Sensitivity Analysis of Physical and Mechanical Properties of Modified Recycled Coarse Aggregate Concrete

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Abstract

The nano-SiO_2 incorporation, water-cement ratio of the cement pulp, PVA fiber content, RCA replacement percentage and strain rate as influencing factors were selected. The inspection indicators are the apparent density of RCA, crush index and water absorption, RAC static compressive strength, dynamic peak stress and peak strain of RAC. Based on the experiment and sensitivity theory analysis method, the sensitivity of each influencing factor level to the inspection index was obtained. The results show that the concentration of nano-SiO_2 solution pre-soaked was the significant influence to the apparent density and crushing index of the RCA, and the main controlling factor of water absorption was the pre-soaked time; the water-cement ratio of the pre-pulped hadn't a significant influence on the physical indexes of the RCAS; the replacement percentage of RCA was the main factor that affects the static compressive strength of RAC, the content of PVA fiber was less sensitive to the RAC compressive strength; the main factor affecting the dynamic peak stress of RAC was impact strain rate, while the PVA fiber was the significant influence to the peak strain of RAC; the direct doped method of nano-SiO_2 had more significant influence to the RAC impact peak stress and peak strain.

Keywords

RAC; nano-SiO2; PVA Fiber; Mechanical Properties; Influencing Factors; Sensitivity.

1. Introduction

With the continuous improvement of social development and economic level, people have been striving to build a world in which energy, economy and ecological environment are balanced and harmonious. However, waste concrete is produced at an average rate of 8% per year [1], which clearly goes against this idea. The emergence of recycled aggregate concrete is in line with the theme of the development of the times [2], which makes the traditional building materials change from one-way circulation to closed circulation. However, compared with natural aggregate, the surface of recycled aggregate is attached with old mortar and micro-cracks, making it smaller in apparent density, larger in porosity and higher in water absorption [3]. Different sources and original concrete strength will have an impact on the quality of recycled aggregates, resulting in increased randomness and variability [4]. Therefore, the efficient use of recycled aggregates and the widening of the application of recycled aggregate concrete have become research hotspots in recent years [5].

Richardson et al. [6] found that the small particle products of cement hydration have large porosity, and the pore size is nano scale. Due to the high surface energy and specific surface area of nano materials, the nano materials fillers in concrete generate core effects and core-shell elements, which stimulate the generation of a new ITZ (Interfacial Transition Zone) phase, which can enhance the ITZ strength [7,8]. Bahadori et al. [9] showed that nano-SiO2 is an effective nano particle used in concrete, and the initial cement content of 2% nano-SiO2 particles was used to replace 20% of cement, and the concrete strength did not suffer a great loss. The research of Wang et al. [10] showed that with the increase of nano-SiO2 content, the compressive strength of recycled aggregate concrete showed a trend of first increase and then decrease, and the optimum strength was obtained at 6% content. Shaikh et al. [11] obtained a recycled aggregate concrete with better strength and pore structure than nano-SiO2 directly mixed with nano-SiO2 solution under the pre-soak method of nano-SiO2 solution at 2% content.

However, the improvement of concrete strength is generally achieved with high content of cementitious materials, low water-cement ratio and water reducing agent, and for the improvement of tensile strength, deformation and ductility, more fibers are used [12]. PVA fiber has the characteristics of high elastic modulus, high tensile strength, and good adhesion to cement [13]. After mixing with concrete, it can effectively inhibit the generation and cracking of concrete micro-cracks, and enhance the fracture performance of recycled aggregate concrete [14]. Wang et al. [15] showed that the incorporation of 0.2% PVA fiber can improve the early shrinkage and cracking of concrete. Wu et al. [16] found through the dynamic mechanical properties of PVA fiber concrete that the mechanical properties of PVA fiber concrete with a volume content of 0.2% were better.

