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QUALITY CONTROL OF DISPERSED COMPONENTS POWDER-ACTIVATED CONCRETE WITH THE HELP OF SHUKHART'S CARDS

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Abstracts. In the construction industry, cement concretes are the most widely used building material. New generation materials with increased strength and durability are used in the construction of critical facilities. Special requirements are imposed on such concretes to ensure their quality. The issues of control and quality of powder-activated concretes of a new generation at the stage of preparation of their constituent components are considered. Author made in the article the analysis of the classifier data for the developed system of quality control (QC) based on Shewhart control charts. For implement an effective classification of critical situations we justified target-conformity application of support vector. We accumulated the base of possible solutions in special cases when process of cement production go out from control limits. For pro-programmatic implementation of support vector we used library application LIBSVM. We described procedures for the preparation of the accumulated data for training models of SVM. We determined optimal parameters of created models nuclei to ensure accurate classification. We created SVM models for all monitored parameters. We created HMI display effective solutions to prevent critical situations for the operator.

Keywords: Shewhart control charts, grinding of cement, statistical controllability, knowledge base, quality control, support vector machine, classification, cross-validation

КОНТРОЛЬ КАЧЕСТВА ДИСПЕРСНЫХ КОМПОНЕНТОВ ПОРОШКОВО-АКТИВИРОВАННЫХ БЕТОНОВ С ПОМОЩЬЮ КАРТ ШУХАРТА

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Аннотация. В строительной отрасли наиболее применяемым строительным материалом являются цементные бетоны. При возведении ответственных объектов используются материалы нового поколения, обладающие повышенными показателями прочности и долговечности. К таким бетонам предъявляются особые требования по обеспечению их качества. Рассматриваются вопросы контроля качества порошково-активированных бетонов нового поколения на стадии подготовки их составляющих компонентов. В работе выполнен анализ применимости классификатора данных для разработанной подсистемы контроля качества (КК) с использованием контрольных карт Шухарта (ККШ). Для осуществления эффективной классификации критических ситуаций обоснована целесообразность применения метода опорных векторов – Support Vector Machine (SVM). Накоплена база возможных решений для особых случаев, соответствующих выходу показателей процесса производства цемента, приготовления наполнителей и заполнителей различных размерных уровней для порошково-активированных бетоновза контрольные пределы. Для программной реализации метода опорных векторов применена библиотека LIBSVM. Подробно описаны процедуры по подготовке накопленных данных для обучения моделей SVM. Подобраны оптимальные параметры ядер созданных моделей, обеспечивающие точность классификации. Созданы модели SVM для всех контролируемых параметров. Разработан человеко-машинный интерфейс отображения предлагаемых эффективных решений по предотвращению критических ситуаций, предназначенный для оператора.

Ключевые слова: контрольные карты Шухарта, помол цемента, статистическая управляемость, база знаний, контроль качества, метод опорных векторов, классификация, перекрестная проверка

I. INTRODUCTION

Modern high quality concretes (HDC) classify a wide range of concretes for different purposes: High-strength (HPB, Hochfester Beton - HFB) and ultra-high-strength (UHFB, Ultrahochfester Beton - UHFB), self-compacting (SVB, Selbstverdichtender Beton - SVB; Self Compacting Concrete - SCC), highly corrosion-resistant, Reaktionspulver Beton - RPB or Reactive Powder Concrete - RPC and others [1, 2, 3, 4, 5, 6, 7].

New generation concretes are used for the construction of unique buildings and structures [3, 8, 9], construction of bridges and roads [10, 11], and as a repair material [5, 12]. They are based on new generation superplasticizers in combination with new formulation of dry components. Concretes are formed by combining dispersed components of different sizes, mutually reinforcing each other [13, 14]. For example, particles of smaller size than cement granules fill in the spaces between cement particles and depending on given interaction mechanism in general polydisperse modifier structure can be crystallization centers, change plastic strength, etc. Fillers and fillers with large sizes form a framework of material with optimal packing of particles. In this case, the pores between the granules are filled with more ground particles.

