

Article

Development and Investigation of a New Low-Cement-Consumption Concrete—Preplaced Aggregate Concrete

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Abstract: Reducing consumption of cement in concrete will achieve huge benefits in decline of carbon emission, conservation of natural resources and reduction of the cost of concrete. In this paper, the low-cement-consumption concrete, preplaced aggregate concrete (PAC), is prepared and 12 types of mixtures including four water–binder ratios (W/B) and three sand–binder ratios (S/B) are designed to detect the effect of W/B and S/B on the mechanical properties and failure mechanism of PAC. Experimental and analytic results indicate that the cubic compressive strength of PAC, splitting tensile strength of PAC and elastic modulus of PAC decrease with increase in W/B and S/B. At a similar compressive strength, more than 20% increment of elastic modulus of PAC is achieved when compared with normal concrete (NC); the descent stage of stress–strain curves of PAC are steeper than that of NC and the peak strains of PAC is lower than that of NC. Guo's model with suitable values of parameters a and b can be used to describe the stress–strain relationship of PAC. Replacing NC by PAC in concrete structures will save 15–20% cement and achieve great environmental and economic benefits.

Keywords: preplaced aggregate concrete; low-cement-consumption concrete; basic mechanical properties; stress–strain relationship; failure mechanism

1. Introduction

Preplaced aggregate concrete (PAC), a novel low-cement-consumption concrete, is prepared by placing coarse aggregate into formworks and then injecting the grout mortar into the void between the coarse aggregate [1,2]. Based on the special preparation technology, compared with normal concrete (NC), development of PAC could achieve a number of benefits, typically in saving cement, solving the segregation of coarse aggregate, reducing energy consumption during the concrete mixing process, increasing concrete stiffness, reducing concrete shrinkage and so on [3–9]. In recent years, PAC has been used in concrete repair engineering, underwater construction, massive concrete structures, concrete track construction, nuclear power plant structures and so on [10–12].

So far, plenty of previous studies have been carried out on PAC. On the aspect of preparation of PAC, Coo et al. [13] reported that the grout effect of PAC was mainly related to the flowability of grout mortar and shape and gradation of coarse aggregate. In order to acquire good flowability of grout mortar, a suitable water–binder ratio and sand–binder ratio should be selected; meanwhile, incorporation of mineral admixtures was also of benefit to enhance the flowability of grout mortar [14–16]. The grout process including gravity process and pumping process also affected the grout effect significantly [17]. The gravity grout process was a grout process of pouring grout mortar on the upper surface of coarse aggregate and then filling the void between coarse aggregate by self-weight, while the pumping grout

process was a grout process of pumping grout mortar into the void between coarse aggregate from bottom to top by pumping. The grout process would be confirmed combination with flowability of grout mortar and shape and gradation of coarse aggregate. On the aspect of mechanical properties of PAC, most of the literatures were focused on the compressive strength, tensile strength and flexural strength, which indicated that the water–binder ratio, sand–binder ratio, properties of coarse aggregate and properties of grout mortar affected the mechanical properties of PAC remarkably [18–22]. The compressive strength, tensile strength and flexural strength of PAC were negatively correlated to the water–binder ratio and sand–binder ratio and positive correlated to the compressive strength of coarse aggregate and grout mortar. On the aspect of durability properties of PAC, owing to the lower cement content, the shrinkage [8], creep and heat of hydration [17] of PAC were all less than that of NC at similar compressive strength.

On the basis of the above characteristics of PAC and in view of the enormous consumption of concrete in reinforced concrete structures, replacing NC by PAC in reinforced concrete structures would achieve huge environmental and economic benefits. However, very little existing research has reported on the application of PAC in reinforced concrete structures. The most recent report on applying PAC in reinforced concrete structures appeared to be Coe et al. [19], in which PAC was attempted to be used in reinforced beams only. Lack of application of PAC in structure members might be ascribed to two causes. On the one hand, despite a number of research studies having been conducted on the properties of PAC, the understanding of mechanical properties and mechanisms of PAC were still far from sufficient and some properties of PAC were still unclear, including the stress–strain relationship of PAC, which played a very important role in guiding the design of PAC structures. On the other hand, compared with NC, the preparation process of PAC was relatively complex. Considering that most of the reinforced concrete structures were cast-in-place reinforced concrete structures, well-prepared PAC in reinforced concrete structures not only needs a better preparation of grout mortar but also a special grout technology. It was difficult to realize the transport of coarse aggregate in high-rise buildings and control the grout effect of PAC under the current construction level. Whereas, in recent years, wide application of precast concrete structures in China has provided an opportunity for utilization of PAC [23–27]. Compared with traditional cast-in-place reinforced concrete structures, precast concrete structures consisted of precast concrete members which were manufactured in factories. During preparation of precast concrete members in factories, placing of coarse aggregate and injecting of grout mortar were easy to accomplish and the pouring quality of PAC could be guaranteed easily. Therefore, replacing NC by PAC in precast concrete structures could be realized and would achieve great environmental and economic benefit. Hence, it was necessary to conduct further research on the properties of PAC to guide the design of precast PAC structures.

For better understanding of the mechanical properties and failure mechanism of PAC to guide the application of PAC in precast concrete structures, a series of experiments, including cubic compressive strength, splitting tensile strength, elastic modulus and stress–strain curves of PAC were conducted in this paper. Based on the existing widely used stress–strain relationship models of NC, the stress–strain relationship model of PAC was established. Considering the strength grade, which is commonly used in precast concrete structures, the mix proportions of strength grade of C30 to C60 of PAC were also given. In combination with the analysis of coarse aggregate distribution characteristics and the interfacial transition zone (ITZ) between coarse aggregate and hardened mortar, the failure mechanism of PAC was revealed.

2. Materials and Methods

2.1. Material Properties

The PAC adopted in this research was prepared with cement, coarse aggregate, sand, water reducer and tap water. Properties of raw materials are given as follows:

Cement: Ordinary Portland cement, grade of 42.5 according to GB 175-2007 [28], from Liquean Conch Cement Co. Ltd. Chemical compositions and physical properties are listed in Table 1.

Table 1. Chemical compositions and physical properties of ordinary Portland cement.