By adding modified cementitious materials and PVA fibers, the properties of concrete materials are improved. However, the influencing factors obtained from different studies and the conclusions of the investigated indicators are different, the performance evaluation system is not unified, and the analysis of the relationship between the modification of the physical indicators of recycled coarse aggregate is less. Studying the sensitivity relationship of each factor-indicator is helpful to guide the experimental design of modified recycled aggregate concrete and deepen the comparative analysis of related experiments. Therefore, this paper is based on the previous experiments [17-19], combined with the relevant dynamic and static mechanical tests of recycled aggregate concrete. Based on the sensitivity theory, it mainly considers the properties of recycled aggregate (water-cement ratio of cement-coated slurry, nano-SiO2 content and mixing method), the replacement percentage of recycled coarse aggregate, the content of PVA fiber, and the impact strain rate. The primary and secondary factors affecting the physical index of recycled coarse aggregate and the dynamic and static mechanical properties of recycled aggregate concrete are analyzed.

2. Experimental Program and Theory

2.1 Test Overview

Raw materials: P•O 42.5 ordinary Portland cement was used for cement, and the water-cement ratio of pre-slurry was 0.5, 0.7 and 0.9; the mixing water was ordinary tap water; natural coarse aggregate was graded crushed stone; recycled coarse aggregate was obtained by crushing waste concrete beams in the room; the fine aggregate was natural medium sand with a fineness modulus of 2.7 and an apparent density of 2610 kg/m3. The properties of the nano-SiO2 colloidal solution were shown in Table 1. The nano-SiO2 sol was diluted with water to a solution with a concentration of 1%, 2%, and 3% for soaking the recycled coarse aggregate; the physical properties of the PVA fiber were shown in Table 2, and the volume dosage was 0.05% and 0.10%; the superplasticizer is a high-efficiency polycarboxylate superplasticizer.

Specimen preparation methods: ① According to the quality screening of SRA (nano-SiO2 modified recycled coarse aggregate) [17], it was determined that the nano-SiO2 sol was diluted with water to a 2% solution, and then the recycled coarse aggregate was added to soak for 48 hours. ② After taking out the SRA for air-drying, it was mixed with additional water and stirred for 3 minutes to obtain the soaked SRA. ③ Mix the wet SRA with cement, sand and natural aggregate for 1min, add 1/2 mixing water and water reducer and stir for 1min. ④ Add 1/2 of the mixing water, and evenly spread the PVA fibers in the mixture and stir for 2 minutes to obtain freshly mixed recycled aggregate concrete, and perform pouring curing.

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Table 1. Properties of nano-SiO2 solution

Component	Exterior	Specific gravity / (g/ml)	SiO_2 Solid content / %	pH value
Nano-SiO_2 solution	Transparent liquid	1.205	30	9.7

Table 2. Physical properties of PVA fiber

Component	Fiber length /mm	Fiber diameter/μm	Elongation at break/%	Young's modulus /MPa
PVA fiber	18	19	7	29×10^3

The concrete mix ratio was designed in Chinese standard JGJ55-2011. The size of the compressive strength specimen of recycled aggregate concrete was 100mm×100mm×100mm; The size of the impact test piece was Φ50mm×25mm; The physical index of recycled coarse aggregate was carried out in Chinese standard JGJ52-2006; The impact performance test adopts the SHPB (Split Hopkinson Pressure Bar) device with a diameter of 50 mm, and the dynamic stress and strain values were calculated according to the two-wave method [20].

2.2 Sensitivity Analysis Theory

Sensitivity is the change of the dependent variable when an independent variable generates a certain disturbance [21]. Therefore, in order to analyze the influence degree of the factor i, the sensitivity was defined as:

$$S_i = \eta_1 / \eta_2 \tag{1}$$

$$\eta_1 = |\Delta Y_j| / Y_{j0} \tag{2}$$

$$\eta_2 = |\Delta X_i| / X_{i,max} - X_{i,min} \tag{3}$$

$$\Delta X_i = X_i - X_{i0} \tag{4}$$

$$\Delta Y_j = Y_j - Y_{j0} \tag{5}$$

Among them: Xi0 and Yj0 are the reference values of Xi and Yj respectively, Xi, max and Xi, min are the maximum and minimum values of factor Xi.