Designing of multicomponent compositions of new generation concretes should be performed using the following basic formulation principles [13, 15, 16, 17]: 1) mandatory use of rock flour with micrometer particle parameters as dispersed fillers, which are rheologically active components; 2) obligatory use of very fine-grained quartz sand of fraction 0,16-0,63 mm with fineness modulus less than 1.2, supporting necessary rheological and structural condition of water-disperse mixture and increasing weighing ability of dispersion fine-grained system, which prevents settling of coarse sand and crushed stone at stratification of concrete mixture; 3) use of reactive pozzolanic additives (microsilica, dehydrated kaolin, etc.), binding hydrolysis of fluidized sand and gravel of concrete mixes. 4) the use of high-quality sand-fillers and crushed stone with specially selected granulometry, providing a high bulk density of the mixture of aggregates; 5) very low ratio of water to the sum of all the dry components in the concrete mixture, not exceeding 0,07-0,08, and an extremely high volume concentration of the solid phase (not less than 80-85%); 6) mandatory use of highly effective superplasticizers, providing the diameter of the spread (of the cone Hagerman) of cement suspensions and suspensions of mixtures of cement with rock flour (at a ratio of "cement : Stone meal" ratio 1:0,5÷1:1) in the range of 260-350 mm at В/Ц (В/Т) less than 0.18 (0.2); 7) for special concretes using in the composition of the fillers nano-sized (particles whose size in one direction are at least 100 nm), polymineral composition binders, activated components, and first of all water mixing, as well as biocide additives.

Technological processing of powder-activated concrete includes the following processes:

preparation of components (cement, fillers and aggregates, mixing water, modifying additives), preparation of self-compacting concrete mixtures, product molding (shoeless or formwork method), curing of products and structures (various methods of heating, heat and humidity treatment, etc.). All operations and processes contribute to the quality of the manufactured products. The quality of the concrete constituents used is one of the most important.

Currently, it is considered that the quality of produced cement, fillers and aggregates of different size levels largely determines the place and role of the enterprise-producer in the modern building materials market. Therefore, introduction of quality control subsystems into automated control systems (ACS) for production of cement, fillers and aggregates of different types is a relevant problem. For its implementation it is necessary to solve two interrelated subtasks. The first one is the recognition (detection) of critical situations, which caused a disruption in the technological process (TP). The second one is the identification of the critical situation itself for subsequent correction of possible deviations in the TP. A well-proven method of production process control is the application of statistical methods based on control charts. In contrast to the methods using histograms and various types of diagrams (scatter, Pareto, Ishikawa), control charts allow forecasting changes in the parameters of technological process. However, the practical issues of using methods of controlling production processes with the use of control charts for the sphere of production of construction materials remain insufficiently disclosed. Therefore, in this article we attempt to comprehensively study the specifics of the application of quality control methods in the production of cement, fillers and aggregates of different dimensional level.

Purpose and objectives of the research

The research is aimed at improving the quality of manufactured powder-activated concrete by applying a virtual analyzer built on the basis of mathematical statistics methods and intelligent technologies in the technological process for the preparation of cement, fillers and aggregates of different dimensional level ARS control.

Research Objectives:

1. Create an algorithm for technology of powder-activated concrete on the basis of literature analysis in the field of creating a new generation of concrete and emphasize the importance of quality control of preparation of cement, fillers and aggregates.
2. To build a dynamic model of the technological process with the use of regression identification methods on the example of Portland cement, taking into account technological processes of concrete components preparation.
3. To develop the method of technological data preparation for statistical analysis and mathematical models for evaluation of statistical parameters of technological processes of concrete components preparation for evaluation of its statistical controllability
4. Create a virtual quality analyzer based on Support Vector Machines (SVM) method и Advanced Process Control (APC) system to monitor and control the quality of manufactured products and implement it in the APCS of cement grinding and grinding of aggregates and fillers of concrete.

II. METHODS

The technological process of concrete production consists of several stages. In the first stage, raw materials for the production of cement, fillers and aggregates are extracted. Then they are crushed in raw material mills to prepare them for the next stage. The second stage involves various types of activation of the dispersed components: co-milling with plasticizers, heat treatment, etc. The most energy-intensive process in this case is the technology of cement production. The obtained raw components for the manufacture of cement (limestone, clay and additives) are fed into cement kilns, where the firing process takes place. At the outlet of the kilns, the so-called clinker is obtained, which in the next step is sent together with the other additives to the grinding shop. After passing through the cement mills, the finished product, Portland cement, is produced. It is the cement grinding process that is the most important in terms of quality control.

