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Study on Calculation Model for Compressive Strength of Water Saturated Recycled Aggregate Concrete

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ABSTRACT

It has been proved that the compressive strength of water saturated concrete is lower than that of air dry concrete. Due to the water absorption of recycled aggregate (RA) is noticeably higher than that of natural aggregate (NA), the mechanical properties of water saturated recycled aggregate concrete (RAC) are quite different from those of water saturated natural aggregate concrete (NAC). At the same time, the calculation of concrete compressive strength is the first step of concrete mix proportion design. Therefore, it is essential to investigate the compressive strength of RAC in water saturated state. In this study, firstly, the water content and effective water absorption of NA, recycled brick aggregate (RBA) and recycled concrete aggregate (RCA), as well as the water content and effective water absorption of concrete specimen were tested; secondly, the effects of water/cement ratio, water saturation and coarse aggregate types on the compressive strength of water saturated concrete were studied; finally, the calculation model for compressive strength of water saturated concrete was proposed. The test results show that: Within 120 hours, the maximum effective water absorption of NA, RCA and RBA is 0.32%, 0.61% and 8.18%, respectively. Within 240 hour, the maximum effective water absorption of NAC, recycled concrete aggregate concrete (RCAC) and recycled brick aggregate concrete (RBAC) is 0.73%, 0.81% and 1.89%, respectively. In air dry and water saturated state, the descending order of compressive strength of concrete is: NAC > RCAC > RBAC. The average relative error of the calculation model for compressive strength of water saturated concrete is 7.1%. In the calculation model, water/cement ratio, effective water absorption, water saturation and coarse aggregate types are considered. The results of this study have great significance for the mix proportion design of water saturated concrete.

1. Introduction

Due to the demolition of the old building, a great of construction wastes are produced in worldwide. Therefore, construction waste recycling is very important to the sustainable development of environmental protection. Recycled aggregate concrete made from crushed brick or concrete has great application potential. Recycled brick aggregate concrete (RBAC) is made of recycled brick aggregate (RBA), cement, sand and water. Recycled concrete aggregate concrete (RCAC) is made of recycled concrete aggregate (RCA), cement, sand and water. Recycled aggregate concrete (RAC) includes RBAC and RCAC.

Different from natural aggregate (NA), RBA and RCA have lower apparent density, higher crushing index and water absorption (Debieb and Kenai, 2008; Younis and Pilakoutas, 2013; Tanja et al., 2017), which negatively influence the strength and durability of RAC. The mechanical properties of RAC have been studied extensively (Dhar et al., 2018; Dimitriou et al., 2018; Kurda et al., 2018). In addition, the frequent occurrence of extreme weather, rainstorm, flood and other natural disasters make urban or village buildings often in short-term water environment, and there are also dams, piers, swimming pools, reservoirs, basements and other underwater structures in long-term water environment. In water environment, water will infiltrate into the concrete through its pores. Previous studies have shown that the compressive strength of wet concrete reduced by about 20% (Wang et al., 2017) and the tensile strength of wet concrete reduced by about 36% (Selyutina and Petrov, 2018) comparison with air dry

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concrete. Therefore, the mechanical properties of water saturated RAC will influence its further application.

Water saturation and loading rate are important factors, which influence the strength, Poisson's ratio, failure mode and elastic modulus of concrete with static and dynamic loading in many studies. It has been found that the strength of water saturated concrete gradually decreased with the increase of water saturation (Xu et al., 2011; Wang et al., 2017). Singh and Xuan et al. (Singh et al., 2008; Xuan et al., 2009) also pointed that water saturation greatly impacted the mechanical properties of concrete. Zhang et al. (2020) indicated that in water saturation state the compressive strength of concrete decreased about 23% and the elastic modulus of concrete increased about 20% compared with air dry state under different concrete strength grades condition. Furthermore, Wang et al. (2017) studied the elastic modulus and strength of fly ash concrete with different water saturation. They found elastic modulus increased gradually with increasing of water saturation, while the compressive strength decreased gradually with increasing of water saturation. In addition, Wang et al. (2009) indicated that under static loading condition the tensile and compressive strength of wet concrete were lower than those of air dry concrete, while under dynamic loading condition the tensile and compressive strength of wet concrete were higher than those of air dry concrete. In addition, Wu et al. (2012) found that under the condition of low loading rare the flexural strength of wet concrete decreased, but the elastic modulus of wet concrete increased; under the condition of high loading rate Poisson's ratio of wet concrete was almost stable, but flexural strength and elastic modulus of wet concrete reduced. Other studies have shown that elastic modulus, strength and impact toughness of water saturated concrete were significantly affected by loading rate. Ranjith et al. (2008) presented the compressive strength decreased with loading rate under the condition of different water saturation of concrete. Similar studies can be found with the literature of Zhou et al. (2011). What is more, Rossi et al. (1992) observed that the compressive and tensile strength were influenced by higher loading rate under the higher water saturation condition. In another study by Fu et al. (2021) found that the compressive strength and elastic modulus of coral aggregate concrete were improved by the pore water pressure with dynamic loading rate. Nevertheless, Ren et al. (2015) found that the strength and impact toughness of water saturated concrete increased with the increase of loading rate, while the elastic modulus of water saturated had no significant change.

Under the condition of confining pressure, the compressive strength of water saturated and dry concrete increased greatly (Chen et al., 2010). But the water saturated concrete was more sensitive to loading speed than dry concrete (Wang et al., 2016b). Under real water pressure, the compressive strength of dry concrete was lower than its uniaxial compressive strength, while the compressive strength of water saturated concrete was more closer to its uniaxial compressive strength (Wang et al., 2016a).

It is widely known that the calculation of concrete compressive strength is the first step of concrete mix proportion design. As a result, some researchers began to focus on the calculation of concrete compressive strength. Younis and Pilakoutas (2013) developed a multivariable model to predict the compressive strength of RAC, in which the density and water absorption of recycled aggregate (RA) were considered. Janani and Santhi (2018) evaluated a multiple linear regression model to predict the strength of concrete by using SPSS (Statistical Package for Social Sciences) software. In the study by Zhang et al. (2018), water/cement ratio and sand rate were used as the independent parameters for compressive strength model of RAC. Furthermore, Chen et al. (2019) presented a model for calculating the compressive strength of RAC, in which the replacement rate of RBA and curing ages of concrete specimen were considered, respectively.

Bolomey Formula is often used to calculate the compressive strength of conventional concrete. The modified parameter A and B values in Bolomey Formula of RAC was discussed by Zhang et al. (2007). Koper et al. (2016) modified Bolomey Formula considering water demand of RA. What is more, Ashish and Verma (2019) proposed impact factor by modifying Bolomey Formula to develop a more accurate model of pozzolanic concrete. According to Kargari et al. (2018), they proposed a calculation model of compressive and flexural strength of concrete by modifing Bolomey Formula, in which sand/cement ratio and cement strength grade were considered. In another study by Rajamane and Ambily (2012), they developed a relationship among water/cement ratio, compressive strength and the volume fraction of lightweight aggregate based on the Bolomey Formula.

In previous studies, the factors of water saturation, loading speed and confining pressure that affected the mechanical properties of concrete were considered, while the factors of water/cement ratio, water absorption and coarse aggregate types were not considered. Although some calculation models for compressive strength of RAC were proposed, the formula for calculating the compressive strength of water saturated RAC is still in the blank. The calculation of concrete compressive strength is the first step of concrete mix proportion design. Therefore, in this paper the water content and effective water absorption of NA, RBA and RCA, as well as the water content and effective water absorption of concrete specimen were tested; secondly, the effects of water saturation, water/cement ratio and aggregate types on the compressive strength of water saturated concrete were studied; finally, the calculation model for compressive strength of water saturated concrete was proposed. The results of this study have great significance for the mix proportion design of RAC.