If a small change in a factor can cause a large change in the index, the greater sensitivity of the factor, the more sensitive the factor is. In order to reflect the increasing or decreasing trend of each factor level on the investigated index, the absolute value involved in the calculation of Si in the above formula is removed, and it was expressed as positive or negative. For the comparison of the comprehensive sensitivity among the factors, the average value of the absolute value of each sensitivity was used.

3. Sensitivity of Physical Indicators of Recycled Coarse Aggregate

3.1 Influence of Water-cement Ratio of Pre-slurry

The physical index of the recycled coarse aggregate without pulping treatment was selected as the reference value. Table 3 shows the value of the influence of water-cement ratio on the physical

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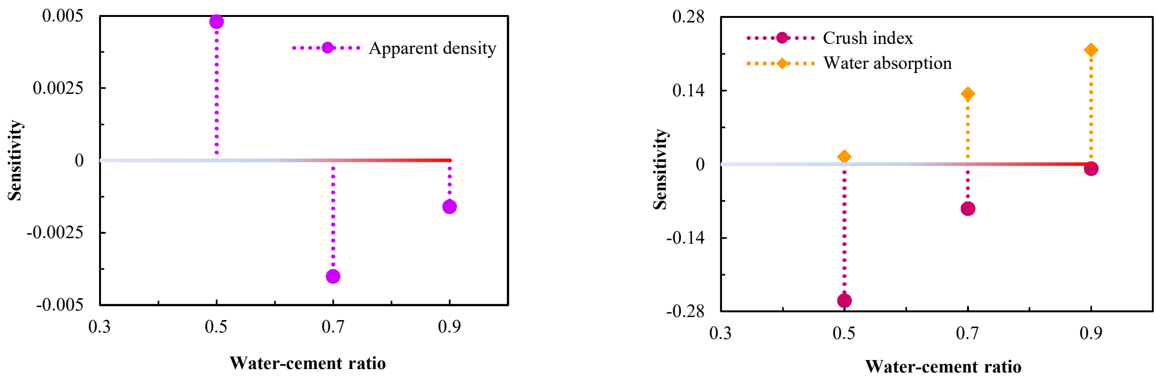
indicators of recycled coarse aggregate, and Table 4 shows the sensitivity of water-cement ratio at each level.

Table 3. Water / cement ratio-influence of physical indexes

Data Sources	Water-cement ratio	Apparent density (kg/m^3)	Crush index / %	Water absorption / %
Experiment test	-	2564	19.70	4.8
	0.5	2545	15.17	5.5
	0.7	2556	18.41	5.3
	0.9	2560	19.54	5.0
Reference[22]	-	2549	15.20	6.32
	0.5	2607	13.60	4.84

Table 4. Water / cement ratio-sensitivity to physical indexes

Water-cement ratio	Apparent density(kg/m^3)	Crush index/%	Water absorption/%
0.5	0.0048	-0.2596	0.0142
0.7	-0.0040	-0.0842	0.1339
0.9	-0.0016	-0.0081	0.2170
$\sum \lvert S_i \rvert$	0.0104	0.3519	0.3651
$\sum \lvert S_i \rvert / n$	0.0035	0.1173	0.1217



(a)Sensitivity to apparent density (b)Sensitivity to crush index and water absorption

Fig.1 Water / cement ratio-sensitivity to physical indexes

It can be seen from Fig.1(a) that when the water-cement ratio of the slurry is 0.5, it has a positive effect on the apparent density of the recycled coarse aggregate, and when it is 0.7 and 0.9, it has a negative effect. It is shown that when the water-cement ratio is 0.5, the apparent density increases, but this increase is extremely unstable. Both 0.5 and 0.7 showed greater sensitivity. When the water-cement ratio changed from 0.7 to 0.9, its effect on apparent density was significantly weakened, but the apparent density of recycled coarse aggregate was still reduced at this time. . It can be seen from Fig.1(b) that with the increase of the water-cement ratio of the slurry, the water absorption sensitivity of the recycled coarse aggregate increases, while the absolute value of the sensitivity to the crushing index decreases sequentially. The water-cement ratio of the slurry had a positive effect on the water absorption of the recycled coarse aggregate, while it had a negative effect on the crushing index. It