Chemical Analysis (%)	Ordinary Portland Cement
CaO	60.32
SiO ₂	22.34
Al ₂ O ₃	4.55
Fe ₂ O ₃	4.18
MgO	2.05
SO ₃	2.87
K ₂ O	0.51
Na ₂ O	0.41
Loss on ignition	2.77
Specific gravity	3.13
Fineness (m ² /kg)	334

Coarse aggregate: Crushed stone (as shown in Figure 1), from the local producer in Xi'an, Shaanxi Province, China, crushing index of 9.5%, apparent density of 2520 kg/m³, loose bulk density of 1360 kg/m³. Particle size ranged from 4.75 mm to 19 mm and particle size distribution is presented in Figure 2.



Figure 1. Coarse aggregate.

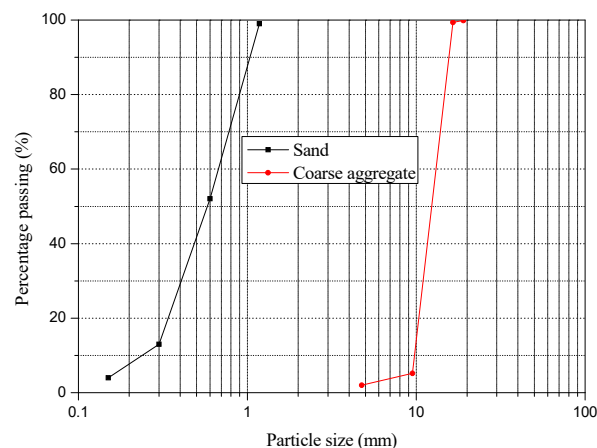


Figure 2. Particle size distribution of sand and coarse aggregate.

Sand: Natural river sand, from Weihe River in Xi'an, Shaanxi Province, China, modulus of fineness of 3.58, apparent density of 2610 kg/m^3 , bulk density of 1450 kg/m^3 . The maximum size was smaller than 2.36 mm and the particle size distribution is shown in Figure 2.

Water reducer: Polycarboxylate superplasticizer, from Sika (China) Limited, solid content of 40%. The dosage of water reducer was ascertained by experiments.

2.2. Mixture Proportions and Specimens Preparation

A total of 12 mix proportions were designed to detect the effect of water–binder ratios (W/B) and sand–binder ratios (S/B) on the mechanical properties of PAC. Based on the characteristics of PAC, the amount of coarse aggregate in all PAC mixtures were fixed to loose bulk density of coarse aggregate, which was 1360 kg/m^3 . The void between coarse aggregates was filled by grout mortar. With different compositions of grout mortar, varying PAC was prepared. The 12 types of grout mortar had four W/B of 0.30, 0.35, 0.40, 0.45 and three S/B of 1.5, 1.75, 2. The dosage of water reducer was determined by experiments to make sure that the fresh grout mortar could acquire a grout efflux time of $20 \pm 2 \text{ s}$ according to ASTM C938-2010 [29]. After previous experiments, for W/B of 0.30, 0.35, 0.40 and 0.45, the amounts of water reducer were set as 1.5%, 1.2%, 0.8% and 0.6%, respectively, by the mass of cement content. The mixture proportions of 12 types of PAC are shown in Table 2.

Table 2. Mix proportions for preplaced aggregate concrete (PAC).

Type of Concrete	Weight per Cubic Meter (kg/m^3)					Water–Binder Ratios (W/B)	Sand–Binder Ratios (S/B)
	Cement	Sand	Coarse Aggregate	Water Reducer	Water		
PAC1	385	578	1360	5.78	116	0.30	1.5
PAC2	365	639	1360	5.48	110		1.75
PAC3	330	660	1360	4.98	100		2
PAC4	370	555	1360	4.44	130	0.35	1.5
PAC5	352	616	1360	4.22	123		1.75
PAC6	320	640	1360	3.84	112		2
PAC7	355	533	1360	2.84	142	0.40	1.5
PAC8	340	595	1360	2.72	136		1.75
PAC9	310	620	1360	2.48	124		2
PAC10	340	510	1360	2.05	154	0.45	1.5
PAC11	327	572	1360	1.97	147		1.75
PAC12	300	600	1360	1.80	135		2

Preparation of PAC specimens included two stages, casting coarse aggregate into molds and injecting grout mortar into molds to infill the void between coarse aggregate. In order to obtain excellent adhesive property between coarse aggregate and hardened grout mortar, the coarse aggregate was washed before utilization. To ensure that the grout mortar could fill the space between coarse aggregate, the coarse aggregate was at a loose state. Grout mortar was mixed in a standard mixer for 4 min and then injected into molds from bottom to top by pumping (seen in Figure 3). Experiments including compressive strength of grout mortar, cubic compressive strength of PAC, splitting tensile strength of PAC, elastic modulus of PAC, stress–strain relationship of PAC and microstructural analysis of PAC were carried out in this research. All specimens were prepared at a controlled environment of $20 \pm 2 \text{ }^\circ\text{C}$ and relative humidity (RH) = $60\% \pm 5\%$ and demolded after 1 day, then cured at $20 \pm 2 \text{ }^\circ\text{C}$ and RH > 95% for 28 days.

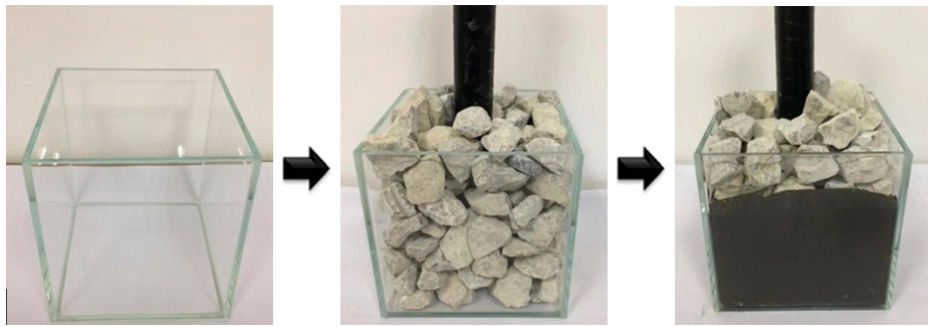


Figure 3. Preparation process of preplaced aggregate concrete (PAC) specimens.

