Research article

A proposed method and monitoring system for evaluating workability of Portland cement concrete during mixing

Xin Rong a,b, Honghai Liu a,*, Cheng Li c

a Key Laboratory of Road Construction Technology and Equipment, Ministry of Education, Chang’an University, Xi’an, Shaanxi 710064, China
b Research and Development Center of Transport Industry of Technologies, Materials and Equipments of Highway Construction and Maintenance. (Gansu Road & Bridge Construction Group), Lanzhou, Gansu 730030, China
c School of Highway, Chang’an University, Xi’an, Shaanxi 710064, China

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ABSTRACT

The objective of this study is to address the problem that the traditional quality control method of fresh Portland cement concrete cannot allow the workability to be evaluated during the mixing process. Based on the rheological theory and observed linear relationship between the shear force and flow deformation of concrete mixtures, a mathematical model was established to characterize the workability of concrete using the stirring power of concrete mixers. In this study, a laboratory-scale two-shaft mixer with a rotation speed control system and a power monitoring system was designed and tested. A LabVIEW program was also developed to process and analyze changes of the stirring power data. Laboratory test results show that the optimal workability of fresh concrete with very different mix designs is usually obtained when the second wave trough of stirring power appears. The test results are also compared to the conventional slump test, which indicate the proposed approach and developed system can be used to evaluate the workability of fresh concrete during mixing and identify the optimal mixing time length.

1. Introduction

Concrete is a solid composite material composed of mineral materials mixed with cementitious materials [1]. Concrete has been widely used in civil engineering due to its wide range of strength grades and good durability [2]. Construction workability is a construction performance index to evaluate the uniform compactness and easy operation of fresh concrete, including the fluidity, plasticity, stability and easy compactness of concrete [3, 4]. It is not only determined by the mixing ratio of the mixture, but also closely related to the construction process, and has an important impact on the construction quality indicators such as the smoothness, compactness and strength of the pavement.

Many scholars have done research on mixing uniformity. Gao et al. analyzed the changes of coarse aggregate in fresh concrete per volume with the change of stirring time, and put forward the concept of coarse aggregate distribution uniformity [5]. Yue et al. used chaos model to determine the reasonably mixing time, proposed pre-mixed aggregate method, aggregate pre-wet method and admixture batch feeding ways to improve mixing uniformity [6]. Gao et al. combined with the concrete mixing process of twin-shaft mixer and studied the gap-graded concrete mixing uniformity variation under different time [7]. Yang et al. determined better parameters under different mixing technology based on the theoretical analysis and experimental research and obtained the better mixing technology through comparative analysis [8]. He et al. used the discrete element software EDEM to simulate the material mixing process and to analyze the mixing uniformity [9]. Fang et al. carried out a series of experiment based on different mixing time to investigate the effect of mixing time on slump, modified VC value and strength properties of concrete in different consistency [10]. Wang et al. analyzed the impact of blade angle of single horizontal shaft mixer on concrete mixture inhomogeneity [11]. Oztas et al. used neural network to predict the compressive strength and slump of high strength concrete [12]. Shaswat used hybridizing sea lion and dragonfly algorithms with a fine-tuned convolutional neural network to predict concrete slump [13].

Testing methods of determining workability of fresh concrete can be divided into two categories which were developed based on empirical and rheological methods. For the empirical-based methods, the slump test is usually used to evaluate the workability of plastic and high flow concrete, and the Vickers consistency test is usually used for semi-dry and dry concrete [14, 15]. For the rheology-based methods, the FCT101 type

* Corresponding author.
E-mail address: 1655170147@qq.com (H. Liu).

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Figure 1. The relationship of the stirring power and torque of a concrete mixer during mixing.