2. Test Details

2.1 Materials

The Portland cement was 32.5R grade. Fine aggregate was river sand with water content of 0.1%, apparent density of 2,640 kg/m^3 and fineness modulus of 2.76. The physical properties of NA,

Table 1. Physical Properties of Coarse Aggregate

Coarse aggregate types	Apparent density/kg/m^3	Bulk density/ kg/m^3	Crushing value/%
RBA	2,100	1,012	22
RCA	2,622	1,336	12
NA	2,713	1,401	10

RCA and RBA are shown in Table 1. The apparent density of coarse aggregate was tested by the standard of ASTM C136 (2014); the bulk density of coarse aggregate was tested by the standard of ASTM C29/C29M (2007); the crushing value of coarse aggregate was tested by the standard of BS 812-110:1990 (1990). The particle size distribution of RA produced by crusher does not comply to ASTM C330/C330M (2017), so the particle size distribution needs to be adjusted by sieves. The adjusted grading curve of RA is shown in Fig. 1.

2.2 Test of Water Content and Effective Water Absorption of Coarse Aggregate

The relationship between water absorption and water content of coarse aggregate is shown in Fig. 2. Water content of coarse aggregate is determined from oven dry state to air dry state, effective water absorption of coarse aggregate is determined from air dry state to saturated-surface dry (SSD) state, and water absorption of coarse aggregate is determined from oven dry state to SSD state. In the design of mix proportion, the coarse aggregate was used with SSD state, so the water content and effective water absorption of NA, RCA and RBA were tested, respectively, and water content plus effective water absorption equals water absorption. The water content and effective water content of coarse aggregate were determined by Test Method ASTM C127 (2015).

2.3 Mix Proportion Design

The effects of water/cement ratio and coarse aggregate types on

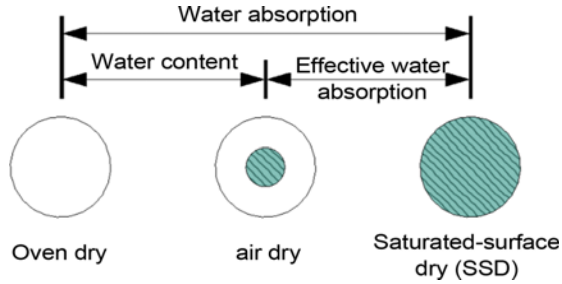


Fig. 2. Relationship between Water Content and Water Absorption of Coarse Aggregate

the mechanical properties of concrete in air dry and SSD state were considered in mix proportion. The water/cement ratio is 0.41, 0.46, 0.52 and 0.63, respectively. The coarse aggregate types include RBA, RCA and NA. The mix proportion was designed according to ACI 211.1 (1991) and ACI 211.2 (1998) as shown in Table 2, in which RBA and RCA were pre-wetted to SSD state before mixing (Salgues et al., 2017).

2.4 Test of Water Content, Effective Water Absorption and Compressive Strength of Concrete Specimen

Concrete specimen is a cube with side length of 150 mm. According to Table 2, with each mix proportion 15 concrete specimens were made to test the compressive strength with water saturation of 0%, 25%, 50%, 75% and 100%, respectively. The concrete specimens were lifted out of the curing room and dried at 28 ± 2°C and 5% relative humidity in the natural environment after 28 days of standard curing. The weight of concrete specimens were measured every 30 minutes, it was found the water content of concrete specimens was stable at about 48 hours. Then, one part of the concrete specimens were tested for compressive strength in air dry state, and the other parts were put into the water tank to ensure that the concrete specimens were completely submerged in water for effective water absorption test.

The water content of concrete specimen was tested by oven

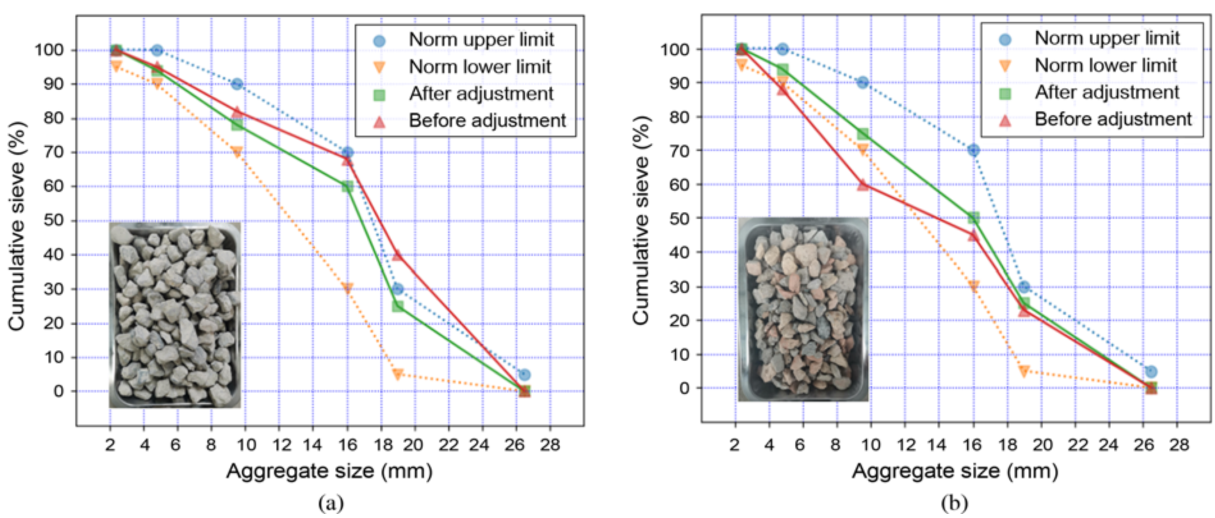


Fig. 1. RA Gradation Curve: (a) RCA Gradation Curve, (b) RBA Gradation Curve

Table 2. Test Mix Proportion

Specimen number	Water/ cement ratio	Dosage of constituent materials in 1m³ concrete/kg(m³)										Sand ratio
		Water/kg	Cement/kg	RBA/kg	RBA/m³	RCA/kg	RCA/m³	NA/kg	NA/m³	Sand/kg	Sand/m³	
H1	0.63	205	325	0	0	0	0	1,309	0.4825	561	0.2125	30%
H2	0.52	205	394	0	0	0	0	1,243	0.4582	558	0.2114	31%
H3	0.46	205	446	0	0	0	0	1,172	0.4320	577	0.2186	33%
H4	0.41	205	500	0	0	0	0	1,085	0.3999	610	0.2311	36%
H5	0.63	205	325	1,013	0.4825	0	0	0	0	561	0.2125	30%
H6	0.52	205	394	962	0.4582	0	0	0	0	558	0.2114	31%
H7	0.46	205	446	907	0.4320	0	0	0	0	577	0.2186	33%
H8	0.41	205	500	840	0.3999	0	0	0	0	610	0.2311	36%
H9	0.63	205	325	0	0	1,265	0.4825	0	0	561	0.2125	30%
H10	0.52	205	394	0	0	1,201	0.4582	0	0	558	0.2114	31%
H11	0.46	205	446	0	0	1,133	0.4320	0	0	577	0.2186	33%
H12	0.41	205	500	0	0	1,049	0.3999	0	0	610	0.2311	36%

method. Firstly, the concrete specimens cured for 28 days were moved to the natural environment for drying. When the water content of the concrete specimen was stable, the concrete specimens were moved to the oven for drying, until the mass of concrete specimen was stable, which was regarded as completely dry.

