Compaction Quality Fine Control of Fresh Concrete Based on Vibration Energy

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Abstract: To solve the problem of difficulty in controlling the construction quality of fresh concrete due to the low applicability and accuracy for the existed referencing vibration time when using internal vibrator, an innovative parameter of vibration energy density is created based on concept of energy and a hardened porosity prediction model is constructed considering the parameter and mix characteristics. The model is used to obtain the minimum porosity value of concrete and corresponding energy density threshold under certain ratio conditions. Finally, the accuracy and effectiveness of method are verified by field tests. The results show the method can realize precise quantitative quality control of concrete vibration and guide the construction work.

1. Research background

Great achievements have been made in the construction of water conservancy projects in China in the past three decades, among which the number of concrete dam projects with height over 100m have accounted for more than 50%[1]. The vibration of concrete is one of the key processes during construction. The vibration construction quality has a significant influence on the mechanical properties and durability of hardened concrete.

At present, the most widely used and efficient concrete vibrator is the internal one or called vibrator rod. When the rod is inserted into concrete, normal vibration duration is generally determined according to construction experience, and it has limitations on applications such as in conditions of reinforced concrete. Thus, the vibration quality is difficult to be control accurately. To overcome the above shortcomings, this paper firstly establishes the parameter of vibration energy density of concrete and builds a model for predicting hardened porosity. Then concrete vibration density threshold used to precisely control the vibration quality is obtained by back analysis, finally effectively guaranteeing the concrete compactness. Compared with previous method by empirical value, this new method which can effectively guide the construction has better applicability and less error.

2. Test scheme

In the scheme, the ordinary Portland 42.5 cement is used and its performance parameters are shown in Table 1. Fine aggregate is natural river sand, with an apparent density of 2.61 g/cm³ and a fineness modulus of 2.8. Coarse aggregate is limestone rubble divided into class A (5-12.5mm) and class B (5-16mm) according to different sources. The specific surface areas of class A limestone are 0.288 m²/kg and 0.236 m²/kg respectively, marked as A1 and A2. The specific surface area of class B
limestone is 0.258 m$^3$/kg. The normal temperature and humidity of test environment is respectively 25±2 °C and relative humidity of 65±20%. Considering the following, Due to the requirement that largest aggregate diameter should be no greater than 1/3 of the minimum size of the specimen[2], the diameter of cored samples within size of coarse aggregate in no more than 18 mm is 5.5 cm. The test methods of density and air content (AC) of fresh concrete refer to SL352-2006 Hydraulic Concrete Test Code[2]. The rheological parameters of concrete are measured by ICAR rheometer[3].

| Loss on ignition/ (%) | Sulfur trioxide/ (%) | Magnesium oxide / (%) | Specific surface area / (m$^2$/kg) | Chloride ion content / (%) | 3-day flexural strength / (MPa) | 3-day compressive strength / (MPa) | 28-day flexural strength / (MPa) | 28-day compressive strength/ (MPa) |
|----------------------|----------------------|-----------------------|-----------------------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|---------------------------------|
| 1.5                  | 2.43                 | 1.63                  | 372                               | 0.026                       | 5.7                           | 27.8                          | 8.0                           | 49.8               |

Φ35 mm hand-held vibrating rod is used, connected with handheld frequency converter by which frequency and amplitude are adjusted. According to the operating experience of concrete vibration, the diameter of acting range of rod is 10 times of that of vibrator[4]. Therefore, in order to obtain accurate test results by avoiding energy reflection from walls, the minimum dimension of mould should exceed 10 times the diameter of rod. The mould is a cylindrical bottomless wooden one with dimensions of Φ50 cm×30 cm. As shown in Figure 1, foam rubber is pasted on the inner wall and bottom of the formwork to ensure better representing actual pouring situation on site. The rod is inserted into the center of mould and fixed by the bracket. The distance from the bottom end of the rod body and the bottom surface of mould is about 1-2 cm to also prevent energy reflection.

![Figure 1. Mould and vibrating device](image1.jpg)

In the tests of hardened concrete performances, the specimens should be covered with plastic film for curing and timely watered as shown in Figure 2. After 20 days, the core samples with a size of 5.5cm × 30cm located at center of each specimen and distances of 7 cm, 11 cm, 14 cm and 16 cm from the center respectively will be drilled out. Three core samples at the same location are listed in one group of which test performance is the average. Once the drilling work is completed, the samples are cut according to different requirements of concrete performance tests, and then the cut ones will be covered by film and watered regularly for curing. The porosity of hardened samples shall be determined according to the regulation of ASTM C642-97[5].

![Figure 2. Vibrated hardened concrete specimens (left) and core samples (right)](image2.jpg)
Tests for concrete density are designed based on orthogonal test method by which the test results have better representativeness\cite{6}. Considered factors include vibration time, vibration energy power for per unit mass of concrete ($W_{mr}$), water-cement ratio, volume fraction of aggregate, sand ratio, specific surface area (SSA) of the aggregate, while the evaluation index is the porosity of hardened concrete. Meanwhile, the yield stress, plastic viscosity, density and gas content of fresh concrete before vibration are also measured. The expression of $W_{mr}$ is\cite{7}:

$$W_{mr} = A f$$ \hfill (1)

Where, $W_{mr}$ is vibration energy power for per unit mass of concrete, $w$/kg; $A$ is the amplitude, m; $f$ is the vibration frequency, Hz.

The specific experimental factors and experimental scheme are shown in Table 2 and Table 3 respectively.

| Table 2. Table of factor and levels |
|-------------------------------------|
| Factor | Time of vibration (s) | $W_{mr}$(w/kg) | W/C | Volume fraction of aggregate (%) | Sand ratio | SSA of coarse aggregate (m$^2$/kg) |
|--------|-----------------------|----------------|-----|-------------------------------|------------|----------------------------------|
| Level 1 | 10                    | 8.9            | 0.40| 64                            | 0.40       | 0.236                            |
| Level 2 | 30                    | 12.1           | 0.45| 65                            | 0.42       | 0.258                            |
| Level 3 | 50                    | 21.3           | 0.50| 66                            | 0.44       | 0.288                            |
| Level 4 | 80                    | 29.3           | 0.55| 67                            | 0.46       | ---                              |

| Table 3. Orthogonal test scheme of compactness of vibrated concrete |
|---------------------------------------------------------------|
| Number | Time of vibration (s) | $W_{mr}$(w/kg) | W/C | Volume fraction of aggregate (%) | Sand ratio | SSA of coarse aggregate (m$^2$/kg) |
|--------|-----------------------|----------------|-----|-------------------------------|------------|----------------------------------|
| C1     | 80                    | 8.9            | 0.45| 64                            | 0.44       | 0.236                            |
| C2     | 50                    | 12.1           | 0.40| 64                            | 0.46       | 0.258                            |
| C3     | 10                    | 12.1           | 0.50| 67                            | 0.44       | 0.236                            |
| C4     | 50                    | 29.3           | 0.55| 67                            | 0.40       | 0.236                            |
| C5     | 10                    | 29.3           | 0.40| 64                            | 0.40       | 0.236                            |
| C6     | 10                    | 12.1           | 0.45| 66                            | 0.40       | 0.236                            |
| C7     | 10                    | 29.3           | 0.55| 64                            | 0.42       | 0.288                            |
| C8     | 30                    | 12.1           | 0.40| 65                            | 0.42       | 0.236                            |
| C9     | 80                    | 21.3           | 0.40| 67                            | 0.46       | 0.288                            |
| C10    | 30                    | 29.3           | 0.40| 64                            | 0.44       | 0.288                            |
| C11    | 50                    | 8.9            | 0.50| 65                            | 0.40       | 0.288                            |
| C12    | 80                    | 29.3           | 0.40| 65                            | 0.40       | 0.236                            |
| C13    | 10                    | 21.3           | 0.40| 66                            | 0.40       | 0.236                            |
| C14    | 10                    | 8.9            | 0.40| 67                            | 0.42       | 0.288                            |
| C15    | 50                    | 21.3           | 0.45| 64                            | 0.42       | 0.236                            |
| C16    | 30                    | 29.3           | 0.45| 67                            | 0.40       | 0.258                            |
| C17    | 30                    | 8.9            | 0.55| 66                            | 0.46       | 0.236                            |
| C18    | 50                    | 29.3           | 0.40| 66                            | 0.44       | 0.288                            |
| C19    | 10                    | 29.3           | 0.45| 65                            | 0.46       | 0.288                            |
| C20    | 80                    | 12.1           | 0.55| 64                            | 0.40       | 0.288                            |
| C21    | 10                    | 29.3           | 0.50| 64                            | 0.46       | 0.236                            |
| C22    | 10                    | 8.9            | 0.40| 64                            | 0.40       | 0.258                            |
| C23    | 10                    | 21.3           | 0.55| 65                            | 0.44       | 0.258                            |
| C24    | 80                    | 29.3           | 0.50| 66                            | 0.42       | 0.258                            |
| C25    | 30                    | 21.3           | 0.50| 64                            | 0.40       | 0.288                            |
3. Vibration quality control based on energy

3.1. Vibration energy density

According to Kirkham’s formula\[8\], the actual vibration energy acting on concrete can be expressed as:

\[ W'_w = \frac{v^2 f}{4\pi} \]

Where, \( W'_w \) is the vibration energy power for per unit mass of concrete, w/kg; \( v \) is the flow velocity of fresh concrete at r distance from the center of bar body, m/s; \( f \) is the vibration frequency, Hz. According to authors’ previous research\[9\], the expressions of \( v \) are different in condition of plain concrete and steel reinforced one. Substitute the expressions into formula (2) and multiply them by \( \rho t \) to obtain \( E'_{uv} \) and \( E''_{uv} \) respectively as follows:

\[ E'_{uv} = \rho f^3 \left[ (1-0.03) \mu^2 \right] (1-0.01) A^2 \left( \frac{R_0}{r} \right)^4 \] (3)

\[ E''_{uv} = 2.42 \rho f \left( k_p \frac{M_{mm}}{d_m} \right) \frac{M_{mm}}{d_m} \left( \frac{\tau_0}{\mu} \right)^{\frac{1}{2}} \left( \frac{5}{2} \right)^{\frac{1}{2}} \left( \frac{R_0}{r} \right)^{2} \] (4)

Where \( E_{uv} \) and \( E''_{uv} \) vibration energy density of plain and reinforced concrete respectively, J/m³; \( \rho \) is density of fresh concrete, kg/m³; \( \tau_0 \) is yield stress, Pa; \( \mu \) is plastic viscosity, Pa.s; \( t \) is vibrating time, s; \( f, A \) and \( R_0 \) are vibration frequency, amplitude and rod body radius of the vibrating rod respectively with units of Hz, m and m; \( r \) is the vertical distance from a certain position of concrete within the range of action of vibrator to the axis of rod body, m; \( k_p \) and \( y \) are process parameters in units m² and m respectively. \( M_{mm} \) and \( M_{ss} \) are the adjacent clear distance of transverse reinforcement and main reinforcement respectively, m; \( d_m \) and \( d_{sm} \) are diameters of transverse reinforcement and main reinforcement respectively, m; \( \phi \) is the void fraction of bar-mat reinforcement.

3.2. Prediction of hardened porosity

The porosity of hardened concrete is mainly influenced by vibration energy and properties of fresh concrete. Considering that there is no simple linear relationship between porosity and the above factors, and the mechanism is still unknown, the support vector machine (SVM) method is adopted to predict the porosity of concrete. As a new machine learning method, SVM having good generalization performance can process small samples and sparse data. Its model structure and number of nodes in hidden layer can be automatically determined by training algorithm, which can reduce dependence on experience.

3.2.1. SVM modeling

Test data is selected from the orthogonal experimental scheme with 25 conditions. In each specific condition, the hardened porosity of core samples respectively drilled out at the distance of 7, 11, 16 cm from the center of specimen are measured. Prof. Lin Zhi-ren’s Libsvm toolbox\[10\] is adopted for a total of 100 sets of data. The sample data could be divided into training set and test one. The training set has 85 groups, with the number of # 1-85, while the rest 15 groups are included in the test set with the number of # 86-100. The algorithm flow is shown in Figure 3.
3.2.2. Input and Output Parameter Selection
The output parameter of model is hardened porosity of plain concrete, and the input ones include the characteristic parameters of fresh material and vibration energy density calculated by formula (3). The input and output parameters in the support vector machine model are shown in Table 4.

Table 4. Input and Output Parameters Table

| Input parameter                               | Output parameter |
|-----------------------------------------------|------------------|
| The air content, yield stress, plastic viscosity, density of fresh concrete, vibration energy density | Hardened porosity |

3.2.3. Preprocessing of original data
Due to the different dimensionality and magnitude between vibration energy and working parameters of fresh concrete, dimensionless processing is needed. The sample data is defined as \( x_p \) (\( p = 1, 2, ..., P \)), the maximum and minimum values are defined respectively as \( x_{\text{max}} \) and \( x_{\text{min}} \), and the normalization formula is:

\[
y = \frac{x_p - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \tag{5}
\]

During training, normalized training samples are used as network input and the inverse calculation process is as follows:

\[
x_p = y(x_{\text{max}} - x_{\text{min}}) + x_{\text{min}} \tag{6}
\]

3.2.4. Kernel function selection and parameters optimization
The Gaussian radial basis function is selected as the kernel function of predicting model, having advantages of simple, small calculation difficulty and high predicting accuracy. The value of error penalty factor (\( c = 5.6569 \)) and kernel width of the Gaussian radial basis function (\( g = 2.8284 \)) are determined by 5-fold cross validation.

3.2.5. Regression prediction
The predicted results are shown in Figure 4 and 5, with mean square error MSE=0.02879. It can be seen from the figure that the predicted values of porosity both in the training set and test one are in good agreement with the measured ones. Except for some points, the relative error is not more than 10%, which proves that SVM method can accurately predict the porosity.

3.3. Inversion of vibrocompaction energy density threshold \( E_0 \)
After modeling by SVM method is completed, properties of fresh concrete as input parameters in the model are constant for a certain mix proportion. By changing value of \( E_{uv} \), different predicted values of porosity are obtained. Then the input parameters of the support vector machine are taken as the individual population in
the genetic algorithm, and the porosity is taken as individual fitness value. The minimum porosity and its corresponding \( E_{uv} \) which is also the energy threshold \( E_0 \) required for compactness are searched through the algorithm. The implementation steps are as follows:

1. Set the number of iterations as 100, the number of individuals in the population as 20, the crossover probability as 0.4, and the mutation probability as 0.2.

2. Floating-point number encoding is adopted for the individual. It can be seen from Table 4 that there are 5 input parameters, so the length of the individual is 5.

3. The initial population is randomly generated, and the porosity value predicted by the support vector machine is taken as the individual fitness value. According to the genetic probability, the selection, crossover and mutation genetic operations are used to generate new population.

4. After reaching iterations set 100 times by repeatedly executing steps 2 and 3, the final value of optimal individual is selected as the result of the genetic algorithm. The flow chart of algorithm is shown in Figure 6.

Taking the C8 condition as example, the concrete water-cement ratio is 0.4, the aggregate volume fraction is 65%, the sand ratio is 42%, the specific surface area of coarse aggregate is 0.236m\(^2\)/kg, the yield stress is 1206.6Pa, the plastic viscosity is 175.6Pa.s, the density is 2473kg/m\(^3\), and the air content is 2.8%. The above parameters are guaranteed to remain unchanged, and the SVM modeling and genetic algorithm are used to find the optimal fitness value. The algorithm evolution process is illustrated in Figure 7 where the curve represents best fitness value. It can be seen that at the beginning of the calculation, the fitness value of each generation changes significantly, and it tends to converge to the optimal solution till about generation 20, finally reaching the optimal solution around generation 23 with the minimum porosity of 9.1% and corresponding \( E_0 \) of about 127.9kJ/m\(^3\).
3.4. Model validation

The vibration energy for per unit mass of concrete in C8 condition is increased from 12.1w/kg to 21.3w/kg, and the concrete is cored at different positions from the rod. The value of energy density of concrete is calculated according to formula (3), and the porosity of the core sample is measured by water saturating method. At the same time, in order to analyze the influence of steels on the relationship between energy density and porosity, double-layer bidirectional reinforcement with main steels of 12mm@200mm and transverse ones of 10mm@200mm is arranged within the concrete. Similarly, the porosity is measured the vibration energy density of steel concrete is calculated according to formula (4). The result is shown in Figure 8.

![Figure 7. Diagram of process of searching the minimum porosity](image)

![Figure 8. Porosity of vibrated hardened concrete](image)

It can be seen that the minimum porosity value of plain concrete is close to that of steel one with only about difference rate 3%. Moreover, the rebars has little influence on the relationship between the vibration energy density of concrete and the hardened porosity, inferring model of predicting porosity can be also applied to the condition of vibrated reinforced concrete. The measured minimum porosity values of plain concrete and reinforced concrete are 9.5% and 9.33% respectively, closing to the theoretical value of 9.1%. Likewise, the vibration energy density values of core samples at the measured minimum porosity are 134.56kJ /m³ and 138.63kJ /m³ respectively, closing to theoretical threshold of the energy density determined by the genetic algorithm (127.9kJ /m³) with relative errors about 5% and 7.7%, respectively. It proves that model of predicting porosity is reliable and the threshold of vibrocompact energy density of concrete can be optimized by genetic algorithm.

3.5. Reasonable vibration time $T_0$

Based on genetic optimization algorithm, the vibrocompact energy density threshold $E_0$ could be determined. Considering fresh concrete within the range with radius equals to 5 times rod diameter can be well
consolidated, the formulas for calculating reasonable vibrating time $t_0$ and $t_1$ in plain and reinforced concrete are respectively obtained by combining with the formula (3) and (4):

$$t_0 = \frac{625E_0}{\rho f^3 \left( (1-0.03\mu^{0.3}) / (1-0.01\mu^{0.4}) \right) A}$$

$$t_1 = \frac{10.25E_0}{\rho f^{2.5} A^2} \left( \frac{d_m}{k_m M_m \phi} \right)^{\frac{1}{2}} \left( \frac{\mu}{\tau_0} \right)^{\frac{1}{2}}$$

$$k_m = \frac{(M_m+d_m)}{16} \left[ 2 \ln \left( y \right) + \left( y-1 \right)^2 / (1+y)^2 \right] + \left( 1-y^2 / 2(1+y) \right)$$

(8)

4. Field test

6-8 sections of C30 concrete floor are poured in 1# installation room of Datang Guanyinyan hydropower station. The bars include carrying steels $\phi 16mm@150mm$ and distribution ones $\phi 10mm@150mm$ and the reinforcement ratio is 0.34%. The water-cement ratio of the concrete is 0.4, the sand fineness mode is 2.7, the gravels are broken stones, the continuous gradation is adopted and the maximum particle size is 30mm, the apparent density is 2.69g/cm$^3$, and the specific construction parameters are shown in Table 5.1. Prediction model of porosity is established based on support vector machine (SVM) and the energy density threshold is determined with the value of 140.6 kJ/m$^3$. According to formula (8), reasonable vibration time (about 20 s) is calculated. After vibration and removing formworks, concrete surface is dense and flat. Till 28 days, the ultrasonic rebound test results of concrete samples show that the strength meets the design requirements. It proves that the quality control method based on the vibration energy index is accurate and effective.

| $\rho$ (kg/m$^3$) | AC (%) | $\tau_0$ (Pa.s) | $\mu$ (Pa.s) | $f$ (Hz) | A (mm) | $D_0$ (mm) | $\phi$ (%) | $d_{sm}$ (mm) | $M_{sm}$ (mm) | $d_{ss}$ (mm) | $M_{ss}$ (mm) |
|------------------|--------|----------------|-------------|-------|-------|---------|-------|-------------|-------------|-------------|-------------|
| 2297             | 4.1    | 796            | 79          | 200   | 2     | 50      | 99.64 | 16          | 134         | 10          | 140         |

5. Conclusions

In this paper, the hardened porosity represents concrete compactness, and its statistical predicting model based on the properties of fresh mix and the vibration-energy density of concrete is established by support vector machine (SVM) method. Relying on genetic algorithm, the minimum porosity value of concrete for concrete with certain mix proportion and corresponding vibrocompaction energy density threshold verified by experiments are determined. Finally, accuracy and validity of the method are proved by field tests. The main conclusions are as follows:

1. There is a concrete vibration density threshold which minimizes the porosity.

2. The steel factors have no influence on the relationship between vibration energy density of concrete and the hardened porosity.

3. The relative error of predicted and the measured porosity values of plain and reinforced concrete are 4.2% and 2.5% respectively, the values of vibrocompaction energy density threshold are 134.56 kJ/m$^3$ and 138.63 kJ/m$^3$ with relative residual errors of about 5% and 7.7% respectively, proving that the model predicts porosity very well and the method of using genetic optimization algorithm to determine the threshold value is feasible and effective in guiding the quality of concrete vibration during construction.
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