2.3. Testing Method

According to GB/T 50081-2002 [30], the cubic compressive strength and splitting tensile strength of PAC were each tested using three cubes of 100 mm × 100 mm × 100 mm, meanwhile the elastic modulus of PAC was evaluated on three prisms of 100 mm × 100 mm × 300 mm. Three prisms of each batch with dimensions 100 mm × 100 mm × 300 mm were utilized to determine the uniaxial compressive stress–strain curves of PAC. The above tests were all carried out by 1000 kN computer-controlled electro-hydraulic servo universal testing machine. The representative value of each test was acquired from the mean value of three experimental values for each batch. For the elastic modulus test, two dial indicators were fixed on the contrary side of specimens to acquire the deformation of specimens under loading. The upper limit and lower limit of the cyclic loading were one-third of the ultimate load and 0.5 MPa, respectively. When the load reached the upper and lower limits, the deformations were recorded. The cyclic loading was loaded six times. The first three cycles of readings were abandoned and the last three cycles of readings were used to calculate the elastic modulus. For obtaining the whole stress–strain curves of PAC, including ascent stage and descent stage, a rigid support device was employed (as shown in Figure 4). The loading rate was set as a constant 0.002 mm/s. The load was recorded by load transducer and the deformation was detected by four dial gauges arranged at the four sides of the specimens. The load transducer and dial gauges were all connected to a DH3820 data acquisition system for saving the data during testing in computer. The test was terminated when the data could construct the whole stress–strain curve.

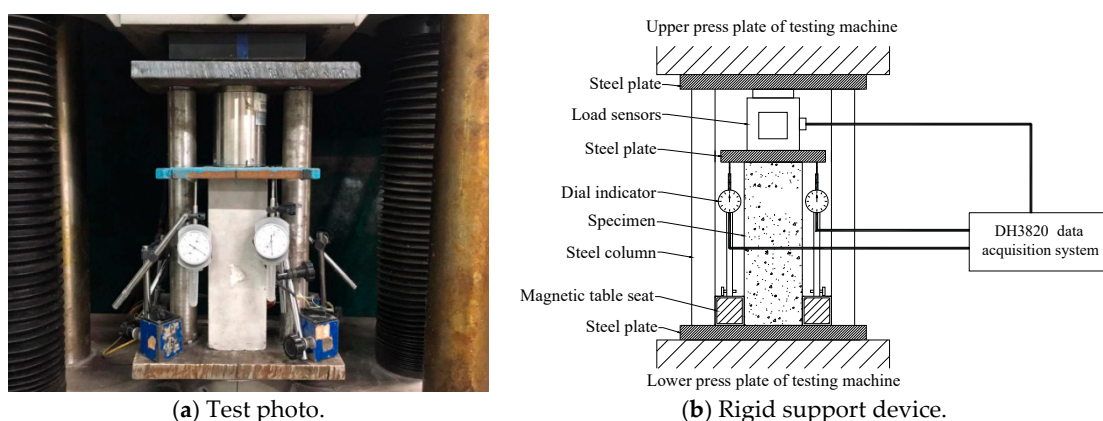


Figure 4. Test setup for acquiring stress–strain curves.

The characteristics of the interfacial transition zone (ITZ) between coarse aggregate and hardened grout mortar were evaluated by scanning electron microscope (SEM, S-4800). The distribution of coarse aggregate inside concrete was measured by taking photos of the sections of the specimens. In order to understand the distinction of distribution of coarse aggregate between PAC and NC, the specimen with dimensions of 100 mm × 100 mm × 100 mm was cut into four pieces with an approximate size of

100 mm × 100 mm × 25 mm, then a high-definition camera was used to photograph the distribution of coarse aggregate on each section. Through analysis of the distribution of coarse aggregate inside PAC, the load transfer path in PAC was inferred and then the failure mechanism of PAC was ascertained.

3. Results and Discussion

3.1. Mechanical Properties of PAC

3.1.1. Cubic Compressive Strength

Figure 6 shows the results of cubic compressive strength of PAC, which ranged from 38.6 to 71.4 MPa under different W/B and S/B. It indicated that the strength grade of PAC could generally achieve C30 to C60 as the W/B varied from 0.3 to 0.45 and the S/B varied from 1.5 to 2. The decrease in cubic compressive strength of PAC with increase of W/B and S/B could be obtained from Figure 5, where an augment of W/B from 0.3 to 0.45 decreased cubic compressive strength of PAC to about 33.8% for S/B = 1.5, to 33% for S/B = 1.75 and to 32.5% for S/B = 2. Comparing with compressive strength of hardened grout mortar, the cubic compressive strength of PAC was much higher. This might be mainly due to the interlocking among coarse aggregate in PAC caused by the high content of coarse aggregate. For NC, owing to the relatively low coarse aggregate content, the cracks extended in hardened mortar easily. So, the compressive strength of NC mainly depended on the compressive strength of hardened mortar and the properties of the interfacial transition zone (ITZ) between hardened mortar and coarse aggregate. However, for PAC, higher coarse aggregate content effectively plays the role of resisting the extension of cracks in hardened grout mortar; meanwhile, the load borne by hardened grout mortar could be partially shared by coarse aggregates which were in contact with each other. The greater participation of coarse aggregate in bearing load effectively remedied the reduction of compressive strength caused by decrease of cement content in PAC. Thus, PAC could fully develop the properties of coarse aggregate and hardened mortar when compared with NC.

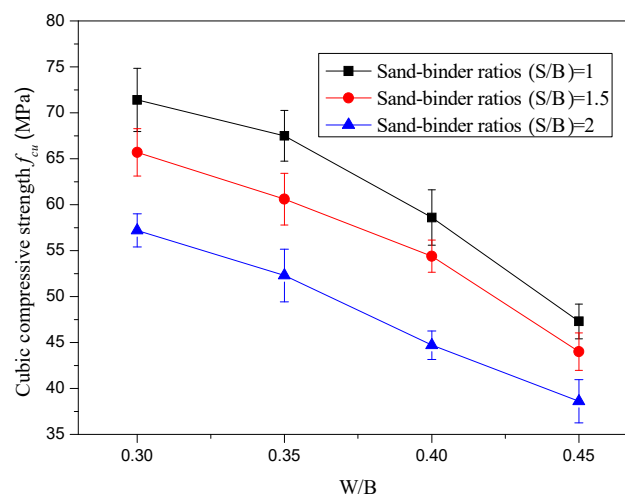


Figure 5. Variation in cubic compressive strength of PAC under different water–binder ratios (W/B).

