Process control system software (in the context of autoclaved aerated concrete production)

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Abstract. Building industry production shall be considered as a complicated hierarchy system, whose conditions are related to multiple factors. To manage such complicated systems, mathematical modeling methods shall be used to organize awareness of manufacturing parameters, to increase the effectiveness of decisions being made by personnel on different positions and within the process, also to develop construction materials production management systems. In turn, synthesis questions with regard to the management of this process are largely resulted from the deficiency in mathematical model concerned, suitable for practice. Outputs of work on the process control system software for autoclaved concrete production are presents in the article. A justification for the most efficient process control stage is given. A control algorithm is developed for the selected process stage, based on a mathematical model of the end product quality as a function of raw materials demand prepared by authors.

1. Introduction

Building industry production shall be considered as a complicated hierarchy system, whose conditions are related to multiple factors. To manage such complicated systems, mathematical modeling methods shall be used to organize awareness of manufacturing parameters, to increase the effectiveness of decisions being made by personnel on different positions and within the process, also to develop construction materials production management systems. In turn, synthesis questions with regard to the management of this process are largely resulted from the deficiency in mathematical model concerned, suitable for practice.

It is known [1-4] that the key problem, when developing process mathematical models, is the labor required for finding different relations between input coordinates, controlling actions and end product quality. It is determined by the lack and heterogeneity of information of the current process conditions.

The modeling of a multi-stage process complicated with a set of interdependent process coordinates, may be facilitated significantly, if it is considered as a combination of simple members, each of which describes the elementary influence of different coordinates on the end product quality [5-8]. In such a case, input coordinates at a certain stage create the intermediate quality indicator vector, which, in turn, will be a set of input coordinates for the next stage. The schematic of parameter intercorrelation at different process stages in the context of autoclaved aerated concrete production (AAC) is given on Figure 1. With such an interpretation of modeling problems, the key questions are: the selection of the most efficient production management stage, the determination of significant
controlling factors and generation of mathematical end product quality model, as well as the development of a control algorithm for a certain process [9,10].

Figure 1. Schematic of parameter intercorrelation at different process stages in the context of autoclaved aerated concrete production.

2. Selection of the most efficient autoclaved aerated concrete production stage

Upon the analysis of AAC production process, three basic stages have been found: components proportioning and mixing, massive pre-curing and autoclave curing.

In order to decrease dimensions and complexity of the mathematical process model, the most significant end product quality management factors shall be selected. The acquisition of more precise and reliable information with regard to the influence of different controls on the end product features vector will be conducing to the expert information in providing with cause-and-effect relationship between variables and output coordinates [11].

Let’s consider a decision for the best selection of a given number of alternatives (m). In this case, the alternative is meant to be an autoclaved aerated concrete production stage, which is comprised of a set of particular quality coefficients (r). Since the production process of AAC is multistage, and the quality of the product is a combination of many criteria, an integrated assessment model for alternatives as a linear convolution has been selected as a basis [12].

When constructing a model, the numerical value of particular coefficient $k$ for alternative $i$ indicate as $J^i_k$, $i = 1, \ldots, m; k = 1, \ldots, r$, and the importance of particular alternative quality coefficient $x$ indicate as $\nu_k$.

All values of preferences and importance are set numerically in the range from 0 (least significant) to 1 (most significant). Assume the best solution is reached at $k \to \max$.

In this case, the preferability function may be written as follows (equation 1):

$$\text{pr}(x_i) = \sum_{k=1}^{r} \nu_k \cdot J^i_k, i = 1, \ldots, m$$

The best alternative is that for which the following condition is met (equation 2):

$$\text{pr}(x_i) > \text{pr}(x_j), \forall i, j = 1, \ldots, m; i \neq j$$

In order to make a collective decision, the experts have been requested to assess discretely the importance of certain end product indicators on a scale from 1 to 4 (compression strength, average
density, frost resistance, thermal conductivity and output humidity), where 1 – not important, 2 – low
important, 3 – very important, 4 – highly important.

The importance assessment given \( \bar{\nu}_k \) is calculated by equation 3:

\[
\bar{\nu}_k = \frac{\nu_k}{\sum \nu_k}
\]  

(3)

The outputs of expert assessments are given in Table 1.