The test steps of effective water absorption of concrete specimen are as follows: 1) the concrete specimens are put into the water tank to ensure that the concrete specimens are completely immersed in water. The mass of concrete specimen is recorded every 30 minutes, and then the recording time is increased gradually. 2) Before measuring the weigh of concrete specimens, the concrete specimens are taken out from the water tank and dried for 3 minutes. Then, wiping the water off the surface of the concrete specimens with a rag. 3) When measuring the weigh of concrete specimens, the concrete specimens should be taken out and put in gently to prevent the concrete specimens from bump. 4) Considering the discreteness of the test data, three concrete specimens are tested for each mix proportion, and the average value of the three test values is adopted. If the maximum error is more than 15%, the maximum and minimum values are discarded and the intermediate value is adopted.

The compressive strength test was determined by Test Method ASTM C39/C39M (2018), and the loading equipment was TYA-2000 electro-hydraulic pressure testing machine.

3. Results and Analysis

3.1 Results and Analysis of Water Content and Effective Water Absorption of Coarse Aggregate

The results show that the water content of NA, RCA and RBA is 0.94%, 1.32% and 2.46%, respectively. The water content of RCA and RBA is approximately 1.4 times and 2.6 times of NA. The attached cement mortar on the RCA surface and the inherent high porosity of RBA are considered responsible for their high water content. The similar conclusion was found in the literature (Chen et al., 2019).

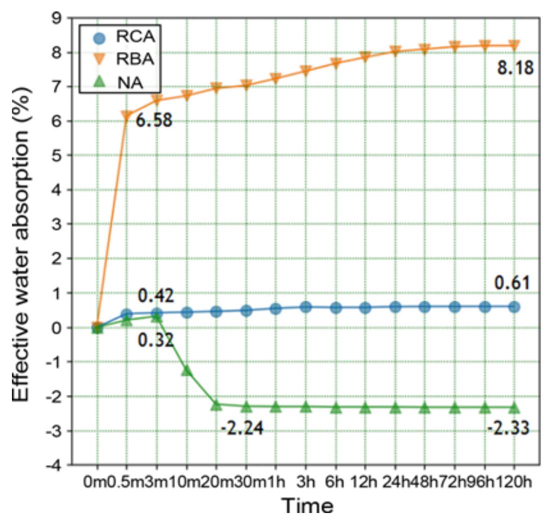


Fig. 3. Relationship between Effective Water Absorption of Coarse Aggregate and Water-Immersion Time

The effective water absorption of coarse aggregate is calculated by Eq. (1):

$$P_{aggregate} = \frac{m_{w-s} - m_{dry}}{m_{dry}}, \tag{1}$$

where $P_{aggregate}$ is the effective water absorption of coarse aggregate; m_{dry} is the mass of air dry coarse aggregate; m_{w-s} is the mass of water saturated coarse aggregate.

The relationship between effective water absorption of coarse aggregate and water-immersion time is shown in Fig. 3. It can be seen that the effective water absorption of three kinds of coarse aggregates is stable at about 24 hours. The final effective water absorption of RBA, RCA and NA is 8.18%, 0.61% and 0.32%, respectively. The effective water absorption of RBA is 13 and 25 times higher than that of RCA and NA, respectively. The reason is that the porosity of RBA are larger than that of NA and RCA. The effective water absorption of RCA is about 2 times than that of NA.

The reason is that the surface of RCA is attached with cement mortar, which leads to large porosity and strong hygroscopicity.

It also can be seen from Fig. 3 that the effective water absorption of the three coarse aggregates rises rapidly within almost 5 minutes of water-immersion, and then gradually slows down. The effective water absorption of RBA rises with water-immersion time and is stable around 24 hours. The effective water absorption of RCA also gradually rises with the increase of water-immersion time, but the rising range is lower than that of RBA. This is because the cement mortar on the surface of RCA falls off after long time water-immersion, which leads to the decline of effective water absorption. The effective water absorption of NA rises first, then declines, and finally tends to be stable. The reason is that the porosity of NA is lower than that of RCA and RBA, and the apparent density of NA is higher than that of RCA and RBA. With the increase of water-immersion time, the dust and dirt on the surface of NA fall off due to the water-immersion, which leads to the negative value of effective water absorption calculated by Eq. (1).

3.2 Results and Analysis of Water Content and Effective Water Absorption of Concrete Specimen

The water content and effective water absorption of concrete specimen are calculated by Eqs. (2) and (3), respectively:

$$w_{concrete} = \frac{m_{c-dry} - m_{c-c-dry}}{m_{c-dry}}, \tag{2}$$

$$w_{effective} = \frac{m_{c-w-s} - m_{c-dry}}{m_{c-dry}}, \tag{3}$$

where $w_{concrete}$ is the water content of concrete specimen; $w_{effective}$ is the effective water absorption of concrete specimen; $m_{c\text{-}dry}$ is the mass of air dry concrete specimen; $m_{c\text{-}c\text{-}dry}$ is the mass of oven dry concrete specimen; $m_{c\text{-}w\text{-}s}$ is the mass of water saturated concrete specimen.

The test results of water content, effective water absorption and water absorption of three kinds of concrete specimens are shown in Fig. 4. It can be found that the water content and effective water absorption of the three kinds of concrete specimens rise with the increase of water/cement ratio. The descending order of both water content and effective water absorption of three kinds of concrete specimens is: RBAC > RCAC > NAC. It is also found that the maximum effective water absorption of RBAC, RCAC and NAC specimen are 1.89%, 0.81% and 0.73%, respectively, within 240 hours of water-immersion. The effective water absorption of RBAC specimen is about 2.3 times and 2.6 times than that of RCAC and NAC specimen, while the effective water absorption of RCAC specimen is close to that of NAC specimen. The reason is that the effective water absorption of RBA is much higher than that of RCA and NA, while the effective water absorption of RCA is close to that of NA.

The effective water absorption of three kinds of concrete specimens shows similar trends, which increases rapidly within 3 hours, slows down gradually after 3 hours, and is stable at about 60 hours. Zhang et al. (2020) pointed that the water absorption of NAC specimen rose rapidly in the first 3 hours, and slowly rose after 72 hours. In addition, Wu et al. (2012) also pointed that the water absorption of NAC specimen was stable in 100 hours. The test results in this study are slightly different with results reported by Zhang and Wu et al. (Wu et al., 2012; Zhang et al., 2020), the main reason is that the effective water absorption of concrete specimen was tested in this study, while the water absorption of concrete specimen was tested in the study of Zhang and Wu et al. (Wu et al., 2012; Zhang et al., 2020).