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shows that the increase of the water-cement ratio of the slurry promotes the increase of the water absorption of the recycled coarse aggregate, but reduces the crushing index. The two reached a relatively stable state when the water-cement ratio of the slurry was 0.5 and 0.9, respectively.

3.2 Influence of nano-SiO2 Solution Pre-soaking

The influence of nano-SiO2 solution pre-soaking on the physical indexes of recycled coarse aggregate was divided into two parts: pre-soaking time and nano-SiO2 pre-soaking concentration. Table 5 shows the value of the influence of pre-soaking time and pre-soaking concentration on the physical indexes of recycled coarse aggregate . The physical index value of recycled coarse aggregate without pre-soaking treatment was selected as the benchmark. Table 6 and Table 7 show the sensitivity of pre-soaking concentration and pre-soaking time of nano-SiO2 solution, respectively.

Table 5. Influence of pre-soaking time and concentration on physical indexes

Sources	Pre-soaking time (h)	Apparent density(kg/m^3)	Crush index /%	Water absorption/%	Sources	Concentration (%)	Apparent density(kg/m^3)	Crush index /%	Water absorption/%
Experiment test	-	2564	19.70	4.80	Experiment test	-	2564	19.70	4.80
	24	2586	17.97	4.22		1	2587	17.02	4.33
	48	2603	15.99	3.92		2	2602	16.51	3.86
	72	2608	15.67	3.81		3	2608	16.09	3.75
Reference[23]	-	2661	11.90	3.89	Reference[23]	-	2661	11.90	3.89
	24	2650	11.60	3.21		4	2646	11.40	3.18
	36	2641	11.20	3.14		6	2632	11.63	3.77
	48	2639	11.50	3.60					
	60	2627	11.60	3.90					
	72	2631	11.80	3.80					

Table 6. Nano-SiO2 concentration-sensitivity to physical indexes

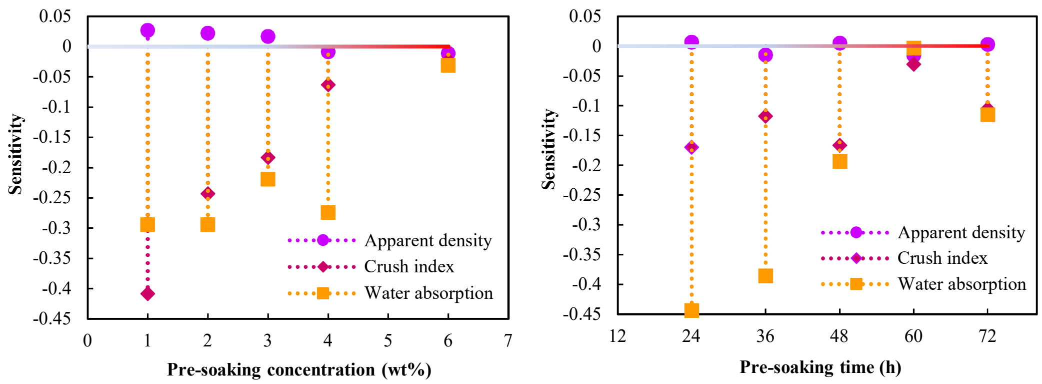
Concentration / %	Apparent density (kg/m^3)	Crush index/%	Water absorption/%
1	0.0269	-0.4081	-0.2938
2	0.0222	-0.2429	-0.2938
3	0.0172	-0.1832	-0.2188
4	-0.0085	-0.0630	-0.2738
6	-0.0109	-0.0227	-0.0308
$\sum \lvert S_i \rvert$	0.0857	0.9199	1.111
$\sum \lvert S_i \rvert / n$	0.0171	0.1840	0.2222