3.1.2. Splitting Tensile Strength

Splitting tensile strengths of PAC under different W/B and S/B are presented in Figure 6. The increase of W/B from 0.3 to 0.45 caused a decrease in splitting tensile strength of PAC, which varied from 4.97 to 3.63 MPa for S/B = 1.5, from 4.62 to 3.34 MPa for S/B = 1.75 and from 4.38 to 3.05 MPa for S/B = 2. The reason that the reduction of splitting tensile strength of PAC with increase of W/B and S/B might be similar to that of NC has been elaborated upon by several researchers [31,32], and was said to be on account of the lower compressive strength of hardened grout mortar and smaller adhesive strength between hardened grout mortar and coarse aggregate. From Figure 7, it could be seen that

plenty of coarse aggregates distributed on the splitting section and most of the coarse aggregates were split under loading. Despite that lower mortar content would result in a reduction of splitting tensile strength of the NC, the increase of coarse aggregate content provided a load-transferring framework which might undertake partial splitting load. Therefore, the splitting tensile strength of PAC might be analogous to that of the NC at a similar compressive strength. As shown in Figure 8, the relationship between cubic compressive strength and splitting tensile strength of PAC was similar to NC, also verifying the above speculation.

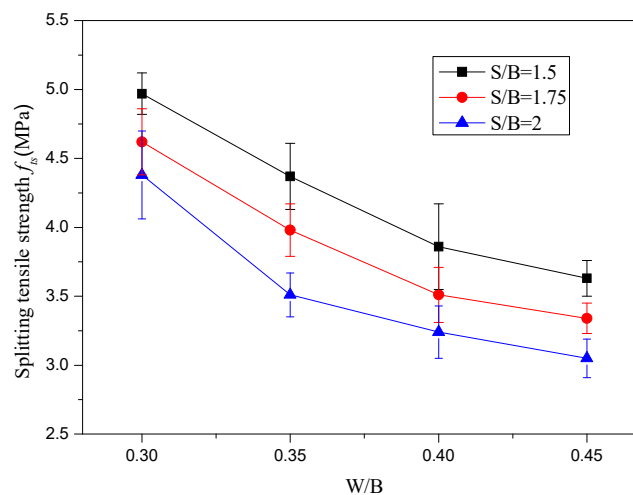


Figure 6. Variation in splitting tensile strength of PAC under different W/B.



Figure 7. Failure section of splitting tensile tests.

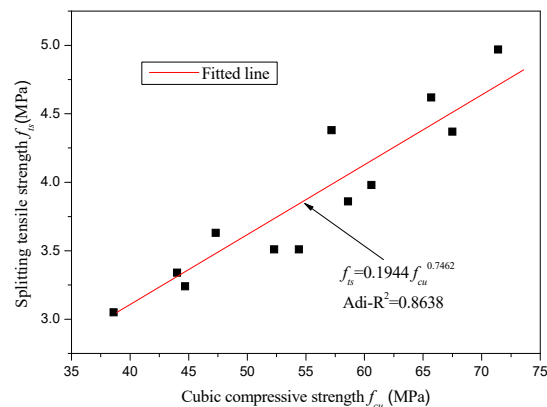


Figure 8. Relationship between cubic compressive strength and splitting tensile strength of PAC.

3.1.3. Elastic Modulus

Elastic modulus of PAC obtained by experiments in this investigation ranged from 37.7 to 45.3 GPa, as presented in Figure 9, which was higher than those of NC at a similar compressive strength (elastic modulus of NC ranged from 30 to 36 GPa [33]). The variations of elastic modulus of PAC under different W/B and S/B were similar to those of cubic compressive strength of PAC. With W/B increased from 0.3 to 0.45, the elastic modulus of PAC decreased from 45.3 to 41.1 GPa at S/B = 1.5, from 44.1 to 39.9 GPa at S/B = 1.75 and from 42.1 to 37.7 GPa at S/B = 2. The higher elastic modulus of PAC as compared to NC indicated that the deformation property of PAC under load was less than that of NC, which was mainly due to the larger elastic modulus of coarse aggregate as compared to hardened grout mortar. The increase of coarse aggregate content might inevitably raise the elastic modulus of PAC. Figure 10 describes the relationship between cubic compressive strength and elastic modulus of PAC. It was found that the relationship between cubic compressive strength and elastic modulus was approximately linear. The higher the cubic compressive strength of PAC was, the larger the elastic modulus of PAC would be.

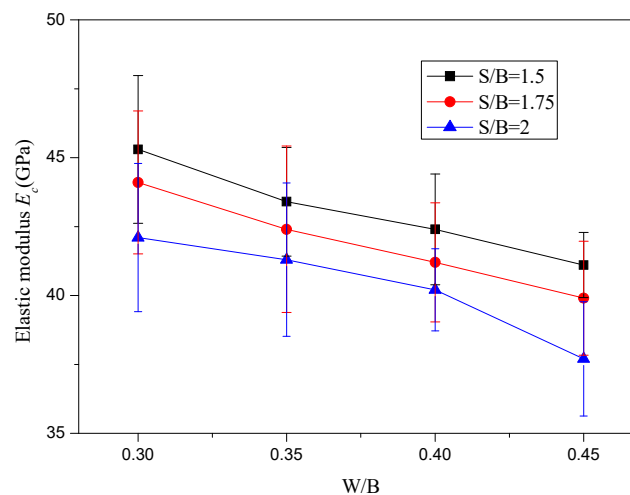


Figure 9. Variation in elastic modulus of PAC under different W/B.

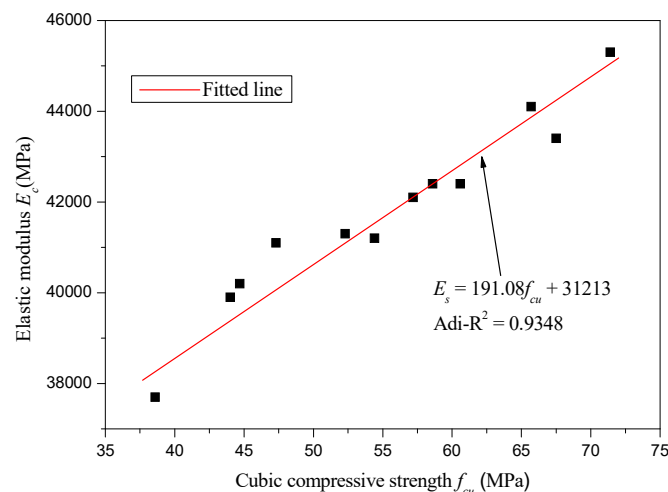


Figure 10. Relationship between cubic compressive strength and elastic modulus.