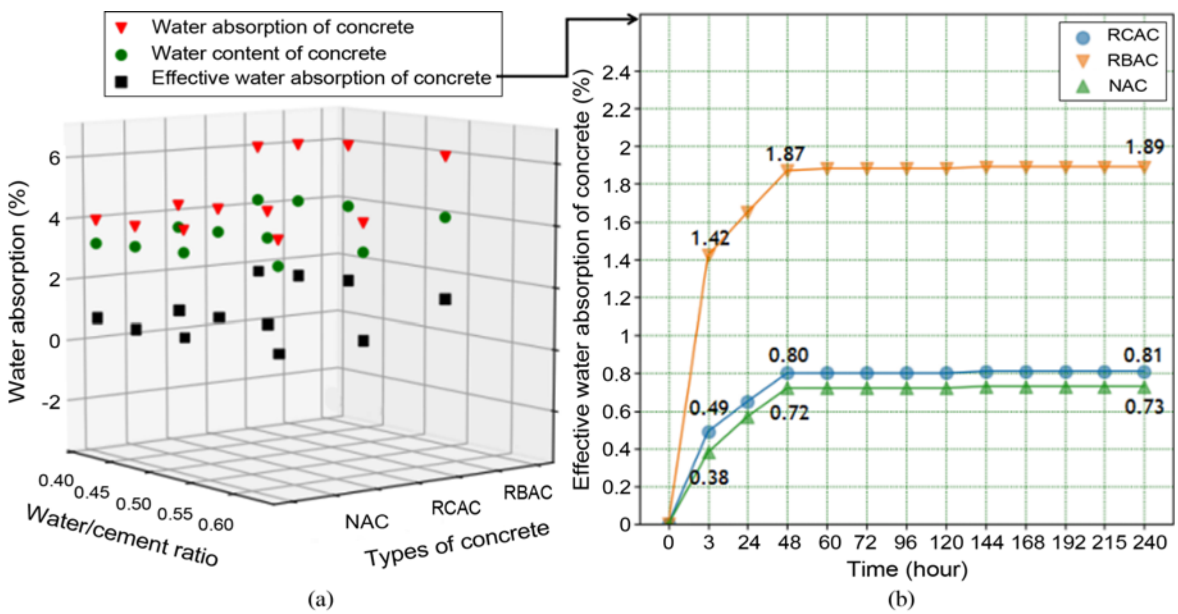
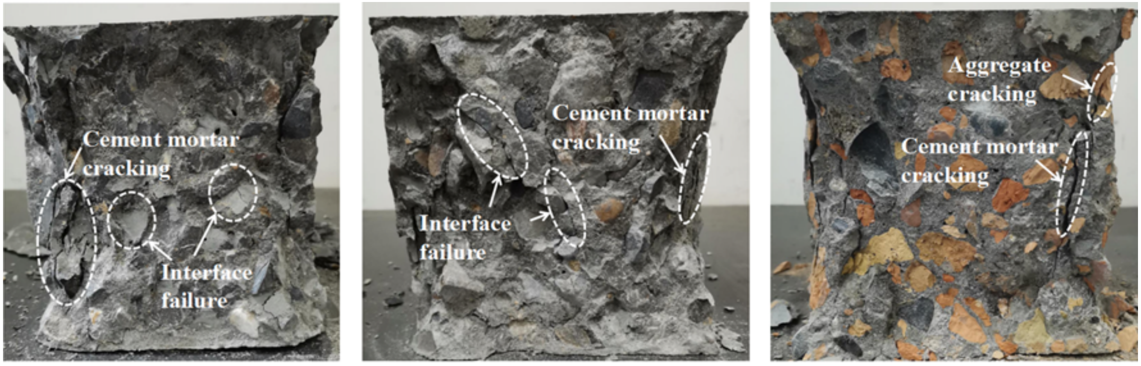


Fig. 4. Relationship between Effective Water Absorption and Water-Immersion Time: (a) Water Absorption, Water Content and Effective Water Absorption, (b) Effective Water Absorption



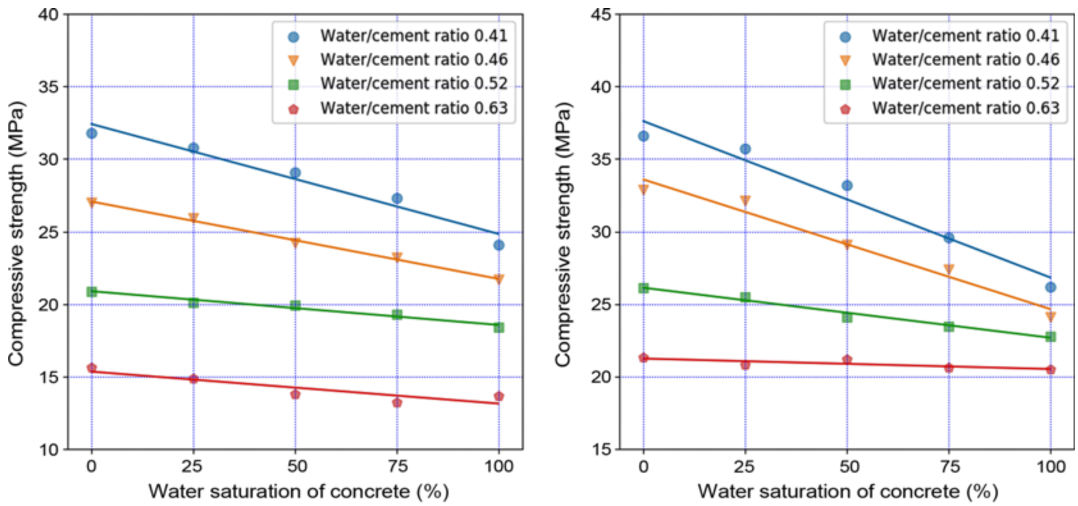
(a) (b) (c)

Fig. 5. The Damage Diagram of Concrete in Air Dry State: (a) NAC, (b) RCAC, (c) RBAC

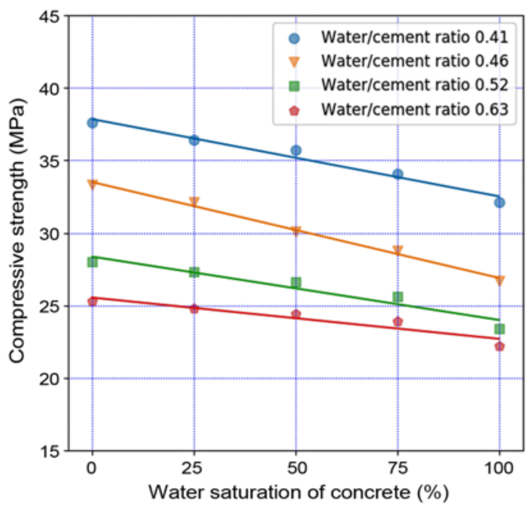
3.3 Results and Analysis of Compressive Strength of Concrete

3.3.1 Damage Phenomena

In air dry state, the damage phenomena of NAC and RCAC is similar, as shown in Fig. 5. At the beginning of loading, vertical microcracks firstly appear on the surface of concrete specimen; vertical microcracks gradually extend and form inclined cracks with the increase of loading; Inclined cracks extend to the entire concrete specimen when approaching the ultimate loading. It is



(a) (b)



(c)

Fig. 6. The Influence of Water Saturation on Compressive Strength of Three Kinds of Concrete: (a) RBAC, (b) RCAC, (c) NAC

found that for NAC and RCAC the inclined cracks mainly appear at the interface transition zone between the coarse aggregate and the cement mortar and the interior of the cement mortar, which indicates that the strength of NAC and RCAC is mainly determined by the bond strength of the interface between the coarse aggregate and the cement mortar and the strength of the cement mortar (Dimitriou et al., 2018; Kurda et al., 2018). The damage phenomena of RBAC is similar to that of RCAC and NAC. The difference is that there are many crushed recycle brick aggregates in the damaged RBAC specimen, which can be found in Fig. 5. This indicates that the strength of RBAC is not only related to the interface between RBA and cement mortar, but also related to the strength of RBA (Chen et al., 2019).

The damage phenomena of three kinds of water saturated concrete is similar with air dry concrete. The difference is that the water saturated concrete is shown the state of powder after damage, and the fragments of water saturated concrete can be crushed by hand, especially water saturated RBAC. Similar phenomenon was also found by Zhang and Wang et al. (Zhang et al., 2018; Wang et al., 2009).