Table 7. Pre-soaking time-sensitivity to physical indexes

Pre-soaking time / h	Apparent density(kg/m^3)	Crush index/%	Water absorption/%
24	0.0067	-0.1696	-0.4435
36	-0.0150	-0.1176	-0.3856
48	0.0052	-0.1665	-0.1934
60	-0.0153	-0.0303	-0.0031
72	0.0030	-0.1053	-0.1147
$\sum \mid S_i \mid$	0.0452	0.5893	1.1403
$\sum \mid S_i \mid / n$	0.0090	0.11786	0.2281

Fig.2(a) shows that with the increase of the pre-soak concentration of nano-SiO2 solution, the sensitivity value of the apparent density of recycled coarse aggregate changes less, indicating that the effect of pre-soak concentration of nano-SiO2 solution on the apparent density is less different. When the pre-soak concentration was 1%-3%, there was a positive effect on the apparent density, and when the pre-soak concentration was 4% and 6%, it has a negative effect. The sensitivity of nano-SiO2 solution concentration to crushing index and water absorption changed greatly, and showed a negative effect. It shows that increasing the concentration of nano-SiO2 solution was beneficial to the reduction of crushing index and water absorption of recycled coarse aggregate. With the increase of concentration, the absolute value of sensitivity to crushing index decreased, while the sensitivity value of water absorption did not show a clear trend.

Fig.2(b) shows that the effect of nano-SiO2 solution pre-soaking time on the sensitivity value of the physical index of recycled coarse aggregate does not show an obvious trend. The sensitivity value of different pre-soaking time to apparent density tends to 0, and the pre-soaking time is 24h, 48h and 72h, all show a positive effect. There was a negative effect on the crushing index and water absorption, indicating that increasing the pre-soaking time was beneficial to the reduction of crushing index and water absorption.



(a)Pre-soaking concentration (b)Pre-soaking time

Fig. 2 Pre-soaking concentration and time-sensitivity to physical indexes

To sum up, the horizontal axes 1, 2, and 3 are defined in Fig.3 to represent the apparent density, crushing index, and water absorption of the recycled coarse aggregate, respectively. It can be seen that the pre-soak concentration of nano-SiO2 solution has a significant effect on the apparent density and crushing index, followed by the pre-soak time and the water-cement ratio of the pre-slurry. For the change of water absorption, the pre-soaking time of nano-SiO2 solution was the most significant,

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followed by pre-soaking concentration and water-cement ratio of pre-slurry. It can be seen that the water-cement ratio of sizing has low sensitivity values for the three physical indicators.

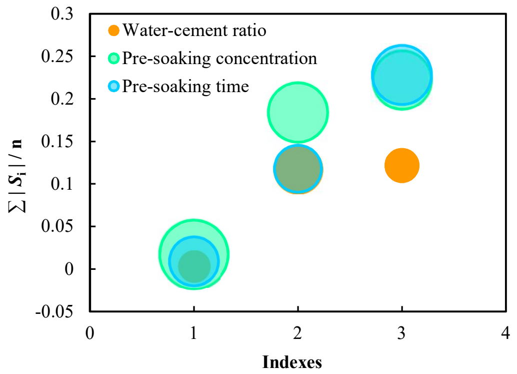

Fig. 3 Comparison of physical index sensitivity

4. Static Cube Compressive Strength Sensitivity

4.1 Influence of nano-SiO2 Doping Method

The nano-SiO2 solution modified recycled coarse aggregate method (referred to as the pre-soak method) selects concentrations of 0.3%, 0.5%, and 2.0%, and the direct incorporation of nano-SiO2 particles selects the cement mass substitution amount of 0.3%-8.0%. Taking the 28d compressive strength of fully recycled coarse aggregate concrete without adding nano-SiO2 as the benchmark value, Table 8 shows the value of the effect of nano-SiO2 addition on the compressive strength of recycled aggregate concrete. Table 9 and Table 10 show the sensitivity of various levels of nano-SiO2 doping methods.