**Table 1.** Importance of certain end product quality coefficients.

| №  | Quality coefficient                     | Importance, \( \nu_j \) | Importance assessment given \( \bar{\nu}_k \) |
|----|----------------------------------------|-------------------------|------------------------------------------|
| 1  | Compression strength, \( R_{\text{compr}} \), MPA | 3.0                     | 0.21                                     |
| 2  | Average density, \( \rho_{\text{average}} \), kg/m³ | 3.7                     | 0.25                                     |
| 3  | Frost resistance, \( F \), cycles      | 3.2                     | 0.22                                     |
| 4  | Thermal conductivity factor, \( \lambda \), W/m°C | 2.0                     | 0.14                                     |
| 5  | End product output humidity, \( W_m \), % | 2.7                     | 0.18                                     |

Then, the experts determined how controls affected on the improvement of certain end product
features at different process stages (Table 2).

**Table 2.** Assessment of controls effect on end product performance.

| Code | Alternative name       | Assessment value, \( J_k^i \) | pr\( (x_i) \) |
|------|------------------------|-------------------------------|--------------|
|      |                        | \( R \) | \( \rho \) | \( F \) | \( \lambda \) | \( W \) |
| \( x_1 \) | Proportioning          | 3.9 | 3.8 | 3.7 | 3.2 | 3.1 | 0.42 |
| \( x_2 \) | Heat curing            | 3.8 | 3 | 1.3 | 2.9 | 2.1 | 0.31 |
| \( x_3 \) | Autoclave curing       | 3.7 | 1.3 | 1.3 | 3 | 2.9 | 0.27 |

Thus, based on alternatives preference assessment, the quality of autoclaved aerated concrete was
found to be controlled in the most efficient way at the stage of components proportioning
\((x_1 \gg x_2 \gg x_3)\).

### 3. Determination of control factors at the stage of AAC components proportioning

As is known [13], the autoclaved aerated concrete includes lime, Portland cement, siliceous
component, gas-forming agent and water. In Russia, the ratio of components given above is calculated
according to SN 277-80 [14], where the ratios of \( n \) (cement portion in limous-cementing material), \( C_{siw} \)
(siliceous component mass to cementing material ratio), \( B/T \) (water to dry components mass ratio), \( A_{li} \)
(lime activity), \( D \) (concrete grade by density) are necessary and sufficient for material quantity
calculations.

Findings of investigations performed by authors before [15] showed that the AAC quality is also
affected by the siliceous component activity resulted from its instability in time. It is confirmed by the
comparison of stability assessment results for different raw materials with certain quality coefficients
using control charts for input and output data change (Figure 2).

Performance consistency level (lower action line (LAL) and higher action line (HAL) action lines)
is presented by variation lines, which may be expressed with the following equations 4-5:

\[
Y_{HAL} = Y_o (1 + V_w),
\]  

(4)

\[
Y_{LAL} = Y_o (1 - V_w),
\]  

(5)
where $Y_{HAL}$ – higher action line; $Y_{LAL}$ – lower action line; $Y_m$ – estimated value average; $V_m$ – variation coefficient, being calculated by equation 6:

$$V_m = \frac{S_m}{Y_m},$$  

(6)

where $S_m$ – estimated value root-mean-square deviation.

Figure 2. Statistical control chart of raw components quality: a) lime activity index; b) silica content index.

Upon analysis of given data, a relative consistence in lime activity may be noted. However, the same consistence in silica content is not observed. Hence, the ratios of $n$ (cement portion in limous-cementing agent), $C_{sv}$ (siliceous component mass to cementing agent ratio), as well as silica content ($SiO_2$) has been taken as control factors.

4. Mathematical quality control model for autoclaved aerated concrete at the stage of components proportioning

To construct a quality control model for concrete as a function of the factors selected before, methods of experimental design and regression analysis were used [16].

Resulting from the full-scale experiment and processing of data acquired, including the examination of experiment repeatability and coefficient importance evaluation, regression equations 7-11 for describing a variation of AAC quality performance as a function of the factors selected, were obtained:

$$\rho = -7196 + 48305 \times n + 69350 \times n^2 + 5596 \times C_{ca} - 868 \times C_{ca}^2 + 14351 \times SiO_2 -$$

$$-17958 \times SiO_2^2 - 44538 \times n \times C_{ca} - 1783 \times n \times SiO_2 + 57148 \times C_{ca} \times SiO_2,$$

(7)

$$R_{str} = -274.1 + 1392 \times n - 1730 \times n^2 + 223.9 \times C_{ca} - 44.2 \times C_{ca}^2 - 544 \times SiO_2 +$$

$$+ 1814 \times SiO_2^2 + 224 \times n \times C_{ca} - 1131 \times n \times SiO_2 - 280 \times C_{ca} \times SiO_2,$$