3.1.4. Experimental Stress–Strain Curves

The experimental uniaxial stress–strain curves of PAC including three curves for each batch are presented in Figure 11. It could be seen that three curves for each batch had a similar shape. In order to evaluate the difference between each series of curves, the normalized mean stress–strain curves of

PAC were calculated and are shown in Figure 12. This indicated that the curves for each batch could be divided into two parts: the ascent stage and the descent stage. The ascent stage and descent stage showed variability between each series. A steeper descent stage for each batch as compared to NC indicated that the brittleness of PAC was higher than that of NC [34–37]. This observation was also verified by the destruction phenomenon of cubic compressive strength tests.

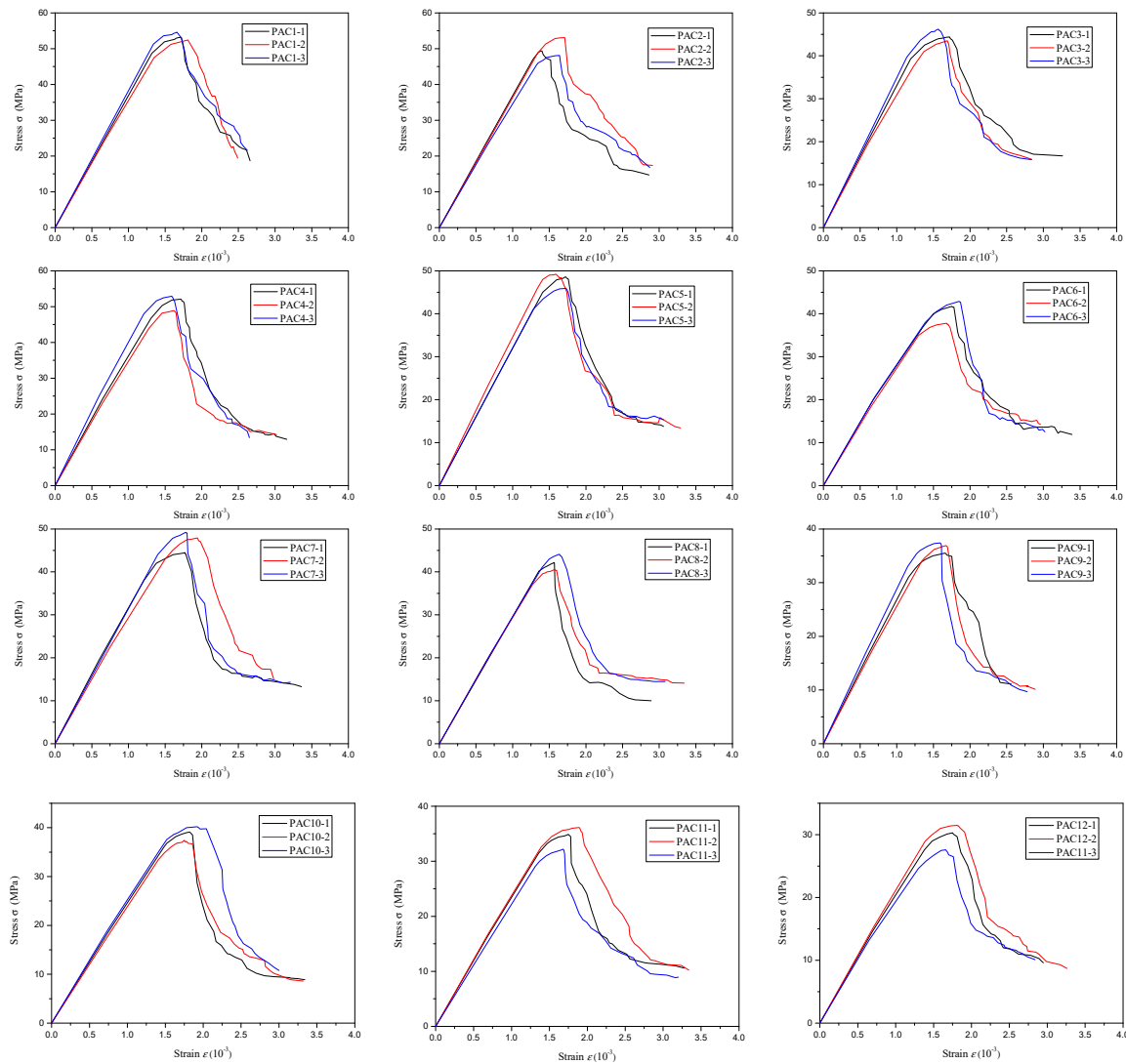


Figure 11. Uniaxial stress–strain curves of PAC.

The variations of peak stress and peak strain of PAC under different W/B and S/B were shown in Figure 13. As shown, the peak stress of PAC decreased with an increase in W/B and S/B, which was in accordance with the variation of cubic compressive strength. The increase of W/B from 0.3 to 0.45 led to a 27.7% reduction with S/B of 1.5, to a 31.5% reduction with S/B of 1.75 and to a 33.3% reduction with S/B of 2. The peak strain of PAC fluctuated between 0.00159 and 0.00183 with variation of W/B and S/B. Compared with NC, the lower peak strain of PAC was acquired, which might be mainly due to the high coarse aggregate content and greater stiffness of coarse aggregate as compared to hardened grout mortar. As there was greater participation of coarse aggregate in bearing load, the stiffness of concrete increased; meanwhile, the deformation ability and elastic modulus of concrete decreased. In Figure 14, the relationship between cubic compressive strength and peak stress is developed. As could be seen, the relationship between cubic compressive strength and peak stress was approximately linear

and the ratios between uniaxial compressive strength and cubic compressive strength of PAC were in the range of 0.74 to 0.82, which was similar to that of normal concrete (0.7 to 0.92) [38].

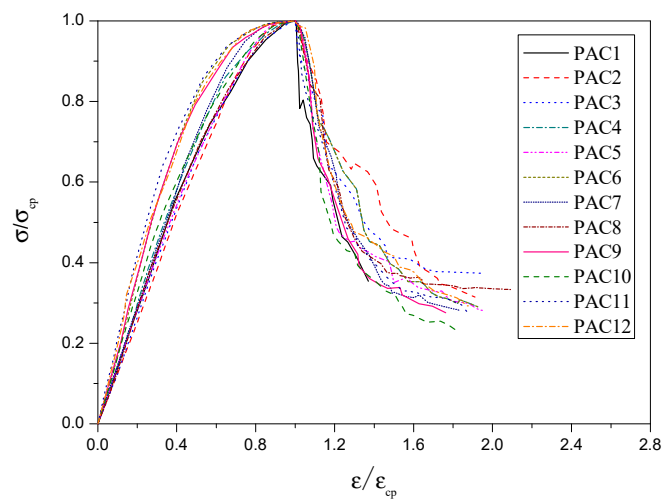


Figure 12. Normalized mean stress–strain curves of PAC series.