Table 8. Adding way of nano SiO2-influence of compressive strength

Data Sources	Add way	Concentration / %	f_{cu} / MPa	Data Sources	Add way	Concentration / %	f_{cu} / MPa
Experiment test	-	0	32.40	Reference [26]	-	0	26.96
	Pre-soaking	2.0	36.43		Direct	3.0	28.69
Reference[24]	-	0	32.10		Direct	6.0	29.21
	Pre-soaking	0.3	33.20		Direct	8.0	30.27
	Pre-soaking	0.5	33.50	Reference [24]	-	0	32.10
Reference [25]	-	0	17.06		Direct	0.3	32.60
	Direct	1.0	20.55		Direct	0.5	30.30
	Direct	2.0	23.08		Direct	1.0	24.20

Table 9. Pre-soaking of nano SiO2-sensitivity to compressive strength

Concentration (%) / Index sensitivity	0.3	0.5	2	$\sum\|S_i\|/n$
Sensitivity to compressive strength	0.0571	0.0436	0.1244	0.0750

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Table 10. Direct adding of nano SiO2-sensitivity to compressive strength

Index sensitivity \ Concentration (%)	0.3	0.5	1	2	3	6	8	$\sum\|S_i\|/n$
Sensitivity to compressive strength	0.0519	-0.1121	0.0815	0.3529	0.1711	0.1113	0.1228	0.1434

It can be seen from Fig.4 that the addition of nano-SiO2 has a positive effect on the compressive strength of recycled aggregate concrete as a whole, indicating that it was beneficial to the increase of the compressive strength of recycled aggregate concrete. Under different doping methods, the maximum sensitivity was reached when the nano-SiO2 concentration and mass substitution rate were both 2%. Compared with the direct mixing method, the sensitivity value of the nano-SiO2 pre-soak method was generally lower, indicating that the direct mixing method has a more significant effect on the compressive strength of recycled aggregate concrete. At 0.3% and 0.5% content, the sensitivity of pre-soak to compressive strength was lower and showed a downward trend. When 0.5% nano-SiO2 was added to replace the cement quality, the direct incorporation method had a negative effect. When the content reached 2%, the sensitivity of the direct incorporation method began to decrease. It shows that the effect of nano-SiO2 on the compressive strength of recycled aggregate concrete was significantly reduced under the addition of high or low dosage, and the enhancement effect of compressive strength will be weakened.

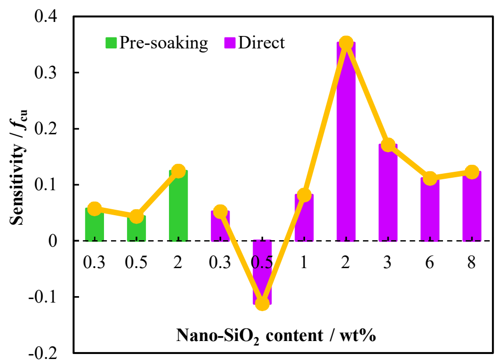

Fig. 4 Adding way of nano SiO2-sensitivity to compressive strength

4.2 Effect of PVA Fiber Content

The volume content of PVA fiber was selected as 0.05%, 0.10% and 0.15%, and the compressive strength of the recycled aggregate concrete without PVA fiber was taken as the benchmark value. Table 11 shows the value of the effect of PVA fiber on the compressive strength of recycled aggregate concrete, and the sensitivity value was shown in Table 12.

Table 11. Adding of PVA fiber-influence of compressive strength

Data Sources	Experiment test			Reference [27]			
Content / %	0	0.05	0.10	0	0.05	0.10	0.15
f_{cu} / MPa	32.40	31.30	30.08	35.39	36.68	37.46	35.94

Table 12. Adding of PVA fiber-sensitivity to compressive strength

Index sensitivity \ Content (%)	0.05	0.1	0.15	$\sum\|S_i\|/n$
Sensitivity to compressive strength	0.0208	0.0081	0.0155	0.0148

Fig.5 shows that the incorporation of PVA fibers has a positive effect on the compressive strength of recycled aggregate concrete. When the dosage was 0.10%, the sensitivity of PVA fiber incorporation to compressive strength reaches the lowest value. It shows that the effect of 0.05% and 0.15% PVA fiber incorporation on compressive strength was more significant than that of 0.10% incorporation. The sensitivity value when the dosage was 0.05% greater than 0.15%. It shows that PVA fiber makes the compressive strength of recycled aggregate concrete change more violently under small dosage, and the increasing effect of compressive strength was weakened under large dosage.

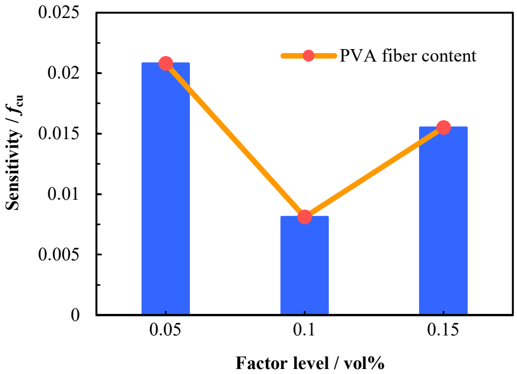

Fig. 5 PVA fiber-sensitivity to compressive strength

4.3 Influence of Replacement Percentage

The replacement percentage of recycled coarse aggregate was 30%, 50%, 70% and 100%, and the compressive strength of ordinary concrete was used as the benchmark value. Table 13 shows the value of the effect of replacement percentage on the compressive strength of recycled aggregate concrete, and the sensitivity value was shown in Table 14.

Table 13. Replacement percentage-influence of compressive strength

Data Sources	Experiment test			Reference [26]			Reference [23]			
Replacement percentege /%	0	30	100	0	50	100	0	50	70	100
f_{cu} / MPa	41.30	35.66	32.40	38.11	31.65	26.96	35.7	32.7	27.9	26.9

Table 14. Replacement percentage-sensitivity to compressive strength

Content (%) / Index Sensitivity	30	50	70	100	$\sum \| S_i \| / n$
Sensitivity to compressive Strength	-0.4552	-0.2536	-0.3121	-0.2515	0.3181

It can be seen from Fig.6 that the effect of the replacement percentage on the compressive strength exhibits a significant negative adjustment. It shows that the addition of recycled coarse aggregate reduces the compressive strength of recycled aggregate concrete, but the rate of change was weakened. The absolute value of the compressive strength sensitivity of the replacement percentage showed a downward trend as a whole, and a lower sensitivity point appeared at 50% and 100% replacement. It shows that the change amplitude of the compressive strength of recycled aggregate concrete under this replacement percentage is small.

In summary, the horizontal axes 1, 2, 3, and 4 in Fig.7 represent the PVA fiber incorporation, nano-SiO2 pre-soak method, nano-SiO2 direct incorporation method, and the replacement percentage of recycled coarse aggregates, respectively. It can be seen that the replacement percentage of recycled

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coarse aggregate was the primary factor affecting the compressive strength of recycled aggregate concrete, while the incorporation of PVA fibers has no significant effect on the compressive strength. Compared with the nano-SiO2 pre-soak method, the effect of the direct incorporation method was more significant.