3.3.2 Influence of Water Saturation on Compressive Strength of Concrete

It can be found from Fig. 6 that the compressive strength of RBAC, RCAC and NAC decreases with the increase of water saturation. Moreover, the compressive strength of RBAC, RCAC and NAC decreases almost linearly with the water saturation with different water/cement ratios. The average linear correlation coefficient of RBAC, RCAC and NAC is 0.9258, 0.8863 and 0.9444, respectively.

At present, there are two main explanations for the strength reduction of water saturated concrete: the first explanation is the theory of pore water pressure, it has been proved that pore water pressure was a major cause for the strength reduction of water saturated concrete (Shakiba et al., 2017). Konovalenko et al.

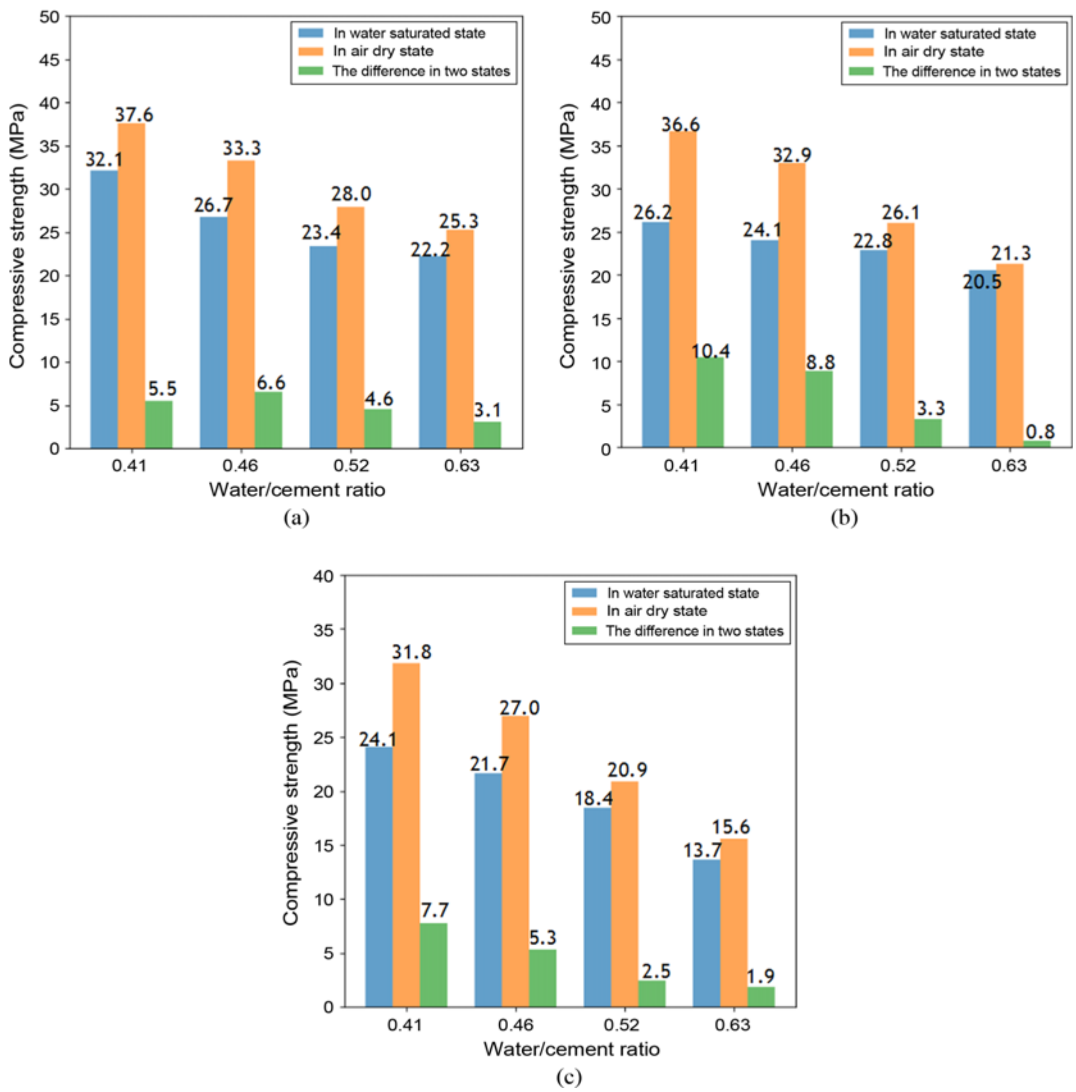


Fig. 7. Compressive Strength of Concrete in Water Saturated and Air Dry State: (a) NAC, (b) RCAC, (c) RBAC

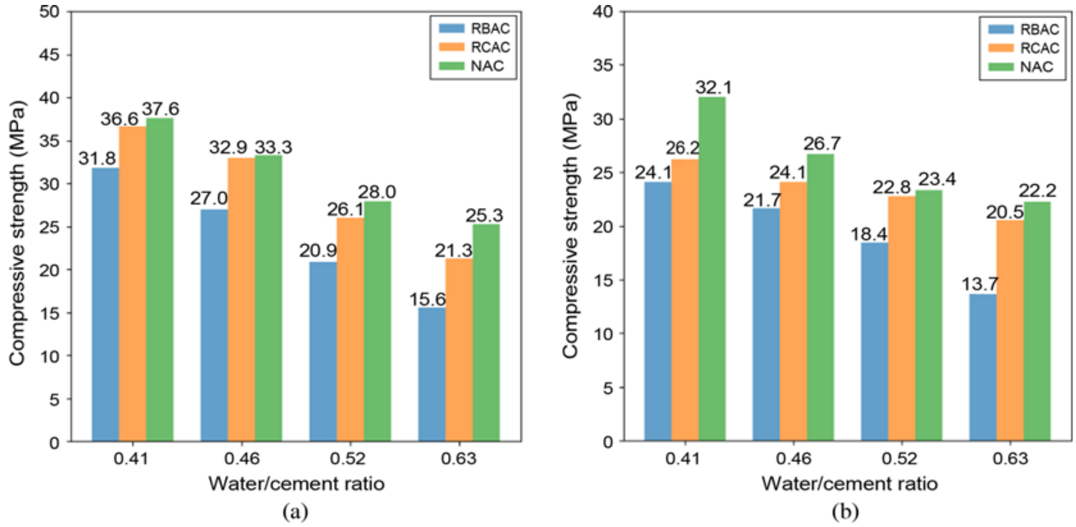


Fig. 8. Compressive Strength of Concrete with Different Water/Cement Ratios: (a) Air Dry State, (b) Water Saturated State

(2020) also reported that with pore water pressure the compressive strength of water saturated concrete reduced. Under loading the pore water was easy to reach the crack tip in concrete. At the same time, pore water accelerated the microcracks extending in concrete and reduced the strength of concrete (Oshita and Tanabe, 2000). The second explanation is the surface energy theory. Under the influence of liquid surface tension, Van der waals' force and surface energy of micro particles in concrete were decreased, which decreased the strength of concrete (Matsushita and Onoue, 2006; Wang et al., 2009).

3.3.3 Compressive Strength of Concrete in Water Saturated and Air Dry State

Figure 7 shows the compressive strength of the three kinds of concrete in water saturate and air dry state. In air dry state, it can be seen that with the four water/cement ratios the compressive strength of concrete is in a descending order as follows: NAC > RCAC > RBAC. When water/cement ratio of RCAC is 0.41, 0.46, 0.52 and 0.63, respectively, the percentage of RCAC strength reduction is 2.7%, 1.2%, 6.8% and 15.8% compared with NAC; when the water/cement ratio of RBAC is 0.41, 0.46, 0.52 and 0.63, respectively, the percentage of RBAC strength reduction is 15.4%, 18.9%, 25.4% and 38.3% compared with NAC. It also can be seen that the compressive strength of RCAC is very close to that of NAC, while the compressive strength of RBAC is much lower than that of NAC. The principal reason is the cement mortar attached the surface of RCA, which weakens the strength of interfacial transition zone between RCA and cement mortar. While the strength of RBA is much lower than that of NA and RCA, which reduces the compressive strength of RBAC.