Figure 2. (a) Test device; (b) the schematic of the developed lab mixer.
Table 1. Operational parameters of the mixer.

| Performance parameters         | Value                   |
|--------------------------------|-------------------------|
| Dimensions (m)                 | $1.5 \times 0.8 \pm 0.6$|
| Capacity (L)                   | 65                      |
| Rotating speed (r/min)         | 0–60                    |
| Maximum output torque (N·m)   | 500                     |
| Power (kW)                     | 4                       |
| Motor speed (r/min)            | 1480                    |
| Reducer speed reduction ratio  | 15                      |

Table 2. AC speed adjustment equipment.

| Device                  | Device model | Device parameters                   |
|-------------------------|--------------|-------------------------------------|
| Motor                   | Y112M-4      | Rated voltage 380 V                 |
|                         |              | Rated frequency 50 Hz               |
|                         |              | Rated power 4 kW                    |
|                         |              | Rated speed 1400 rpm                |
| Controller PLC          | S7-200 CPU224 AC/DC/Relay | DC 24 V, AC 100–230 V |
| Analog module           | EM232 AQ2    | DC 24 V, 2 W                        |
| Inverter                | Siemens MM430| 380–480 V ± 10%, Three phase, AC,  |
|                         |              | 7.5–250 kW                           |
| Incremental encoder     | Phase A, 100P/R| 100 Pulses Per Revolution           |

fresh concrete tester is widely used, which can quickly estimate the slump, water-cement ratio and other properties [16, 17]. These testing methods are easy to be conducted, and the test results can reflect the fluidity of fresh concrete, but none of them can monitor the workability and the mixing quality of concrete during the mixing process. Therefore, the objective of this study was to develop a monitoring system installed on concrete mixers to monitor the workability and uniformity of fresh concrete during the mixing process and identify the optimal time period to stop the mixing.

In view of the above problems, in order to reflect the construction workability of concrete more comprehensively, especially to realize the online detection and identification of the mixing quality of the mixing equipment during the mixing process, this paper proposes a method for judging workability by mixing power and an online identification technology for mixing quality based on the rheological properties of concrete in this paper and the physical test is carried out to verify.

2. The relationship between mixing power and rheological properties of concrete

The rheology theory that is the study of deformation and flow of matters can be used to analyze workability of fresh concrete [18, 19]. Fresh concrete is a special solid-liquid mixture system, because the relationship between its deformation and stress is time dependent. The system continuously changes with time under constant shear stress, which is called the rheological behavior of concrete. Under the action of external force, the fresh concrete can yield elastic behavior or flow deformation. When the external force is small, it mainly shows the elastic deformation; when the external force is large (beyond the yield force), the flow deformation will occur.

The Bingham model is widely used to analyze the rheological properties of fresh concrete [20, 21]. The characteristic equation is shown below:

$$\tau = \tau_0 + \eta \frac{dv}{dt}$$  

where: $\tau$ is the shear stress; $\tau_0$ is the yield shear stress; $\eta$ is the plastic viscosity coefficient; $dv/dt$ is the shear deformation rate.

In the equation, $\tau_0$ is mainly determined by the adhesion and friction between particles of a mixture. The main factors influencing $\tau_0$ are the amount and gradation of aggregate, its particle size and shape, and the type of admixture, which contribute the most to the shear strength to prevent plastic deformation of fresh concrete. Lager $\tau_0$ indicates poorer flow properties. The $\eta$ of Eq. (1) is governed by the velocity gradient and the shear stress of fresh concrete, which may quantitively describe the internal structural performance of fresh concrete. When $dv/dt$ less than a certain value, $\eta$ is assumed as a constant $\eta_0$, so the mixture exhibits solid state characteristics. With the increase of $dv/dt$, the $\tau$ value increases and $\eta$ decreases, because the shear stress is higher than the strength provided by cohesion between particle, then the flow deformation occurs. When $dv/dt$ increases beyond a certain value ($\tau \geq \tau_0$), the cohesion between particles decreases to the minimum value, the $\eta$ value decreases to the minimum value $\eta_n$ and remains relatively unchanged, which may indicate that the fluidity of the mixture reaches to the maximum.