The cement grinding process is monitored in a special room equipped with several monitors, on which the mnemonic diagrams of the technological production are displayed. The operator is able to control almost every stage of the cement grinding process. He controls dosage of clinker and additives, rotational speed of separator rotor, fan speed of suction system (thus he can change air rarefaction in the whole grinding system). However, due to the large amount of information loaded from the screens, the operator is not always able to react promptly to critical situations in the grinding process, and in some cases cannot foresee the occurrence of such situations.

The quality level of fillers and aggregates preparation of different size also determines the quality of concretes based on them. Continuous planetary mills are used for preparation of aggregates up to specific surface of 3000-5000 cm^2/g. For fine-grained sand, filler sand, fine-grained aggregates jaw and cone crushers are used. Grinding of fine-grained materials is possible with the use of various mills: ball, vibratory, vario-planetary.

Practice shows that the optimal characteristics for grinding dispersed materials are achieved by grinding in a vario-planetary mill. This and the fact that the dispersed constituents of concrete have different grindability, makes the Vario Planetary Mill the most suitable one. The combinations of pressure, friction and impact are controlled in the Vario Planetary Mill.

Filler grinding in a Vario Planetary Mill promotes the formation of electron acceptor centers in the particles. This has a positive effect on the rheological characteristics of self-compacting concrete mixtures without the additional consumption of mixing water and superplasticizer.

It is effective to use for the manufacture of powder-activated concrete as fillers and fine aggregates the rock screening fractions < 5 mm, which form multi-tonnage dumps and storages, occupying large areas and disturbing the ecological balance of regions [18]. To solve the first of the problems mentioned in the introduction (recognition of critical situations), a well-proven quality control tool based on Schuchart control charts (SCC) was chosen [19]. The following is an example of research related to quality control of Portland cement. The use of SCC as part of the ACS can provide detection of changes in the TP (including the process going beyond the statistical controllability) even before it has reached a non-emergency state [20, 21].

In [22] an experimental implementation of the subsystem of monitoring and identification of critical situations in the TP on the basis of control data in JSC "Mordovcement", Republic of Mordovia is described. Six characteristics were selected for monitoring: specific surface of cement (1); cement grinding fineness, when sifting through sieve No.008 (2); mass fraction in percentage of sulfuric acid anhydride in cement (3); mass fraction of opock in cement (4); mass fraction of calcium oxide in cement (5); percentage of moisture content in cement (6).

There are allowable limits for all these parameters [23], exceeding which indicates the presence of defects in the produced cement.

As a result of the research, an ACS subsystem [22] was developed, which displays SCC in real time. With the help of this subsystem the operator can monitor graphs of change over time of quantities determining cement quality and, depending on the displayed information, perform actions, which are recorded in the use case diagram. There are several rules for detecting loss of statistical controllability. However, for the practical application of SCC it is sufficient to use the first four rules - this reduces the probability of false positives [21]. A script was implemented in the C language that monitors the "triggering" (execution) of these four rules: one point corresponding to the TP indicator exceeds the three-sigma limits (1); at least two of three consecutive points lying on one side of the center line exceed the two-sigma limits (2); at least four of five consecutive points lying on one side of the center line exceed one sigma (3); at least eight consecutive points lie on one side of the center line (4).

During the three months of subsystem testing, about 3,000 values were processed for each monitored process parameter, i.e., a total of about 10,000 values. During this period of time, the SCC for all characteristics of parameters revealed the loss of statistical controllability for each of the above four rules. All effective decisions taken by the operator to return the TP to the state of statistical controllability, as well as parameters of the production process (temperature, separator rotation speed, etc.) were entered into the knowledge base - to form an expert evaluation for identifying the causes of deviations from the TP. Thus, it was possible to implement a classifier that links the accumulated data in the knowledge base with special events leading to the loss of statistical controllability. In this case, the values of parameters "1-6" are used as input data. A promising solution for this problem is the use of a classifier based on the SVM reference vector method. The main idea of this method is to translate the initial vectors of controlled parameters (corresponding to the actual sets of indicators for a certain moment in time) into a space of higher dimensionality and to search for a separating hyperplane with the maximum gap between it and two parallel hyperplanes built on both sides of it (Fig. 1).