(8)

$$F = 14612.6 - 2514.4 \times n + 3911.1 \times n^2 - 11228.5 \times C_{ca} + 2305.1 \times C_{ca}^2 - 24187.3 \times SiO_2 +$$

$$+ 418.7 \times SiO_2^2 + 8597.3 \times n \times C_{ca} + 143.14 \times n \times SiO_2 - 2174.5 \times C_{ca} \times SiO_2,$$

(9)

$$W = -1351.7 + 406.7 \times n - 2277.8 \times n^2 + 659.9 \times C_{ca} - 74.4 \times C_{ca}^2 + 2228.3 \times SiO_2 -$$

$$- 2683.3 \times SiO_2^2 + 683.3 \times n \times C_{ca} - 566.7 \times n \times SiO_2 + 3469 \times C_{ca} \times SiO_2,$$

(10)

$$\lambda = -176.1 + 872 \times n - 1010 \times n^2 + 136.1 \times C_{ca} - 25.32 \times C_{ca}^2 - 421.2 \times SiO_2 +$$

$$+ 48.7 \times SiO_2^2 + 187 \times n \times C_{ca} + 13.14 \times n \times SiO_2 - 987.9 \times C_{ca} \times SiO_2,$$

(11)
where $\rho$, $R_{str}$, $W$, $\lambda$ - response functions of average density, compression strength, frost resistance, humidity and thermal conductivity, respectively.

The comparison of empirical and theoretical values of F-ratio test allows us to say that obtained mathematical models are adequate and allow describing the experimental processes with a probability of 95%. The resulting algebraic equations combined in a system, is a mathematical autoclaved aerated concrete quality control model at the stage of raw mixture components proportioning.

5. Development of the control algorithm for AAC components proportioning

A development basis for autoclaved aerated concrete quality control algorithm was a mathematical model of autoclaved concrete proportioning obtained at the previous stage. The gain in efficiency of autoclaved aerated concrete production control is possible through the use of an integrated autoclaved aerated concrete quality criterion, which is obtained by aggregating the initial set of particular AAC quality coefficients [17-20]. In this context, the integrated quality criterion will be a numeric evaluation, being obtained by aggregating the number of particular criteria $N = \{1, 2, ..., b\}$, the assessments $y_i \in Y$ for which specify the values from the range $Y_i \in \mathbb{N}$ (equation 12).

$$F(\cdot) : Y^b \to Y$$

(12)

that is $y_0 = F(y)$, where $y = (y_1, y_2, ..., y_b) \in Y = \prod_{i=0}^b Y_i$. It is clear that the estimation of integrated assessment $F_0 = F(y_0)$ is only possible, when the vector of particular values $y_0 \in X'$ is known. In general, the fuzzy assessment $y_0$ being obtained by aggregating two particular criteria, may be determined with the following membership equations 13.

$$\mu_{y_0}(y_0) = \sup_{\{y_1, y_2\} \in F(y_1, y_2)} \min\{\mu_{y_1}(y_1), \mu_{y_2}(y_2)\}, y_0 = 1, 4$$

(13)

The vector of particular values $y_0$ has been given and justified before. In this regard, the integrated quality criterion of autoclaved aerated concrete may be presented as follows (equations 14):

$$\tilde{y}_0 = [(y^{R_{str}} \circ y^W) \circ y^\lambda] \circ [y^\rho \circ y^\nu]$$

(14)

Graphically, the integrated quality criterion of autoclaved aerated concrete may be presented as a tree (Figure 3).

![Figure 3. Dichotomic tree of AAC quality integrated assessment.](image)
– «excellent». In this regard, reduction functions are calculated for certain quality values of autoclaved aerated concrete from phase \((y_i)\) to qualimetric space \((\hat{y}_i)\), where on X-axis – physical quantities of end product quality performance, and Y-axis is a qualimetric scale from 1 to 4. For example, the average density reduction function becomes (equations 15):

\[
\begin{align*}
\hat{y}_\rho &= 4, y_\rho \leq 300, \\
\hat{y}_\rho &= 33.77 \times 2.72^{(-0.007 \times y_\rho)}, 300 < y_\rho < 500, \\
\hat{y}_\rho &= 1, y_\rho \geq 500.
\end{align*}
\]

(15)