The shear stress $\tau$ is an important factor influencing the workability and uniformity of fresh concrete during mixing, paving, and compaction. Therefore, rheological parameters $\tau_0$ and $\eta$ are the main parameters reflecting the workability of fresh concrete [22]. When the shear deformation rate $dv/dt$ of the concrete is kept constant, the actual shear stress $\tau$ of the concrete can characterize the plastic vis-
viscosity coefficient $\eta$ and the yield shear stress $\tau_0$. Therefore, the actual shear stress of fresh concrete can be used to evaluate its workability under a constant shear rate. Based on this finding, G.H. Tattersall [23, 24, 25] in the United Kingdom used a food agitator to measure the rheological parameters of concrete, and then developed the corresponding rotary viscometer and established the relational expressions as shown in Eq. (2):

Table 3. Cement concrete mixture ratio.

| Mix Design | water (kg/m³) | Cement (kg/m³) | Sand (kg/m³) | Gravel (kg/m³) | Additives (kg/m³) |
|------------|---------------|----------------|--------------|----------------|------------------|
| Mixture 1  | 247.0         | 360.0          | 814.5        | 990.6          | 0.0              |
| Mixture 2  | 197.4         | 420.0          | 641.7        | 1141.0         | 0.0              |
| Mixture 3  | 160.0         | 372.0          | 710.0        | 1158.0         | 2.3              |

![Figure 4. Power identification system flow chart.](image)

![Figure 5. (a) The stirring power changes with stirring time and (b) filtered results.](image)
\[ T = g + hN \tag{2} \]

where: \( T \) is the agitator shaft torque (N·m); \( N \) is the agitator shaft rotational speed (r/min); \( g \) is a constant proportional to the yield shear stress; \( h \) is a constant proportional to the plastic viscosity.

By analyzing and comparing the rheological equations, it indicates that the torque of the mixing blade can reflect the workability of fresh concrete during the mixing process. If the rotational speed of the stirring apparatus is maintained at a constant value, the stirring power shows a strong linear relationship with the stirring torque in Figure 1.

The rotational speed of a mixer can be monitored and controlled by installing a variable frequency speed control system and a speed sensor, and a torque sensor can be used to detect the agitator shaft torque. During the mixing process, the mixer is controlled to rotate at a constant speed, the stirring power is calculated by monitoring the magnitude of the torque, and the workability of fresh concrete is analyzed based on changes of the power data during the mixing process.

3. Design of the proposed testing system

3.1. The testing mixer

In this study, to perform the laboratory concrete mixing power tests, a lab scale twin-shaft mixer was designed as shown in Figure 2(a) and (b). A torque sensor and a speed sensor are mounted on the agitating shaft, the main operational parameters of the mixer are summarized in Table 1.

3.2. The control circuit system

The rotational speed of the mixer is required to be constant during the mixing process. In this study, to control the speed and collect power data, according to requirements of the motor’s operational and output parameters, a Programmable Logic Controllers (PLC), an analog module, an inverter and encoder, and other components and equipment were selected as shown in Table 2.

A high-speed counter in the PLC was selected. Connections of the circuit are shown in Figure 3. For the PLC programming, a high-speed counter was used for speed data acquisition, through a PID loop and an analog module with D/A converter output 4 mA–20 mA adjustment signal. A frequency converter was used to adjust the frequency and change the motor speed. An encoder was used to measure the motor speed and provide feedback to the PLC to form a closed-loop speed control system. According to concrete test mixer specifications [26, 27], the rotational speed is controlled at 55 ± 1 r/min in this study.

To ensure the mixer rotates at a constant speed, a power control and monitoring system was also designed, which consists of a torque sensor, a torsion detection, a control device, RS485/RS232 communication cables, a switching power supply, and a custom-developed LabVIEW program. The system can collect, process, analyze, and store the stirring power data of during the mixing process.

Figure 4 shows the signal flow chart of the system. A torque sensor was installed on the stirring shaft of the mixer, and the torque and measure controller were connected to display the torque value. Through the RS485/RS232 communication cables connected to the PC side, the LabVIEW program can establish serial communications. A corresponding program was also developed to display the collected waveform data. When the mixing quality meets the requirements, a signal was sent to the mixer to terminate the mixing process and discharge the mixture.

4. Materials and mix designs

For commercial mixers, different stirring apparatus and methods are used, so the time for the concrete to achieve the best workability may not be the same. In addition, different concrete mix designs may not yield the same optimal mixing time. Therefore, lab tests using the design system were conducted on different mix designs to study the mixing time required for the optimal workability.