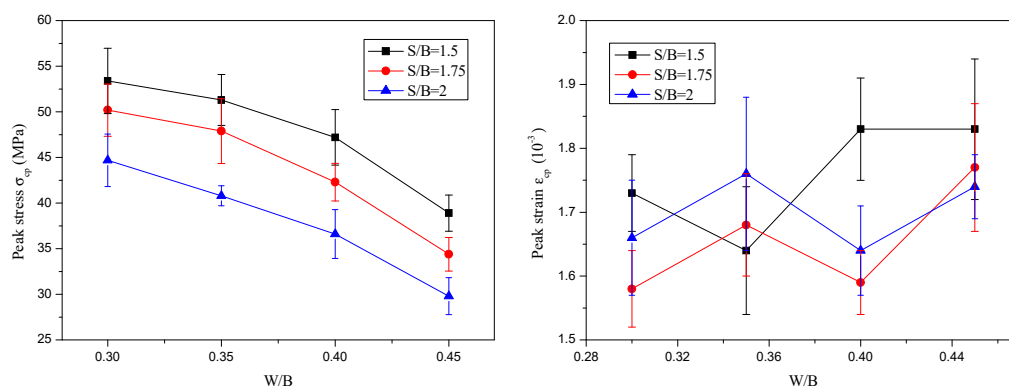


Figure 13. Variation in peak stress and peak strain of PAC under different W/B.

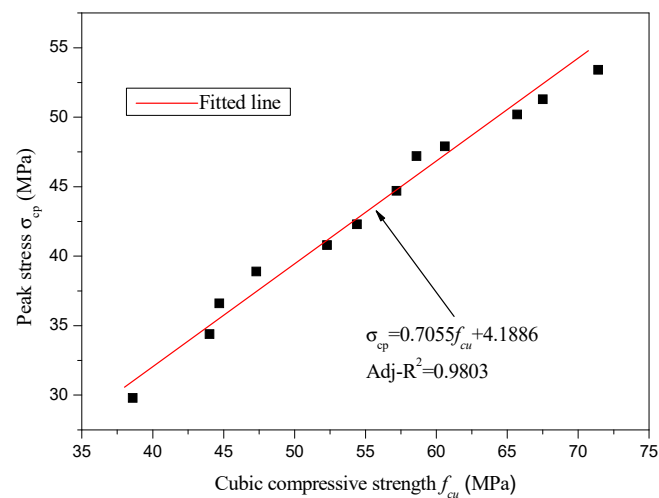


Figure 14. Relationship between cubic compressive strength and peak stress of PAC.

3.1.5. Stress–Strain Relationship of PAC

As one type of concrete, according to the above experimental results of stress–strain curves, the stress–strain relationship of PAC might be described by the models depicting the stress–strain relationship of NC. In this paper, three widely used models including Chinese code model, Eurocode model and Guo’s model were attempted to describe the stress–strain relationship of PAC. The details of three models were given as follows.

(1) Chinese code model

In current Chinese code GB50010 [33], the stress–strain relationship of NC was described by Equation (1):

$$\sigma = (1 - d_c)E_c \varepsilon \quad (1)$$

where σ is compressive stress at every point (MPa); E_c is elastic modulus (MPa); ε is strain under compression at every point; d_c is the damage parameter under uniaxial compression and can be calculated using the following formula:

$$d_c = \begin{cases} 1 - \frac{\rho_c n}{n-1+x^n} & x \leq 1 \\ 1 - \frac{\rho_c}{\alpha_c(x-1)^2+x} & x > 1 \end{cases} \quad (2)$$

$$\rho_c = \frac{\sigma_{cp}}{E_c \varepsilon_{cp}} \quad (3)$$

$$n = \frac{E_c \varepsilon_{cp}}{E_c \varepsilon_{cp} - \sigma_{cp}} \quad (4)$$

where $x = \varepsilon/\varepsilon_{cp}$; σ_{cp} is peak stress (MPa); ε_{cp} is peak strain; α_c is a parameter related to descent stage of stress–strain curves and can be calculated by the following formula [39]:

$$\alpha_c = 0.157\sigma_{cp}^{0.785} - 0.905 \quad (5)$$

(2) Eurocode model

The Eurocode model for describing the stress–strain relationship of concrete was mentioned in EN 1992-1-1 [40], which described the ascent stage and descent stage of stress–strain curve by one equation:

$$\frac{\sigma}{\sigma_{cp}} = \frac{k \cdot x - x^2}{1 + (k-2)x} \quad (6)$$

where $x = \varepsilon/\varepsilon_{cp}$; $k = 1.05E_c \cdot |\varepsilon_{cp}|/\sigma_{cp}$.

(3) Guo’s model

Guo’s model, proposed by Guo et al. [41], is expressed as follows:

$$y = \begin{cases} ax + (3-2a)x^2 + (a-2)x^3 & 0 \leq x \leq 1 \\ \frac{x}{b(x-1)^2+x} & 1 \leq x \end{cases} \quad (7)$$

where $x = \varepsilon/\varepsilon_{cp}$; $y = \sigma/\sigma_{cp}$; $a = E_0/E_p$; E_0 is the initial tangential modulus (GPa); E_p is the peak secant modulus (GPa); b is a parameter related to the descent stage of stress–strain curves.

The stress–strain curves of PAC, including three prediction curves and an experimental curve, are compared in Figure 15. Most of the parameters used in three existing models were calculated by the indexes determined from uniaxial compressive tests and elastic modulus tests. The value of parameter b in Guo’s model was determined by comparison of the shape of descent stages of the stress–strain curves with the theoretical curve. It was found that all of the three predicated curves coincided well with the experimental curves at the ascent stage. For the descent stage of stress–strain curves, the stress ratio calculated by Guo’s model was much less than those of the other two models. Comparing the prediction of the three models, the descent stage of the stress–strain curves predicted by Guo’s model

was much closer to the experimental result. On the basis of the above analysis, in order to ensure the predicted curves coincided well with the experimental results both at the ascent stage and descent stage, Guo's model was chosen as a suitable model to describe the stress–strain relationship of PAC with the values of parameters a and b shown in Table 3.