However, the reduced physical value may be distinct from whole-number values when filling convolution matrices (discretely from 1 to 4). From this perspective, a procedure for the calculation of this function is given for a more general case, which allows to fill the convolution matrix with fuzzy information of the required function in nodes that correspond to whole-number combinations of arguments. For this purpose, designate arbitrary values of fuzzy arguments in the qualimetric space as \(X_1 = A_1, B_1; X_2 = A_2, B_2\), \(A_1, A_2 \in [1,4], B_1, B_2 \in (0,1),\) where \(A_1, A_2\) - integer parts of values, and \(B_1, B_2\) - fractional parts. So, fuzzy convolution arguments in the qualimetric space, including the assumed fuzzy number model, will become (equations 16–17):

\[
\begin{align*}
\tilde{X}_1 &= \frac{A_1}{1-B_1} + \frac{A_1 + 1}{B_1}, \\
\tilde{X}_2 &= \frac{A_2}{1-B_2} + \frac{A_2 + 1}{B_2}
\end{align*}
\]

(16)

(17)

In view of the above, a variant for filling paired-comparison matrices of autoclaved aerated concrete quality values, which, based on fulfillment of obligatory rules (canons), will be written with the following topological view given on Figure 4, has been proposed.

![Figure 4. A variant for filling paired-comparison matrices with the integrated assessment of autoclaved aerated concrete quality.](image)

The «canonization» of convolution matrices with restrictions to the dynamics of development results in a functionally completed system of standard convolution functions and their topological interpretation using a family of similar value lines – isolines. Such an approach opens new methodic possibilities on solving problems of convolution matrix synthesis, ranging the groups of objects and states of certain objects with the purpose to evaluate and justify their dynamics of development.
Generally, the autoclaved aerated concrete quality control algorithm may be presented as flow diagram at the stage of component proportioning (Figure 5).

![Control algorithm for AAC raw materials proportioning.](image)

At the first stage, control factors are selected, and a mathematical process control model is constructed (unit №1). At the second stage, incoming raw materials are monitored (unit №2). At the third stage, the vector of output parameters $\mathbf{y}$ is generated, and the integrated quality assessment of autoclaved aerated concrete is made $\mu(\mathbf{y}) = f(\mathbf{x}, \mathbf{u})$ (unit №3). At the fourth stage, the current integrated quality criterion $\mu_{\text{cur}}$ is compared to the predictive evaluation in case of any change in raw materials quality $\mu_{\text{pl}}$ (unit №4). If (unit №5) the predictive value of integrated quality criterion exceeds the current value $\mu_{\text{pl}} \geq \mu_{\text{cur}}$, an enumeration (unit №6) of different control variations $\mathbf{u} = \{u_1, u_2\}$ with existing perturbations $X = \{x_1, x_2, \ldots, x_m\}$ is performed to achieve the highest integrated quality criterion of finished materials ($\mu_{\text{pl}} \rightarrow \max$). Variations obtained (unit №7) are given to a product engineer to make a decision (unit №8), and the algorithm is repeated again (unit №2). If (unit №9) the predictive value of integrated quality criterion ($\mu_{\text{pl}}$) does not reach the current value ($\mu_{\text{cur}}$), but is higher than the minimum permissible value provided with state standards, the decision maker is given (unit №7) a limited set of alternative controls to make a unique decision (unit №8). The limited set of alternative controls is selected from a range (unit №10) using the normal sorting algorithm (the largest value selection).

If the condition $\mu_{\text{pl}} \geq \mu_{\text{min}}$ is not met, possible causes of an emergency are studied deeper (unit №11), a matter of a change in the set of controls is resolved (unit №12). If the selection of other controls is appropriate, the algorithm is repeated from the beginning (unit №1), and if the efficiency of control replacement is low, raw materials are replaced (unit №13).

6. Conclusion

Thus, in the course of paper, the following results are produced: the proportioning stage of cellular-concrete mixture components is the most efficient from the perspective of autoclaved aerated concrete production control; the selection of control factors, which significantly affect the quality of autoclaved aerated concrete, is justified, in particular – cement portion ($n$) and siliceous component ratio ($C_{\text{sil}}$) in the mixed cementing agent, as well as the content of active silica ($\text{SiO}_2$) in the sand; a mathematical model of autoclaved aerated concrete quality control is constructed as a function of selected factors, a
control algorithm of component proportioning is given, if it is implemented, it may lead to an increase in autoclaved aerated concrete production efficiency through decreasing the reject rate of finished products.

The model developed will serve as the basis for an automated production control system of autoclaved aerated concrete products with desired quality performance under the conditions of cost-effective use of resources and energy saving.

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