In this study, crushed limestone aggregate with three size ranges (19 mm–26.5 mm, 9.5 mm–19.0 mm, and 4.75 mm–9.5 mm), the
Type I/II cement, and an air-entraining agent were used for testing. Three typical mix designs of ordinary concrete are prepared as shown in Table 3. A water reducer was added to the Mixture 3 to observe its influence on the optimal mixing time in terms of workability.

| No. | 1st Trough (s) | 2nd Trough (s) |
|-----|----------------|----------------|
| 1   | 44             | 90             |
| 2   | 46             | 88             |

5. Testing results

5.1. Analysis of stirring power data

For the Mixture 1, the slump value was 19 cm due to its high water cement ratio. During the mixing process, the materials were fed in the order of sand, gravel, cement, and water. The aggregate and cement were added in the first 20 s, water was added after 20 s, and the total mixing time was 150 s. The raw and wavelet-processed stirring power data are shown in Figure 5(a) and (b). To filter the data noise, the one-dimensional discrete wavelet analysis was used, and the db5 wavelet function with 4-level decomposition was performed.
Because the stirring power is related to the relative movement speed of the material, the yield shear stress, cohesive force and other factors [28], and the hydration reaction occurs during the mixing process, changes in the mechanical properties of concrete can affect the workability of fresh concrete [29]. Therefore, the stirring power consumed during mixing is an important indicator of workability, and the mixing process can be divided into four stages as following:

Stage 1 (approximate 0–20s): Since no water was added, particle interlocking between aggregates were severe due to lack of lubrication. The stirring power increased dramatically with the addition of materials. After all the materials were added, the stirring power reached to the maximum value.

Stage 2 (approximate 20s–45s): Due to the lubrication of water, the friction and shearing between particles decreased. After adding cement, the aggregate particles started forming clusters, and the relative motion of each component decreased. Therefore, the required stirring power to maintain the constant rotational speed rapidly decreased. When the uniformity of the mixture reached to the optimal, the stirring power reduced to the lowest point. However, water had not yet fully reacted with cement at this point, so the workability may not achieve the best value.

Stage 3 (approximate 45s–70s): The amount of cement participating in the hydration reactions increased, and the mixing resistance gradually increased. The lubrication effect of water started decreasing, so the stirring power increased again.

Stage 4 (after 70s): As the hydration continued, workability of the mixture gradually increased, and the stirring power decreased again. When the fresh concrete workability reached to the optimum value, the stirring power reduced to the lowest point. If stirring was continued, the particles began to peel off from the mixture, and the breakage of the aggregate started to increase, so the stirring power slightly increased again.

Based on the observations, the stirring power of the mixer experienced two troughs, and the mixture yielded the best workability at the second wave trough. Therefore, this study proposes a method for evaluating mixing quality and workability of fresh concrete as shown in Figure 6. A LabVIEW program was developed to collect the stirring power data in real time and to perform the wavelet analysis for smoothing the power data. The processed power data were used to identify the second wave trough using a minimum detection function. When the second trough appears, the workability of the fresh concrete was determined as the best, and the corresponding mixing time was considered as the optimal mixing time.

### 5.2. Verifications of the proposed method

To verify that the proposed method, a second test was conducted on the Mixture 1 of Table 3. The same power monitoring system was used for

| No. | 1st Trough (s) | 2nd Trough (s) |
|-----|---------------|----------------|
| 1   | 60            | 89             |
| 2   | 65            | 91             |
| 3   | 61            | 92             |

No. 1st Trough (s) 2nd Trough (s)
1 60 89
2 65 91
3 61 92

| No. | 1st Trough (s) | 2nd Trough (s) |
|-----|---------------|----------------|
| 1   | 73            | 109            |
| 2   | 75            | 106            |

Table 6. The occurrence time of the two troughs of the three replicated tests on the Mixture 3.

Figure 9. The raw and processed stirring power data of the two replicated tests on the Mixture 3.
data display, filtering and analysis. The trend line of the string power data is shown in Figure 7. The occurrence time of the two troughs are compared in Table 4, which show that the occurrence time for the two troughs were about the same.

In this study, the proposed testing method was also conducted on a drier mix design with the slump value of 9 cm (Mixture 2 of Table 3) with three replicated tests. The raw and processed power data are presented in Figure 8, and the occurrence time of the two troughs for each test are summarized in Table 5. The test results show that changing trends of the processed power data are consistent for the three tests, and the second wave trough appears at approximately the same time, which indicates that the proposed method can be applied to mixtures with very different mix designs.