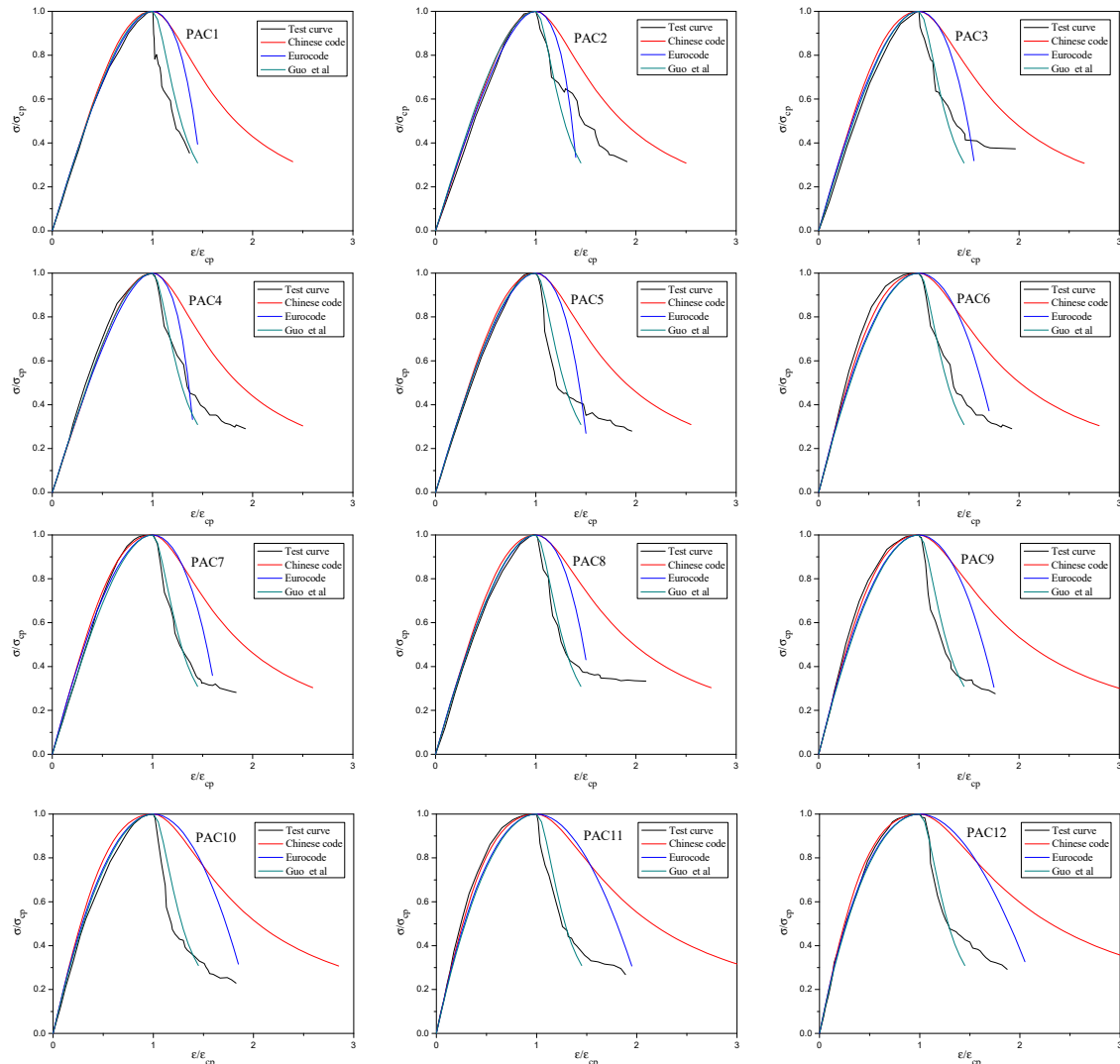


Figure 15. Comparison of stress–strain curves of PAC obtained from existing stress–strain models.

Table 3. The value of parameters a and b .

Parameters	PAC1	PAC2	PAC3	PAC4	PAC5	PAC6	PAC7	PAC8	PAC9	PAC10	PAC11	PAC12
a	1.47	1.39	1.56	1.39	1.49	1.78	1.64	1.55	1.8	1.93	2.05	2.2
b	16											

3.2. Failure Mechanism of PAC

Figure 16 presents the distribution of coarse aggregate of PAC and NC. It could be observed that the difference between the cross-section characteristics of PAC and NC were quite distinct. On one hand, an obvious higher coarse aggregate content of PAC as compared to NC could be seen from the cross-section. On the other hand, the hardened mortar in PAC was much denser than that in NC. High coarse aggregate content made the load transfer path inside concrete change. For NC, in general, most of the loads transmitted between hardened mortar, coarse aggregate and ITZ between hardened mortar and coarse aggregate. The failure pattern of NC showed that the cracks prolonged in hardened mortar

and the interface between hardened mortar and coarse aggregate. Nevertheless, for PAC, high coarse aggregate content made a large proportion of coarse aggregate directly contact each other, therefore, partial loads might be transferred through contact points between coarse aggregates which would avoid the premature failure of hardened mortar. Furthermore, skeleton formation by coarse aggregate might enhance the mechanical properties of PAC, which was beneficial to remedy the reduction of mechanical properties of PAC caused by lower cement content.



Figure 16. Comparison of the distribution of coarse aggregate between PAC and normal concrete (NC).

Despite that the PAC specimens were prepared by placing coarse aggregate in the mold firstly and then injecting the grout mortar into the void between coarse aggregate from bottom to top by pumping without vibration, the grout mortar was still very dense (as shown in Figure 16), meanwhile the interfacial transition zone (ITZ) between coarse aggregate and hardened mortar was also compact (as shown in Figure 17). This indicated that the PAC specimens could be prepared compactly by the special technique which would make sure that the load could be effectively transferred between hardened mortar, ITZ and coarse aggregate. PAC under lower cement content and higher coarse aggregate could still obtain favorable mechanical properties as compared with NC.