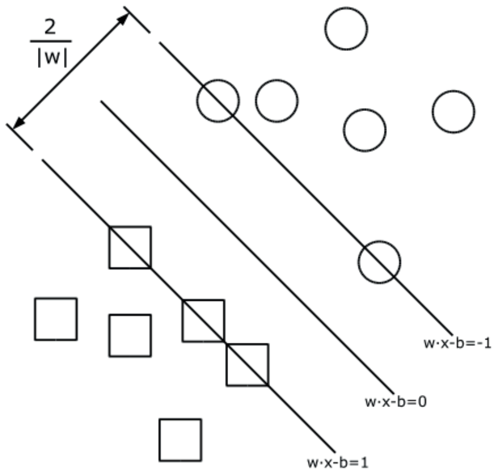

Figure 1. Geometric representation of the SVM vector reference method

Mathematically, the training sample of controlled parameters is written as $(x_1, y_1), \ldots\ldots, (x_m, y_m), x_i \in R^n, y_i \in \{-1,1\}$ [24, 25]. The reference vector method constructs a classification function in the form:

$$F(x) = siqn(\langle w, x \rangle + b), \qquad (1)$$

where $\langle , \rangle$ is the scalar product, w is the perpendicular to the separating hyperplane, and b is equal modulo to the distance from the hyperplane to the origin. In this case the objects for which $F(x) = 1$, fall into one class, and the objects with $F(x) = -1$ fall into another class. This function is used because any hyperplane can be given in the form $\langle w, x \rangle + b = 0$ for some w and (Fig. 7). It is necessary to choose such and b, which maximize the distance to each class. It can be shown that this distance is equal to $1/\|w\|$. The problem of finding a $1/\|w\|$ maximum is equivalent to the problem of finding a minimum and is reduced to an optimization problem:

$$\begin{cases} arq\min\|w\|^2 \\ y_i\left(\langle w, x_i\rangle + b\right) \geq 1, i = 1,\dots,m. \end{cases} \quad (2)$$

It is a standard quadratic programming problem and is solved analytically using Lagrange multipliers. If there is no linear class separability [24, 25], one should resort to expanding the space by increasing its dimension by choosing to map $\varphi(x)$ vectors x into a new space. This results in a new scalar product function:

$$K(x, y) = \varphi(x) \cdot \varphi(y). \quad (3)$$

The function $K(x, y)$ is called the kernel. It is the basic parameter for tuning the SVM method. From the mathematical point of view, any positively defined symmetric function of two variables can serve as the kernel. Positive definiteness is necessary so that the corresponding Lagrange function in the optimization problem is bounded from below. Thus, the optimization problem would be correctly defined. The accuracy of the classifier depends, in particular, on the choice of the kernel. In practice, the following types of kernels are (are) used:

- Polynomial: $k(x, x') = (\langle x, x'\rangle + \text{const})^d$;
- radial basis function (the most common type of kernel): $k(x, x') = \exp(-\gamma\|x - x'\|^2)$;
- Gaussian radial basis function: $k(x, x') = e - \|x - x'\|^2/2\sigma^2$;
- sigmoid: $k(x, x') = \tanh(k\langle x, x'\rangle + c), k > 0, c < 0$.

The software module for operation with Schuchart maps, in the absence of statistical controllability for a particular technological parameter, sets the variable corresponding to this parameter to unity. Thus, the cement grinding quality control subsystem allows you to identify for which technological characteristic a special case took place. The SVM method is then applied. First, the subsystem recognizes which of the four rules the statistical controllability was lost, i.e., it assigns the case to one of the four classes.

At the second stage SVM will determine whether the process indicator (parameter) went beyond statistical controllability by its upper or lower boundary (limit), i.e. it will separate one class from the other.

III. ALGORITHMIC AND SOFTWARE IMPLEMENTATION OF THE PROPOSED METHOD

As a tool for software implementation of this method it was decided to use the freely distributed library LIBSVM. To achieve the most effective classification it is necessary to perform actions for preparation of data sets and search for the best kernel for them, namely to do the following.

Convert the numerical data corresponding to the TP out of statistical controllability to the format of the information system using SVM:

- to perform data scaling in the range from 0 to 1;
- use the kernel RBF: $k(x, x') = \exp(-\gamma\|x - x'\|^2)$;
- use cross-validation to find the best parameters C and γ. The constant "C" is a control parameter of the method. This parameter allows to find a compromise between maximizing the distance between the two hyperplanes and minimizing the total error; to use the found values of C and γ to train the model in order to obtain a classifier for a particular technological parameter; to test the obtained classifier on a test case.