5.3. Test results of mixture with the water reducer

Water reducer can help reduce the water usage to meet slump requirements. The addition of water-reducing agent in concrete cannot only increase the fluidity of the concrete, but also help disperse cement particles, which promotes the hydration and further increase of strength. To verify whether the proposed method can be applied on mixtures with water-reducing agent, two replicated tests with 180 s mixing time were conducted on the Mixture 3 of Table 3. The results are shown in Figure 9 and Table 6, which show that changing trends of the string power of the two replicated tests are very similar, and the occurrence of the second wave trough were about the same but later than those of the mixtures without the water reducer.

Figure 10. The change of slump values of the Mixture 1 and 2 versus the mixing time.

Figure 11. The change of slump values of the Mixture 3 versus the mixing time.
5.4. Comparison between the proposed method to the slump test

In this study, to verify whether the test results of the proposed method are consistent with those obtained from the traditional method for evaluating the workability, a separate batch for conducting slump test at different mixing time was conducted (Table 3). The slump values of the Mixture 1 and 2 measured at different mixing time are shown in Figure 10, which shows that the maximum slump of the two mixtures occur at approximate 80s. The optimal mixing time of the two mixtures determined by the proposed method was around 90s (See Tables 4 and 5). The R² of the fitted curves are 0.9554 and 0.9402, respectively.

The slump test was also performed on the Mixture 3 with water-reducing agent at different mixing time. The test results are shown in Figure 11. The R² of the fitted curve is 0.9092.

As can be seen in Figure 11, the maximum slump occurs between 90s and 110s. Comparing to Table 6, the time of the second trough occurs within the range, which indicates the proposed method and system can be applied to mixtures with very different mix designs and with/without water reducers.

6. Conclusion

In this study, a lab two-shaft mixer with a rotation speed control system and a power monitoring system installed was designed and tested to address the problem that the traditional quality control technology cannot allow workability of fresh concrete to be monitored during the mixing process. The lab mixing test conducted using the developed system was performed on different mix designs and compared to the conventional slump test, and testing results indicate that the proposed approach and developed system can be used for fresh concrete with very different mix designs.

The stirring power during the mixing process can be determined by controlling the mixer to operate at a constant speed, and the magnitude of the torque can be monitored. By monitoring changes of the power data, the optimal workability of fresh concrete usually occurs when the second wave trough of the filtered power data observed. Test results of different types of concrete show that the proposed method can be applied on fresh concrete with very different mix designs. The comparison with the slump test shows that the proposed method can accurately identify the optimal mixing time for fresh concrete in terms of workability.

Declarations

Author contribution statement

Xin Rong: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Honghui Liu: Conceived and designed the experiments.
Cheng Li: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/ supp. material/referenced in article.

Declaration of interest’s statement

The authors declare no conflict of interest.

No additional information is available for this paper.