3.3. Discussion

The experimental results displayed that, at a similar compressive strength, PAC reached a higher elastic modulus, a lower cement content and a steeper descent stage of stress–strain curves when compared with NC. The obvious difference between PAC and NC was the high coarse aggregate content. Most of the coarse aggregate suspending in NC resulted in a failure of hardened mortar and ITZ under load; coarse aggregate had not fully played role of bearing load. Differently, in PAC, skeleton formed by plentiful coarse aggregates could also transfer partial load through contact points between coarse aggregates. Therefore, favorable mechanical properties of PAC could be still obtained when the mortar content dropped. Disparate W/B and S/B affected the properties of grout mortar which further affected the mechanical properties of PAC. Based on the above-mentioned analysis, it could be seen that lower W/B with smaller S/B could result in high mechanical properties of PAC, conversely, higher W/B with greater S/B could result in low mechanical properties of PAC. Nevertheless, lower W/B with greater S/B, or higher W/B with smaller S/B, could obtain similar mechanical properties of PAC.

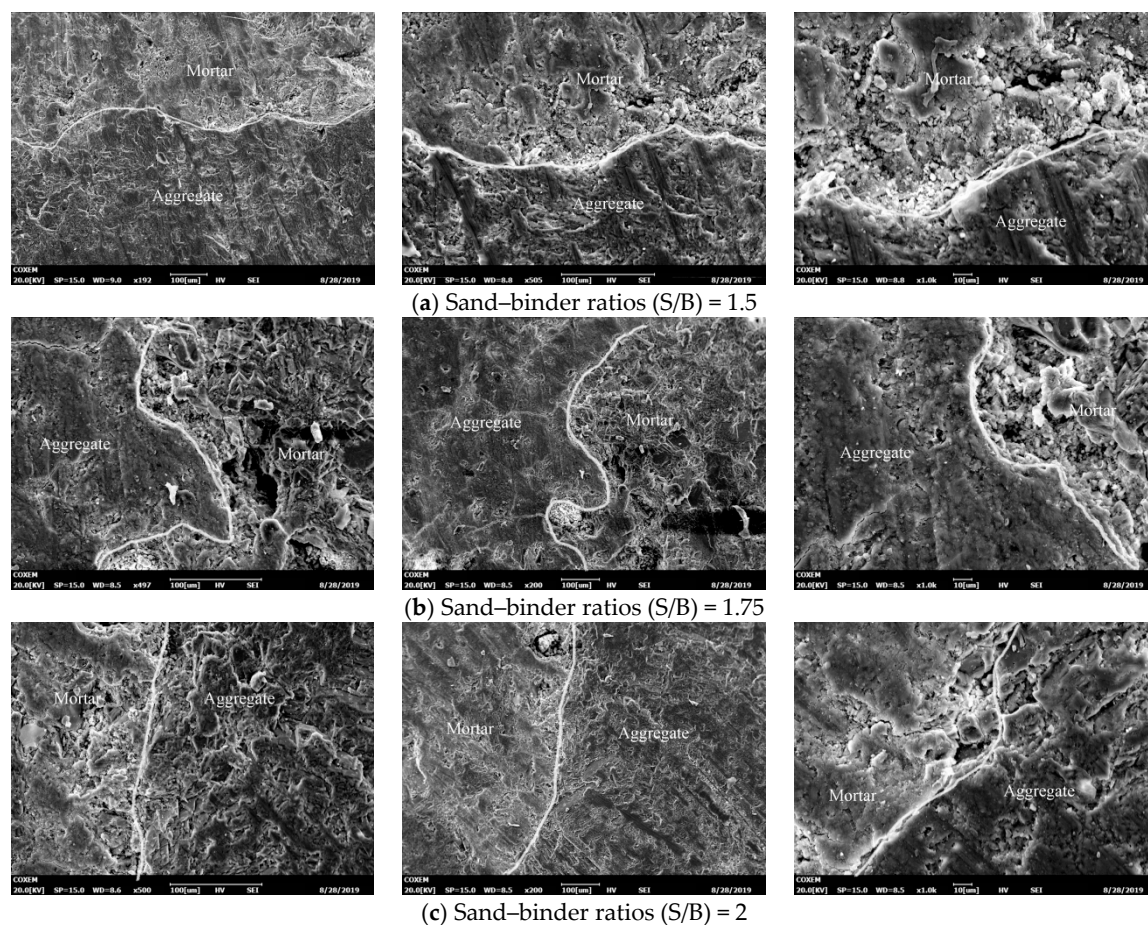


Figure 17. Typical SEM images of interfacial transition zone (ITZ) between coarse aggregate and hardened mortar ($W/B = 0.4$).

Considering the practical construction situation, suitable W/B and S/B could be selected to prepare the PAC. For example, in order to save cement content, lower W/B with higher S/B might be a good option, while for the sake of saving sand and water reducer content, higher W/B with smaller S/B might be a good option. Regardless of reducing the amount of cement or sand, it was all of benefit to reduce the cost of concrete and save natural resources. Taking the cubic compressive strength of about 50 MPa as an example [42], the cement content could reach 320 kg/m^3 for PAC, while the cement content was about 400 kg/m^3 for NC, making this approximately a 25% reduction. In general, 15–20% savings of cement content could be achieved when the NC is replaced by PAC at a similar compressive strength. Thus, popularization and application of PAC would help promote green and low-carbon development of concrete.

4. Conclusions

The stress–strain relationship of PAC along with basic mechanical properties of PAC, including cubic compressive strength, splitting tensile strength and elastic modulus, were investigated by experiments in this paper. Furthermore, the failure mechanism of PAC was also discussed. The main findings that could be drawn are as follows:

- (1) The increase of W/B and S/B led to a decrease of cubic compressive strength, splitting tensile strength and elastic modulus of PAC. The relationship between cubic compressive strength and splitting tensile strength of PAC was similar to that of NC. At a similar compressive strength, up to a 20% increase of the elastic modulus of PAC could be achieved as compared with NC.

- (2) Twelve types of PAC specimens had a similar stress–strain curve. A steeper descent stage of stress–strain curve of PAC as compared to NC was obtained. At the similar compressive strength, the peak strain of PAC was less than that of NC. Guo’s model with suitable values of parameters a and b could be used to describe the stress–strain relationship of PAC.
- (3) Compared with NC, at a similar compressive strength, 15–20% reduction of cement content of PAC could be achieved, in general. With the wide popularization and application of precast concrete structures in China, replacing NC by PAC in precast concrete structures would obtain great environmental and economic benefits and help promote further green and low-carbon development of precast concrete structures.

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