In water saturated state, when the water/cement ratio of NAC is 0.41, 0.46, 0.52 and 0.63, respectively, the percentage of water saturated NAC strength reduction is 14.6%, 19.8%, 16.4% and 12.3% compared with air dry NAC; when the water/cement ratio of RCAC is 0.41, 0.46, 0.52 and 0.63, respectively, the percentage of water saturated RCAC strength reduction is 28.4%, 26.7%, 12.6% and 3.8% compared with air dry RCAC; when the water/cement ratio of RBAC is 0.41, 0.46, 0.52 and 0.63, respectively, the percentage of water saturated RBAC strength reduction is 24.2%, 19.6%, 12% and 12.2% compared with air dry RBAC. Wang et al. (2017) pointed out that the percentage of water saturated NAC strength reduction is 22.5% compared with air dry NAC. Zhang et al. (2020) also pointed out that the percentage of water saturated concrete strength reduction is 23.1% compared with air dry concrete. The results in this study are in accordance with Wang and Zhang's results (Wang et al., 2017; Zhang et al., 2020), but the compressive strength of RBAC decreases more significantly in water saturated state. The main reason for this is that the physical properties of RBA are inferior to those of NA and RCA.

3.3.4 Influence of Water/cement Ratio and Coarse Aggregate Types on Compressive Strength of Water Saturated Concrete

It can be found from Fig. 8 that the compressive strength of three kinds of concrete decreases with the increase of water/cement ratio in air dry state. The compressive strength of NAC is the highest, followed by RCAC, and RBAC is the lowest. The results show that the compressive strength of water saturated concrete is similar to that of air dry concrete. Water saturated NAC has the highest compressive strength, water saturated RCAC takes the second place, and water saturated RBAC has the lowest compressive strength. It can also be found from Fig. 9 that the compressive strength of three kinds of concrete exists a linear relationship with water/cement ratio, whether it is in air dry state or water saturated state.

4. Calculation Model for Compressive Strength of Water Saturated RAC

4.1 Modification of Bolomey Formula

A linear relationship is described by Bolomey Formula between

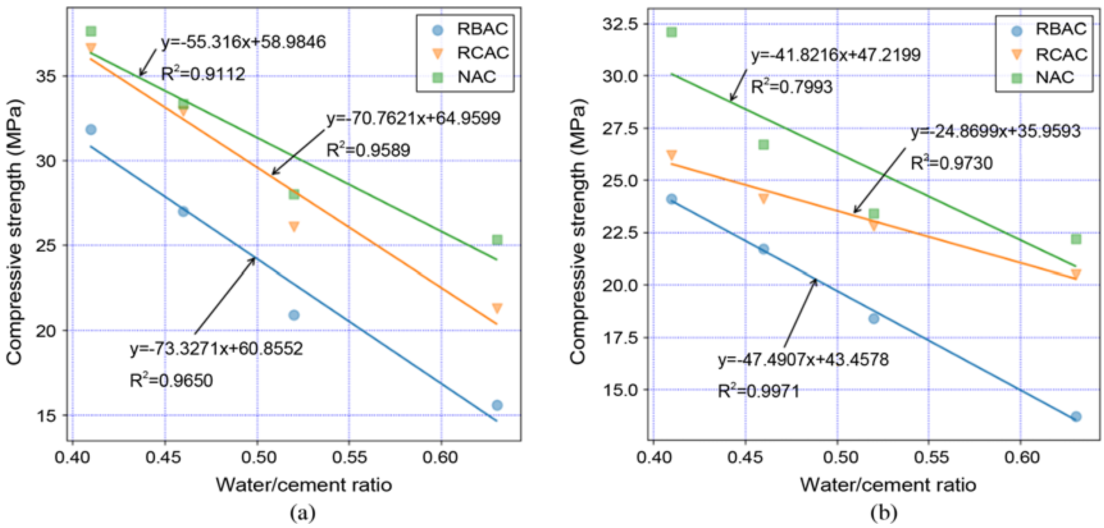


Fig. 9. The Relationship between Compressive Strength of Concrete and Water/Cement Ratio: (a) Air Dry State, (b) Water Saturated State

compressive strength of concrete and cement/water ratio as shown in Eq. (4):

$$f_{cu} = A\frac{m_c}{m_w} + B\,, \tag{4}$$

where m_c is the mass of cement; m_w is the mass of water; $A = \alpha_a f_{ce}$, $B = \alpha_a\alpha_b f_{ce}$; f_{ce} is the 28-day compressive strength of cement mortar; α_a and α_b are the regression coefficients.

Equation (4) is used to calculate the compressive strength of concrete in air dry state, while the compressive strength of RAC is lower than that of NAC, so Eq. (4) can not be used for RAC directly. Although some researchers (Zhang et al., 2007; Koper et al., 2016) have revised the Bolomey Formula for calculating the compressive strength of RAC, the study on the formula for calculating the compressive strength of water saturated RAC is still in the blank.

It can be found from Fig. 9 that the compressive strength of air dry and water saturated concrete is a highly linear relationship with the water/cement ratio. The essential reason for concrete strength reduction is that the surface energy of micro particles in concrete is reduced after water immersion into concrete. Therefore, the influence of surface energy on the concrete strength can be reflected by introducing parameter η. And parameter α is used to reflect water saturation. Then the calculation model for compressive strength of water saturated concrete can be formulated to Eq. (5) as follows:

$$f_{cu,wet} = f_{cu}\alpha(1-\eta\frac{m_{c,wet}}{m_{c,dry}})\,, \tag{5}$$

where $f_{cu,wet}$ is the compressive strength of water saturated concrete; f_{cu} is the compressive strength of air dry concrete; α is the influence factor of water saturation, $\alpha = 1$ at 100% water saturation; η is the influence factor of surface energy; $m_{c,wet}$ is the mass of water saturated concrete specimen; $m_{c,dry}$ is the mass of air dry concrete specimen.

Table 3. Calculated Value of η

Coarse aggregate types	Water/cement ratio			
	0.41	0.46	0.52	0.63
NA	0.1474	0.1996	0.1655	0.1234
RCA	0.2865	0.2697	0.1284	0.0379
RBA	0.2467	0.2000	0.1219	0.1241

The equivalent transformation of Eq. (5) can be obtained Eq. (6) as follows:

$$\eta = (1-\frac{f_{cu,wet}}{\alpha f_{cu}})\cdot\frac{m_{c,dry}}{m_{c,wet}}\,. \tag{6}$$

Table 3 shows the value of η calculated by Eq. (6) with different water/cement ratios and coarse aggregate types:

4.2 Calculation Model for Compressive Strength of Water Saturated Concrete

The influence factor η of concrete surface energy is determined by water/cement ratio, coarse aggregate types and liquid surface energy, and is closely related to water absorption of coarse aggregate and water absorption of concrete specimen. Under different cement/water ratios, five models were developed, as shown in Table 4. Eq. (7) is expressed one-dimensional linear relationship between η and m_w/m_c; Eq. (8) is expressed one-dimensional nonlinear relationship between η and m_w/m_c; Eq. (9) is expressed one-dimensional linear relationship between η and P_c; Eq. (10) is expressed two-dimensional relationship among η, m_w/m_c and P_g; Eq. (11) is expressed two-dimensional relationship among η, m_w/m_c and P_c. The meanings of the symbols in Table 4 are as follows: m_w/m_c is water/cement ratio; P_c is effective water absorption of concrete specimen; P_g is effective water absorption of coarse aggregate.