References

[1] B.T. Ly, H. Far, Investigation on properties of coarse reclaimed aggregates and their effects on concrete strength and workability, Struct. Concr. 20 (5) (2019) 1622–1630.
[2] J. Thomas, N.N. Thaikavil, P.M. Wilson, Strength and durability of concrete containing recycled concrete aggregates, J. Build. Eng. 19 (2018) 349–365.
[3] E.N. Amajean, M. Mouree, T. Vidal, Effect of design parameters on the properties of ultra-high performance fibre-reinforced concrete in the fresh state, Construct. Build. Mater. 224 (2019) 1007–1017.
[4] S.M. Dehghan, M.A. Najafzad, V. Baneshi, et al., Experimental study on effect of water-cement ratio and sand grading on workability and mechanical properties of Masonry Mortars in Iran, Iran. J. Sci. Technol.-Trans. Civ. Eng. 43 (1) (2019) 21–32.
[5] Haipeng Gao, Bo Tian, Hao Gaojun, et al., Evaluation method of uniformity of new cement concrete mixture, J. Highway. Transp. Res. Dev.(Chin. Ed.) 31 (12) (2015) 25–30.
[6] Aijun Yue, Junlin Liang, Jianping Xiong, Research on the Road concrete mixing uniformity control technology, Appl. Mech. Mater. 94–96 (2011) 2157.
[7] Haipeng Gao, Bo Tian, Ziyi Hou, Experimental study on gap-graded concrete mixing uniformity, Adv. Mater. Res. 857 (2014) 42.
[8] Peng Yang, Junliang Weng, Gongzheng Lv, et al., Research of mixing technology of double helix concrete mixer mixing high-strength concrete, Concrete 2 (2013) 152–156.
[9] Zhiyong He, Tao Wang, Optimal design of the key structure of planetary concrete mixers based on EDEM, Int. J. Mater. Prod. Technol. 62 (4) (2021) 295–310.
[10] Fang Dong, Mingkai Zhou, Huangang Wang, Influence of mixing time on workability and strength properties of concrete in different consistency, Adv. Mater. Res. 217–218 (2011) 1224–1228.
[11] Liye Wang, Ming Lu, Jieng Dong, Influence of blade angle of single horizontal shaft mixer on mixture concrete inhomogeneity, Water Resour. Power. 33 (6) (2015) 98–106.
[12] A. Oztas, M. Pala, E. Ozbay, et al., Predicting the compressive strength and slump of high strength concrete using neural network, Construct. Build. Mater. 20 (9) (2006) 769–775.
[13] K. Shaswati, Concrete slump prediction modeling with a fine-tuned convolutional neural network: hybridizing sea lion and dragonfly algorithms, Environ. Sci. Pollut. Res. (2021).
[14] Xiao Liu, Application research on high performance concrete water-binder ratio test method, Low Carbon World 10 (2016) 181–182.
[15] Lv Chunmei, Application research on quality inspection technology of fresh concrete, Fujian Build. Mater. 4 (2016) 13–15.
[16] J.Y. Zhang, X.J. Gao, Y. Su, Influence of Poker vibration on aggregate settlement in fresh concrete with variable rheological properties, J. Mater. Civ. Eng. 31 (7) (2019).
[17] V. Mechtcherine, A. Gram, K. Kremer, J.H. Schwabe, et al., Simulation of fresh concrete flow using Discrete Element Method (DEM): theory and applications, Mater. Struct. 47 (4) (2014) 615–630.
[18] D. Feys, J.E. Wallevik, A. Yahia, et al., Extension of the Reiner-Riwlin equation to concrete Mater. Struct. 47 (4) (2014) 615–630.
[19] Z. G. Li, G.D. Cao, Rheological behaviors and model of fresh concrete in vibrated state, Cement Concr. Res. 120 (2019) 217–226.
[20] W. Cui, T.Z. Ji, M. Li, et al., Simulating the workability of fresh self-compacting concrete with random polyhedron aggregate based on DEM, Mater. Struct. 50 (1) (2017).
[21] L. Prasittisopin, D. Troef, Effects of mixing time and revolution count on characteristics of blended cement containing rice husk ash, J. Mater. Civ. Eng. 30 (1) (2018).
[22] D. Troef, L. Prasittisopin, Effects of mixing variables on early-age characteristics of Portland cement systems, J. Mater. Civ. Eng. 28 (10) (2016).
[23] M.H. Bae, Y.T. Bae, D.J. Kim, The strength analysis of differential planetary gears of gearbox for concrete mixer truck, in: 4th International Conference on Advanced Engineering and Technology, 2018, p. 317.
[24] Wei Ding, et al., Introduction to general concrete mixing ratio design regulations (JGJ 55-2011), Qual. Stand. 12 (2011) 76–79.
[25] Jian Feng, Several points in the application of new version of concrete mix design, China Concr. Gem. Prod. 10 (2012) 36–39.
[26] M.K. Kim, H. Sohn, C.C. Chang, Active dimensional quality assessment of precast concrete using 3D laser scanning, Comput. Civ. Eng. (2013) 621–628.
[27] Alessandro P. Fantilli, Bernardino Chiaia, Barbara Frigo, A simplified approach to the evaluation of the strength of old concrete, Construct. Mater. 171 (6) (2017) 257–266.
[28] L. Klus, V. Vaclavik, T. Dvorsky, et al., Reuse of waste material from a concrete plant in cement composites: a case study, Appl. Sci.-Basel 9 (21) (2019).
[29] S.H. Chu, Effect of paste volume on fresh and hardened properties of concrete, Construct. Build. Mater. 218 (2019) 284–294.