All the accumulated data on the process exiting the state of statistical controllability were reduced to the LIBSVM format and procalated in the range from 0 to 1 - to provide more accurate model training (Fig. 2).

```
11:0.3471          6:0.332117:0.3400
21:0.3465
22:0.3472      10:0.3521    18:0.3626
24:0.3621
33:0.3645          6:0.367817:0.3691
31:0.3699
42:0.3934         17:0.386522:0.3878
36:0.3812
```

Figure 2. Data fragment for training the SVM model

The data format for LIBSVM is a string of the form:: <label><index>: <value>. The parameter <label> characterizes the class to which the following values belong. At the first stage of classification it is required to identify to which of the four rules of loss of statistical controllability a particular special case belongs. Therefore the training (training) file must contain values for the four classes. It should be noted that in case of a loss of statistical controllability by several rules simultaneously, the highest priority is given to rule No.1, while the lowest is given to rule No.4. The <index> : <value> pair gives the characteristic of the value of the controlled parameter. The <index> parameter is an integer number starting with "1" and increasing with each step. The <value> parameter is a real number reflecting the value of the selected characteristic, scaled from "0" to "1".

When using the RBF kernel, at least two coefficients are selected: the regularization coefficient "C" and the kernel parameter "γ". Since it is impossible to assess a priori the optimal value of these parameters by mathematical methods, in practice we resort to an empirical procedure - cross-validation (cross-validation). The essence of this procedure is the following: the range, within which the values of parameters "C" and "γ" will vary, and the sampling step for it are set. As a result, we obtain a "grid", whose nodes specify a set of pairs of "C" and "γ" values, among which it is necessary to select the optimal one; for each pair of "C" and "γ" values, the training sample is divided into n parts. One part is used for training at given values of "C" and "γ", and another part is used for testing. This procedure is repeated n times (to get more accurate result). Finally, each of the n parts is used for testing; then the values obtained are averaged. The procedure is repeated for all values of combinations of parameters "C" and "γ". Sometimes cross-validation with large step of "C" and "γ" changes is performed at first to preliminarily localize the best solution. Then in that interval (on that subinterval), where the best results were achieved, cross-validation is carried out again, but with a smaller step.

The disadvantage of this method of parameter fitting is the high computational complexity and, consequently, the long execution time.

After cross-validation, the best parameters "C" and "γ" for each case were found for each classifier model using the LIBSVM library. Four statistical metrics are introduced as part of machine learning to evaluate the quality of the classifier performance.

All samples for which the classifier gave an answer can be divided into four groups: positive results correctly found by the classifier as positive (true positive); negative results incorrectly found by the classifier as positive (false positive); negative results correctly defined by the classifier as negative (true negative); positive results incorrectly found by the classifier as negative (false negative).

On the basis of these four statistical metrics, the LIBSVM library allocates the metric Accuracy = (true positive + true negative) / (true positive + false negative + false positive + true negative). In content terms, this corresponds to the fraction (from "1") of correct classifier responses among all responses. When testing the trained SVM models on test data, this figure did not fall below 96.875%.

In the process of grinding of cement, fillers and aggregates, in case of loss of statistical controllability by any technological parameter, the subsystem retrieves the solution from the knowledge base (formed on the basis of opinions of experts in the field of cement production technology, preparation of fillers and aggregates of various sizes) corresponding to the choice of the classifier - this choice is made in automatic mode. After that, the operator's display shows advice on how to solve the critical situation.

For all parameters of the technological process, knowledge bases were formed in relation to the effective solutions adopted (eight solutions were entered in the base for each parameter). So, for all six process parameters, 48 possible solutions (subclasses) were identified for special cases. Five SVM models were created for each of the six process parameters. The first model determines, when a critical situation occurs, which of the four rules is triggered by the CCH. Then, depending on the rule number, the corresponding classifier (one of the four) is selected. The selected classifier determines whether the special case occurred at the upper or lower limit, and associates it with the corresponding solution in the knowledge base (proposed solutions).

CONCLUSIONS

The issues of quality control of the technological process of production of powder-activated concrete of a new generation are considered. In the course of this study, a classifier based on the method of reference vectors was introduced into the subsystem of quality control of cement grinding, filler and aggregate grinding using SCC. To implement the classifier LIBSVM library was applied. During the testing of the classifier the optimal values of the settings of the SVM models were selected. This allowed the share of correct answers to be at least 96.875%. Improved using the proposed classifier, the quality control subsystem showed sufficient accuracy in identifying critical situations and increased the efficiency of operator actions aimed at preventing such situations.

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