The calculation models for compressive strength of water

Table 4. The Relationship among η, m_w/m_c, P_g and P_c

Index	Linear or nonlinear regression equation	Average correlation coefficient
(7)	$\eta = a_1 \frac{m_w}{m_c} + b_1$	0.6698
(8)	$\eta = a_2\left(\frac{m_w}{m_c}\right)^3 + b_2\left(\frac{m_w}{m_c}\right)^2 + c_2\left(\frac{m_w}{m_c}\right) + d_2$	0.9979
(9)	$\eta = a_3 P_c + b_3$	0.9572
(10)	$\eta = a_4 \frac{m_w}{m_c} + b_4 P_g + c_4$	-
(11)	$\eta = a_5 \frac{m_w}{m_c} + b_5 P_c + c_5$	-

Note: a_i, b_i and c_i are undetermined coefficients, respectively, $i = 1 - 5$.

Table 5. Calculation Models for Compressive Strength of Water Saturated Concrete

Index	Calculation models
(12)	$f_{cu,wet} = f_{cu}\alpha\left[1-\left(a_1\frac{m_w}{m_c}+b_1\right)\frac{m_{c,wet}}{m_{c,dry}}\right]$
(13)	$f_{cu,wet} = f_{cu}\alpha\left\{1-\left[a_2\left(\frac{m_w}{m_c}\right)^3+b_2\left(\frac{m_w}{m_c}\right)^2+c_2\left(\frac{m_w}{m_c}\right)+d_2\right]\frac{m_{c,wet}}{m_{c,dry}}\right\}$
(14)	$f_{cu,wet} = f_{cu}\alpha\left[1-\left(a_3P_c+b_3\right)\frac{m_{c,wet}}{m_{c,dry}}\right]$
(15)	$f_{cu,wet} = f_{cu}\alpha\left[1-\left(a_4\frac{m_w}{m_c}+b_4P_g+c_4\right)\frac{m_{c,wet}}{m_{c,dry}}\right]$
(16)	$f_{cu,wet} = f_{cu}\alpha\left[1-\left(a_5\frac{m_w}{m_c}+b_5P_c+c_5\right)\frac{m_{c,wet}}{m_{c,dry}}\right]$

saturated concrete are derived as shown Table 5 by substituting Eqs. (7) – (11) in Table 4 into Eq. (5):

The compressive strength of water saturated concrete is calculated by Eqs. (12) – (16). The relative errors distribution between the calculated values and the true values are shown in Fig. 10. It can be found that the average relative error in ascending order is: 0.89% (16) < 1.23% (14) < 2.02% (15) < 2.73% (12) < 2.76% (13). The absolute value of relative error is mainly within 4%, which indicates that the prediction accuracy calculated by Eqs. (12) – (16) is very precise. Especially the prediction results of Eq. (16), the absolute value of relative error calculated by Eq. (16) is mostly within 2%, and the relative error distribution is very concentrated. However, the absolute value of the maximum relative error calculated by Eqs. (12) and (13) is more than 5%. The main reason is that although the correlation coefficient calculated by Eqs. (12), (13) and (14) is very high, the influence of water/cement ratio is not considered, while in Eqs. (16) and (15) the influence of water/cement ratio is considered by using two-dimensional fitting. Fig. 11 is the thermal diagram of correlation among η, m_w/m_c and P_g in Eq. (10). It can be found that for NAC the linear correlation coefficient of between η and m_w/m_c is -0.3412, and that of between η and P_g is 0.9640; for RCAC, the linear correlation coefficient of between η and m_w/m_c is -0.9497, and that of between η and P_g is 0.9692; for RBAC, the linear correlation coefficient of between η and m_w/m_c is -0.9528, and that of between η and P_g is 0.9691. Fig. 12 is the thermal diagram of correlation among η, m_w/m_c and P_c in Eq. (11). It can be found that for NAC the linear correlation coefficient of between η and m_w/m_c is -0.9961, and that of between η and P_c is 0.4997; for RCAC, the linear correlation coefficient of between η and m_w/m_c is -0.9990, and that of between η and P_c is 0.9708; for RBAC, the linear correlation

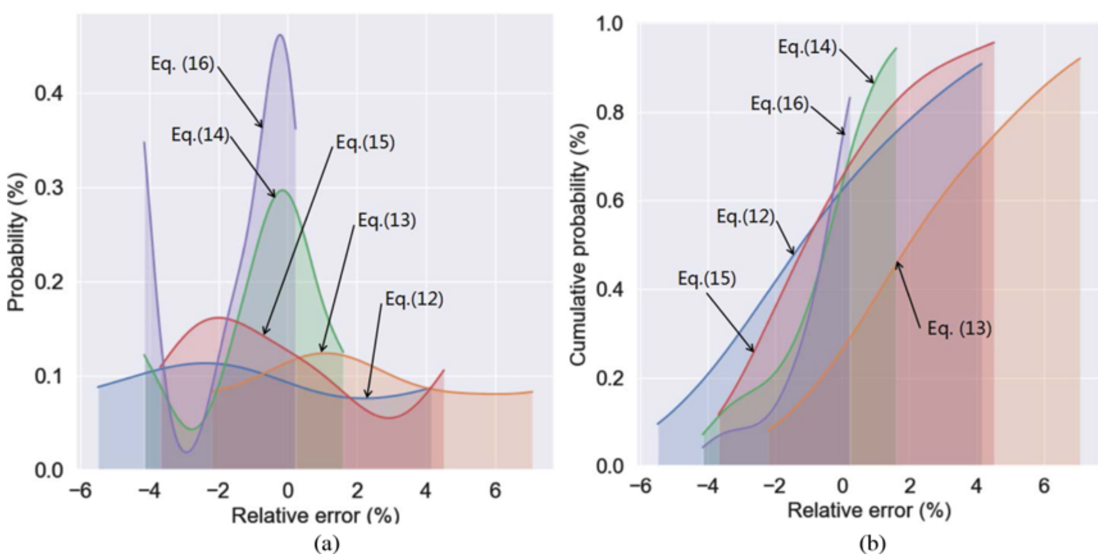


Fig. 10. Error Distribution between Calculated Values and True Values: (a) Error Probability Distribution, (b) Cumulative Error Probability Distribution

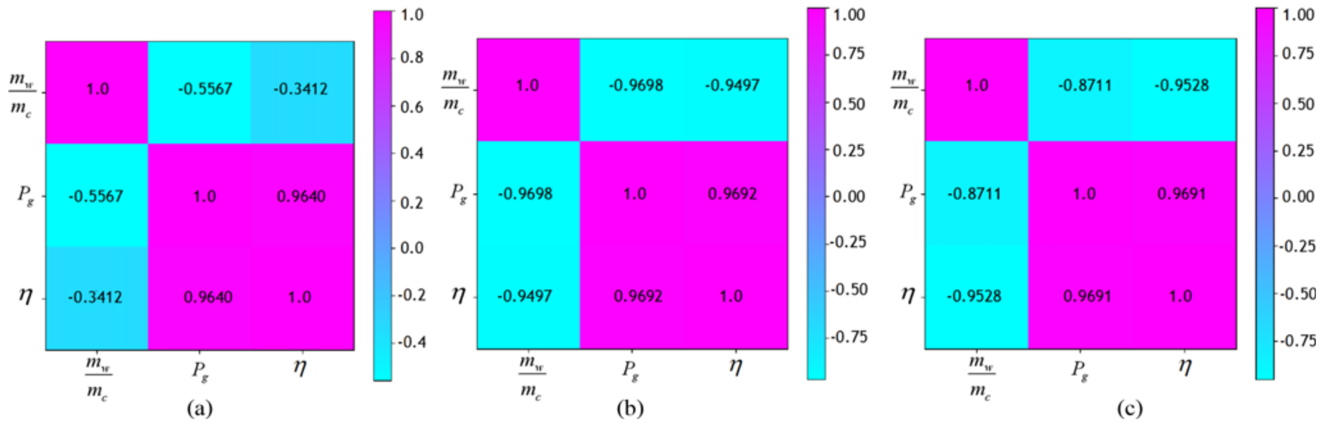


Fig. 11. The Thermal Diagram of Correlation among η, P_g and m_w/m_c: (a) NAC, (b) RCAC, (c) RBAC

