.55</td>
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<td>RM</td>
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<td>0.979</td>
<td>0.979</td>
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<td>snext</td>
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<td>Rsnext</td>
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<td>0.978</td>
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<td>Rs</td>
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<tr>
<td>RG</td>
<td>0.997</td>
<td>1.00</td>
<td>0.990</td>
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</tbody>
</table>

5.2 Combined Implementation of the Control Charts and PI controller

The monitoring of the 28 days strength moving average by using the first model and the application of the PI controller are shown in Figures 5, 6 for 2010 and CEM B-M (P-L) 32.5, CEM A-L 42.5 correspondingly. Equation (6) is applied with $\lambda=0.5$. Due to the implementation of the PI controller, clinker composition is changing according to the 28 days strength predicted from the first model. The following P and I coefficients are utilized. CEM B-M 32.5: $k_p=0.3$, $k_i=0.4$; CEM A-L 42.5: $k_p=0.2$, $k_i=0.4$. The zone placed for the minimum and maximum clinker is much narrower than the one permitted from the norm that is 15% for both cement types.

Figure 5. Control chart of actual 28 days strength, predicted from 1 day and clinker content for CEM B-M (P-L) 32.5.

Figure 6. Control chart of actual 28 days strength, predicted from 1 day and clinker content for CEM A-L 42.5.

Figure 7. Control chart of actual 28 days strength and predicted from 7 days for CEM B-M (P-L) 32.5.
Due to the efficient implementation of the analyzed techniques, 28 days strength varies in a span noticeably narrower than the one allowed by EN 197-1, which is 20 Mpa. Moreover, clinker content has been kept near to the low limits provided by the cement standard. The above actions result in a good level of strength standard deviation.

![Figure 8](image)

Figure 8. Control chart of actual 28 days strength and predicted from 7 days for CEM A-L 42.5.

The control charts of the 28 days strength predicted from the second model and the actual one are shown in Figures 7, 8 for the cement types mentioned. Owing to the very good level of prediction but the higher delay, the second model can be used to evaluate more permanent trends of the strength evolution.

5.3 Evaluation Based on Type I and Type II Errors

To define the Type I and Type II errors, firstly the setting up of a criterion and an assessment procedure are required. A Type I error occurs when an actually conforming product to this criterion is considered as non-conforming according to the assessment procedure. In this case the producer suffers, because he has taken an action to correct the non-conformity. On the contrary a Type II error happens if an actually non-conforming product is thought as conforming by applying the assessment procedure.

To evaluate the first predicting model, utilized for daily control of the strength, according to this methodology, initially a two side criterion is placed for low and high limits, around the strength target. For a margin of $a_s$ Mpa, the acceptable strength results shall belong to the zone $(A)=[\text{Str}_T-a_s, \text{Str}_T+a_s]$. Afterwards the subsequent cases are examined:

(i) If both actual strength and predicted Str$_{28\_L}$ belong to zone $(A)$ or both do not belong to this zone, then the prediction is correct.

(ii) If actual strength is inside to zone $(A)$ and Str$_{28\_L}$ is out of this zone, then a Type I error arises.

(iii) If Str$_{28\_L}$ is found within zone $(A)$ and actual strength does not, then a Type II error appears.

The estimation of the Type I and II errors is performed in two ways: The models parameters (a) to (d) shown in Table 4 are applied for the data of the year from where they have been extracted and for the data of the next year where they have been applied. This procedure is demonstrated in Table 6. The column (1) of this table corresponds to Type I and II errors inherent in the modeling, while the column (2) corresponds to errors of the model implementation in daily basis. For each year the strength target decided from the plant is considered.

![Figure 9](image)

Figure 9. Type I, II errors inherent in modeling.

![Table 6](image)

<table>
<thead>
<tr>
<th>Set of Parameters</th>
<th>Inherent Errors (1)</th>
<th>Implementation Errors (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>2006-2007</td>
<td>2008</td>
</tr>
<tr>
<td>(b)</td>
<td>2008</td>
<td>2009</td>
</tr>
<tr>
<td>(c)</td>
<td>2009</td>
<td>2010</td>
</tr>
<tr>
<td>(d)</td>
<td>2010</td>
<td>2011</td>
</tr>
</tbody>
</table>

Per type of error, the probability of occurrence is computed by counting the number the error appears and dividing with the total number of strength data. The results are depicted in Figures 9, 10. The margin $a_s$ is permitted to vary from 2 to 6 Mpa.

From the curves of type I and II errors as function of margin $a_s$, the following can be observed:
- For each cement type, there is no significant difference between modeling and application error.
- As regards CEM B-M 32.5, for a strength target of 38 Mpa, a 5% type II error appears in the zone [34.6, 41.4] in Figure 9 and [34.4, 41.6] in Figure 10. The meaning of the above is that there is a probability 5%, the calculated strength to be within these zones and the actual one to be outside.
- The two side zone of EN 197-1 norm for 32.5 cements is [32.5, 52.5] where a 5% type II error is permitted for each one of the two margins.
- As concerns the CEM A-L 42.5 and for a strength target of 50 Mpa a 5% type II error appears in the zone [45, 55] in Figure 9 and [45.4, 54.6] in Figure 10. The corresponding zone of EN 197-1 for cements of 42.5 strength class is [42.5, 62.5].
- The significance of these remarks is that the application of the presented technique to regulate cement strength and composition provides margins adequately narrower than the permissible by EN 197-1, leading to an efficient quality control.

6 Conclusions

In the present study the combination of some statistical tools is implemented in the quality control of cement production. The control charts technique has been connected with multivariable regression models, aiming to forecast the 28 days cement strength. The derived models predict adequately the cement strength using daily analysis data, like clinker percentage, cement fineness and early strength. These models can be characterized as “static”, because for given cement analysis and early strength, the 28 days strength is estimated.

The strength predictions provide the possibility to develop simple PI controllers acting on the cement composition and regulating the 28 days strength. In this case, the EWMA function acts like a filter on the function of strength prediction. The long term implementation of these techniques has been noticeably contributed in improving the cement quality by maintaining a low variance of typical strength.

Aiming in ameliorating the tools daily applied in the quality control of a cement plant, the analysis presented can be extended in the subsequent fields.
- Development of models predicting strength of higher accuracy involving dynamical characteristics of the daily cement production by maintaining the simplicity of implementation.
- Deeper investigation of the EWMA control charts in monitoring of cement properties and utilization of other filters to smooth the trends.
- Parameterization of PI or PID controllers using techniques which take into account the robustness of the control.

References:


