PREDICTION OF RHEOLOGICAL PROPERTIES OF MORTAR FOR SHOTCRETE USING NEURAL NETWORK

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ABSTRACT: Rheological properties of shotcrete mortar largely affect the conveying as well as the placing process of shotcrete. There have been many researches on the rheology of mortar or concrete. However, conventional fitting techniques fail to give a universal prediction of rheology from given parameters of mixing such as water cement ratio, fineness modulus of fine aggregate, elapsed time, etc. This research is to find the correlation between rheological properties and material parameters of shotcrete mortar using neural network. A simple network was developed to predict rheology from water by cement ratio, sand by cement ratio, filling ratio and time.

KEYWORDS: Concrete, rheology, neural network, fresh mortar experiment, data processing, rheometer.

1. INTRODUCTION

Though shotcrete has been used and studied for decades, people are still trying to obtain a high quality shotcrete through various studies, both experimentally and analytically. Doing shooting experiments under various conditions of shooting conditions, mix proportions and materials is one way to learn the effect of various factors on the quality of shotcrete. In the order hand, analytical study all shotcrete using neural network, distinct element method or any, is another approach for finding a better understanding. This research follows the latter approach but

the root of it has come from the former. It has been reported that the rheological properties of mortar in shotcrete largely affects the shooting pressure, shotcrete velocity and rebound ratio [1]. In this paper, the authors would like to report only the results of theology prediction and leave the connection with actual shotcrete system for the next paper. The aim of this study is to point out the rheological properties of mortar and help the design of shooting process, such as determining the shooting pressure, concrete flow, distance, so than the rebound ratio is minized. In addition, this research also provides the data for a three-dimensional simulation of shotcrete using distinct element method [6]. There have been many studies on rheology of concrete, mortar or cement paste. In most of these studies. the common methodology is to keep constant most of



Figure 1. Schematic structure of neural network

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parameters of mixture and vary only one parameter, such as water by cement ratio, to check its effect on rheological properties. Then, linear or nonlinear fitting technique is used to process the data of rheological tests. Some theoretical models have also been proposed for rheology of mortar or concrete. These studies have been very useful for understanding rheological behaviors of cement-based, fresh materials. However, the application of published results seems to be difficult for an arbitrary case of concern. The reason is that these results depend on a particular set of parameters. In our shotcrete research program, neural network has been used successfully to predict the quality of shotcrete, including the predictions of strength and fresh properties [3]. In this research, for the first time, neural network was used to predict the rheological properties of mortar in shotcrete. Neural network is a data processing method simulating the structure and functions of human brain. Briefly, for a given matter with some available data, output parameters are correlated with corresponding input parameters, just like the strength, slump of concrete are the output and mix proportions and materials properties are the input. Then, ideally, with any new set of input parameters, it is possible to predict the outcomes without the need to perform the experiments. This paper is to report the results of using neural network to predict the flow, yield stress and viscosity from four parameters: water by cement ratio, sand by cement ratio, filling ratio and time after mixing. \mathbf{X}_1

2. ARTIFICIAL NEURAL NETWORK

Artificial neural network are relatively crude electronic models based on the neural structure of the brain. The brain basically learns from experience. It stores information as patterns. Some of these patterns are very complicated and allow us the ability to recognize individual faces from manv different angles. This process of storing information, as patterns, utilizing those and then solving problems patterns, encompasses a new field in computing: using neural network. This field does not use traditional programming but involves the creation of massively parallel networks and the training of those networks to solve specific problems.

Fig. 1 shows the schematic structure of a neural network. A simple neural network consists of an input layer, one or more hidden layers and an output layer. Each neuron in hidden layer receives the signals (x_i in **Fig. 2**) from all of the neurons in a layer before it, which is input layer in this case. After a



Figure 2. A basic artificial neuron



Figure 3. Bingham model applied on fresh mortar (Data from test number 18)

neuron performs its function, it passes its output to all of the neurons in the next layers, providing a feed forward path to the output (**Fig. 2**). In this study, the so-called supervised training was used in processing the data. In supervised training, both inputs and outputs are provided. The network then processes the inputs and compares its resulting outputs against the desired outputs. The least mean square algorithm is used to evaluate the error of training process. Errors are then propagated back through the system, causing the system to adjust the weights which control the network. This is called back-propagation technique of learning. The training process is ceased when the total error becomes smaller than a threshold. Then the monitoring data are used to check how well the networks in converging on the ability to predict the right answer. For more information on the neural network, reader can refer to literatures [3], [4].

3. RHEOLOGY OF FRESH MORTAR

In this research, it was assumed that rheological behavior of fresh mortar follows the Bingham's model (**Fig. 3**). It means two parameters, yield stress and viscosity, are required to describe the rheology of a mixture [5]. Yield stress is the least stress required for the flow to start. Once the flow starts, the shear stress and shear rate are proportional by a factor: viscosity (Eq. 1)

(1)

$$\boldsymbol{t} = \boldsymbol{t}_0 + \boldsymbol{m} \cdot \boldsymbol{g}$$

Where, τ , τ_0 , μ and γ are shear stress, yield stress, viscosity, and shear rate, respectively.

In this paper, the results of tests in which super-plasticizer was not used are reported. In some cases of high water cement ratio, little bleeding was observed. This surely has some influence on the accuracy of this network. However, from the characteristics of neural network which requires a wide range of data for supervised training, cases whose bleeding were not so serious, were accepted. As for this matter, more discussion is provided in Discussion section.

4. EXPERIMENTS

4.1 MATERIALS, MIX PROPORTION AND TESTING APPARATUS

| Test number | W/C | S/C | Fv | Time |
|----------------|----------|----------|-------|---------------|
| | (Weight) | (Volume) | 1, | (Minute) |
| 1, 2, 3 | 0.38 | 1.60 | 0.727 | 5, 25, 45 |
| 4, 5, 6 | 0.38 | 1.40 | 0.636 | 5, 25, 45 |
| 7, 8, 9 | 0.38 | 1.00 | 0.454 | 5, 25, 45 |
| 10, 11, 12 | 0.5 | 1.60 | 0.620 | 5, 25, 45 |
| 13, 14, 15 | 0.5 | 1.80 | 0.698 | 5, 25, 45 |
| 16, 17, 18 | 0.45 | 1.70 | 0.702 | 5, 25, 45 |
| 19, 20, 21 | 0.5 | 2.00 | 0.775 | 5, 25, 45 |
| 22, 24, 25 | 0.45 | 1.40 | 0.578 | 5, 25, 45 |
| 25, 26, 27, 28 | 0.55 | 2.10 | 0.767 | 5, 25, 45, 90 |
| 29 | 0.3 | 1.00 | 0.513 | 5 |
| 30, 31, 32, 33 | 0.5 | 2.20 | 0.853 | 5, 25, 45, 65 |
| 34 | 0.38 | 1.40 | 0.636 | 15 |
| 35 | 0.38 | 1.00 | 0.454 | 35 |
| 36 | 0.5 | 2.20 | 0.853 | 50 |

Table 1. Mix proportion and testing time

Table 1 shows the mix proportions and testing time (time elapsed after mixing). In the tables, W/C, S/C, Fv, stand for water by cement ratio, sand by cement ratio and filling ratio, respectively.

Filling ratio is calculated by dividing sand volume to that of water and cement (Eq. 2).

$$Fv = \frac{Volume \text{ of sand}}{Volume \text{ of cement + Volume of water}}$$
(2)

Ordinary Portland cement was used in all the tests. W/C was varied from 0.3 to 0.55 and S/C was selected from 1 to 2.2. These ranges cover the mix proportion of shotcrete [1] so that the rehological properties of shotcrete can be predicted using results of this network. The same kind of sand with constant surface water contents was used. B-type viscometer developed by Tokimec Corp. was used. In this test, a rotor is deepened and rotated at different velocities in mortar when the corresponding torque value recorded.

4.2 EXPERIMENT PROCEDURE

Temperature of materials and testing room was maintained at 20 degrees Celsius during the experiment. The volume of each mixing batch was 1.6 litters. Cement was mixed with sand for 30 seconds. Then, water was added and mixture was again mixed for 90 more seconds. Two minutes after mixing, the cone flow (**JIS R 5201**) of mortar was measured using the apparatus as in **Fig. 5**. In this test, on the top of the steel plate, a cone with large diameter of 100mm was filled with mortar, then it was removed and the resulting diameter of mortar measured. Then, rheological tests were performed at 5, 25, and 45 minutes after mixing. Rheological tests were also performed at 65 and 90 minutes after mixing for cases No. 33 and No. 28. In all cases, shear rates were varied (by varying the speed or the rotor) from 1.34 to $5.36s^{-1}$ while corresponding torque value recorded.



Figure 4. B-type viscometer

Yield stress and viscosity were obtained by linear fitting the recorded data for each case (Fig. 3).

5. RESULTS AND DISCUSIONS

5.1 EXPERIMENTAL RESULTS AND PREDICTION OF NEURAL NETWORK

In all cases of testing, fresh mortar followed the Bingham's model of linear relationship between yield stress and viscosity. Yield stress was seen to increase with time while viscosity slightly decreased. The larger the water cement ratio, the smaller was the yield stress of mortar.

For the flow of mortar, total 11 cases were used, in which 9 cases were for supervised training and 2 other cases for monitoring the accuracy of network. As can be seen in **Fig. 6**, the flow of mortar can be well predicted by the trained neural network, though the dispersion of training data is still large. If the number of experimental cases becomes larger,



Figure 5. Flow test of mortar

more accurate results are anticipated. In this network, the total square error of training was of 0.134. The authors also applied this neural network for the dynamic flow (D-flow; the flow after applying 15 drops on the flow test, **Fig. 5**) but did not obtain a good prediction after training (**Fig. 7**).

As for the yield stress and viscosity, 36 cases of 11 mix proportions with different testing time were used. The neural network was trained with data from 33 cases and the remaining cases were used as monitoring data. The results are shown in Fig. 8 and Fig. 9 for yield stress and viscosity, respectively. In these figures, the circular points are training data, which means the data for supervised training of the neural network. Triangle points are the monitoring data, which means the data for evaluating the accuracy of trained network. The total mean square errors of training and estimating processes were of 0.127 and 0.0148, respectively.

As can be seen in **Fig. 8**, the yield stress was well predicted by the trained network though two in three monitoring points were slightly underestimated. Similarly, in **Fig. 9**, viscosity of mortar was successfully predicted with total mean square error of 0.015.

5.2 DISCUSSIONS

The reason for not using water reducing agent or super-plasticizer in tests of this paper lies on the difficulty in numerically expressing its effect on rheological properties of mortar. This obstacle narrows the range in which mix design is acceptable for testing (no serious bleeding, theology measurable without slip, etc.). Nowadays, when the problems of durability are of great concerns, reducing



Figure 6. Network -estimated and measured flow



Figure 7. Network-estimated and measured D-flow



Figure 8. Network-estimated and measured yield stress

water content in mixture is considered as a common requirement in mix design. In such a circumstance, super-plasticizer has been used widely for high performance concrete and pumpable concrete. The authors are trying to include super-plasticizer as an input parameter of neural network. For example, it can be input in percentage of binder, water reducing factor, etc.

As for the future works of this study, the effect of surface water content, density and fineness modulus of fine aggregate must be taken into account. In addition, temperature is out of similar concern. Rheology of fresh screen mortar extracted from concrete is also an issue in this research.

The monitoring data were extracted from data in the same set of experiment. Therefore the accuracy of this network has not been fully confirmed. After all the main governing factors of a mixture are taken into account, it may be possible to predict the rheological properties of any given mixture.



Figure 9. Network-estimated and measured viscosity

The prediction of dynamic flow was not successful in this study. It may be due to some dynamic factor involving the test, which has not been taken into account.

6. CONCLUSIONS

- (1) A neural network has been developed to predict the rheology of mortars. Its training was carried out from initial input and output data of a set of experiments. The results prove that the neural network is a potential tool to quantitatively predict the rheology of mortar or cement-based fresh mixture.
- (2) At the time being, this study enables the prediction of rheology from given water by cement ratio, sand by cement ratio, time and filling ratio.
- (3) For the coming time, more efforts should be made to include the effect of other factors, such as surface water content and fineness modulus of fine aggregate, super-plasticizer, etc, so that the prediction of rheology of any given conditions becomes possible.
- (4) Once this neural network is accomplished, the quality of not only shotcrete, but also of normal concrete, can be controlled from the stage of mix design.

REFERENCES

- 1. Ishizeki Y., et al., "The Effect of Materials on the Execution of Shotcrete", JSCE annual conference, Vol. 5, 2000, pp. 213-214 (in Japanese).
- 2. Hattori K., Izumi K. "A new viscosity equation for non-Newtonian suspensions and its applications", Rheology of Fresh Cement and Concrete, E&F.N. Spon, 1990, pp. 83-92
- 3. An Introduction to Neural Networks, UCL Press, 1 Gunpowder Square, London
- 4. Hosokawa Y. et al., "Prediction of shotcrete quality using neural network", ICCMC/IBST 2001 International Conference on Advanced Technologies in Design, Construction, and Maintenance of Concrete structure, 2001, pp. 276-282
- 5. Tattersall, G.H. and Banfill, P.F.G., "Rheology of Fresh Concrete", Pitman, London, 1983.
- 6. Q. H. D. Phan, T. Uomoto, "Three-dimensional simulation of shotcrete using distinct element method" JCI annual conference, 2001, pp. 1357-1362