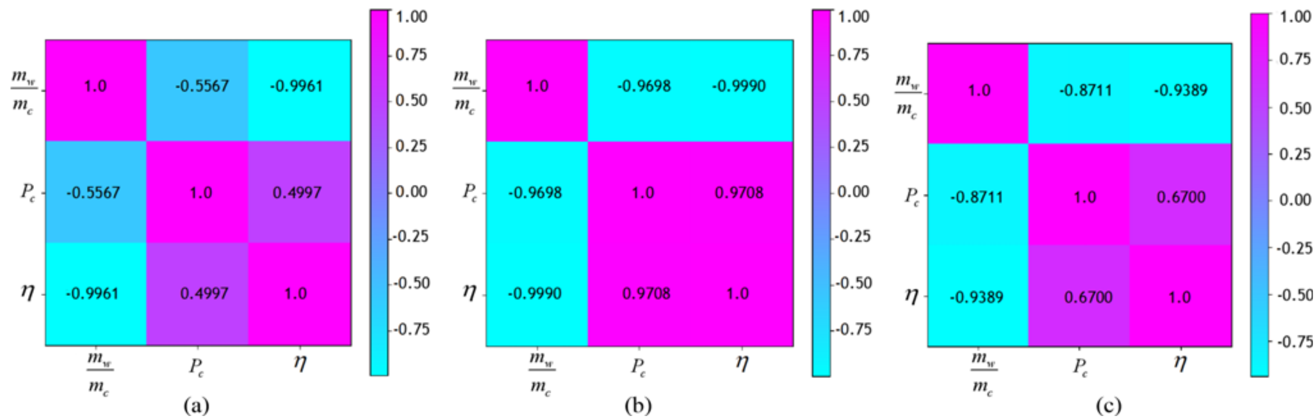


Fig. 12. The Thermal Diagram of Correlation among η, P_c and m_w/m_c: (a) NAC, (b) RCAC, (c) RBAC

coefficient of between η and m_w/m_c is -0.9389, and that of between η and P_c is 0.6700. Neglecting the influence of m_w/m_c in Eqs. (12) and (13) is the main reason for large relative error. It is also found in Fig. 10 that the calculation accuracy of Eqs. (14) and (16) is higher than that of Eq. (15), the main reason is that P_c is more accurate than P_g in reflecting the reduction mechanism of compressive strength of water saturated concrete. The reduction of compressive strength of water saturated concrete is not only associated with the reduction of surface energy of coarse aggregate after water absorption, but also associated with the reduction of surface energy of cement mortar after water absorption.

4.3 Verification of Calculation Model for Compressive Strength of Water Saturated Concrete

Through the above comparison, it can be seen that the calculation accuracy of Eq. (16) is the highest. So the Eq. (16) is determined as calculation model for compressive strength of water saturated concrete. In order to verify whether the calculation model has a wider scope of application, 68 experimental datasets obtained from the literatures (Zhang, 2014; Ma and Ruan, 2017; Wang et al., 2017; Zhang et al., 2020; Sun et al., 2020; Fu et al., 2021) are predicted by the calculation model, and the prediction results are shown in Fig. 13.

It can be found from Fig. 13 that there is a good linear relationship between the predicted values calculated by Eq. (16) and the true values, and their correlation coefficient reaches 0.9719. The average error predicted by Eq. (16) is 7.1% for data from the literatures (Zhang, 2014; Ma and Ruan, 2017; Wang et al., 2017; Zhang et al., 2020; Sun et al., 2020; Fu et al., 2021). Therefore, the Eq. (16) in the prediction of the test data of other literatures

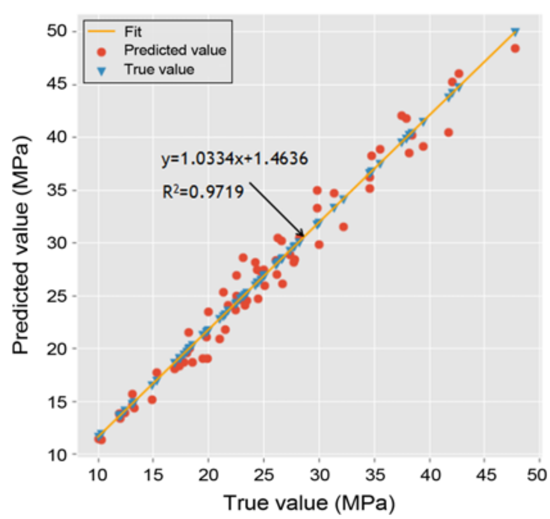


Fig. 13. Correlation between Predicted Values and True Values

will show some discreteness. This is because the Eq. (16) is fitted on the basis of the test data in this paper, and the factors such as mix proportion, test conditions and test environment cause the discreteness of the test data. But on the whole, the predicted values of the calculation model have a high correlation with the true values. Significantly, the factors of water/cement ratio, effective water absorption, water saturation and aggregate types are considered in the calculation model. At the same time, the process of establishing calculation model provides a new idea for concrete strength prediction.

5. Conclusions

1. The water content of NA, RCA and RBA is 0.94%, 1.32% and 2.46% in air dry state, respectively. The effective water absorption of the three aggregates increases rapidly within 3 minutes, then gradually slows down, and is stable at about 24 hours. Within 120 hours, the maximum effective water absorption of NA, RCA and RBA is 0.32%, 0.61% and 8.18%, respectively.
2. The water content and effective water absorption of NAC, RCAC and RBAC specimen increase with the increase of water/cement ratio. The effective water absorption of three kinds of concrete increases rapidly within 3 hours, then gradually slows down, and is stable at about 60 hours. Within 240 hour, the maximum effective water absorption of NAC, RCAC and RBAC is 0.73%, 0.81% and 1.89%, respectively.
3. In air dry and water saturated state, the descending order of compressive strength of three kinds of concrete is: NAC > RCAC > RBAC. In air dry state, the compressive strength of RCAC is reduced by 1.2% – 15.8% compared with NAC; the compressive strength of RBAC is reduced by 15.4% – 38.3% compared with NAC. In water saturated state, the compressive strength of water saturated NAC is reduced by 12.3% – 19.8% compared with air dry NAC; the compressive strength of water saturated RCAC is reduced by 3.8% – 28.4% compared with air dry RCAC; the compressive strength of water saturated RBAC is reduced by 12% – 24.2% compared with air dry RBAC.
4. The calculation model for compressive strength of water saturated concrete was proposed. The average calculation error of the calculation model is 7.1%. Significantly, water/cement ratio, effective water absorption, water saturation and coarse aggregate types are considered in the calculation model.

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