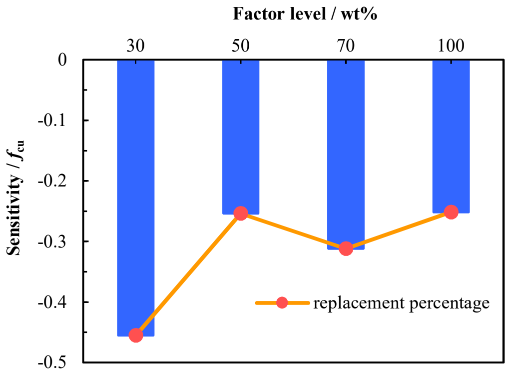

Fig. 6 Replacement percentage-sensitivity to strength

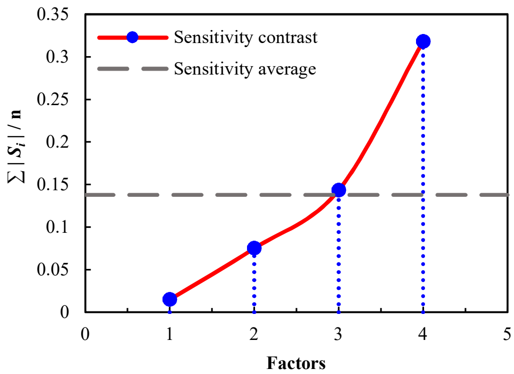

Fig. 7 Comparison of compressive strength sensitivity

5. Sensitivity of Dynamic Mechanical Properties

5.1 Impact of Impact Strain Rate

Table 15. Relationship of strain rate on peak stress and peak strain of impact specimens

Data Sources	$\dot{\varepsilon}$ / s^{-1}	Strength reference value / MPa	σ_p / MPa	ε_p / 10^{-3}
Experiment test (22.4/s-44.7/s) Based on static	22.4	32.40	37.91	5.493
	31.3	32.40	43.74	5.974
	44.7	32.40	48.92	6.100
Reference [28] (39/s-111/s) Based on quasi-static	39.0	26.72	41.01	4.765
	54.0	26.72	45.29	5.101
	78.0	26.72	49.66	4.594
	111.0	26.72	63.15	5.320
Reference [29] (134.1/s-215/s) Based on quasi-static	134.1	26.35	65.24	3.469
	178.1	26.35	71.58	4.612
	215.4	26.35	79.90	5.492

Note: σp and εp represent peak stress and peak strain, respectively.

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Table 16. Strain rate-sensitivity to peak stress

Strain rete / s^{-1} Index Sensitivity	22.4	31.3	44.7	39.0	54.0	78.0	111.0	134.1	178.1	215.4	$\sum\|S_i\|$ / n
Sensitivity to peak stress	0.3394	0.4998	0.5099	1.5221	1.4286	1.2218	1.3634	2.3707	2.1219	2.0300	1.3408

The strain rate was selected as 22.4s-1~215.4s-1, and the static compressive strength or quasi-static compressive strength of fully recycled aggregate concrete was used as the reference value. Table 15 shows the effect of strain rate on the peak stress and peak strain of recycled aggregate concrete, and the sensitivity of strain rate to dynamic peak stress was shown in Table 16. Since the ratio of peak stress to static compressive or quasi-static compressive strength represents a dynamic growth factor [28, 30], the static and quasi-static strengths were given constant values. The sensitivity change of peak stress also reflects the influence of strain rate on the dynamic growth factor to a certain extent.

It can be seen from Fig.8 that the increase of the strain rate has a positive effect on the peak stress of recycled aggregate concrete. It shows that increasing the strain rate increases the peak stress of recycled aggregate concrete. Relative to the static compressive strength of recycled aggregate concrete, the increase of peak stress shows a significant strain rate effect [18,29]. The overall comparison of the three sets of curves shows that with the increase of the strain rate, the peak stress sensitivity shows an increasing trend. It shows that the increase of strain rate has a more significant effect on the peak stress change of recycled aggregate concrete. Comparing the sensitivity curves of each group, the peak stress sensitivity shows an upward trend at a lower test strain rate; at a higher strain rate [29], the peak stress sensitivity decreases gently, and the effect of the strain rate on the peak stress reaches a relatively stable state; At medium strain rate [28], it showed a trend of first decreasing and then increasing.

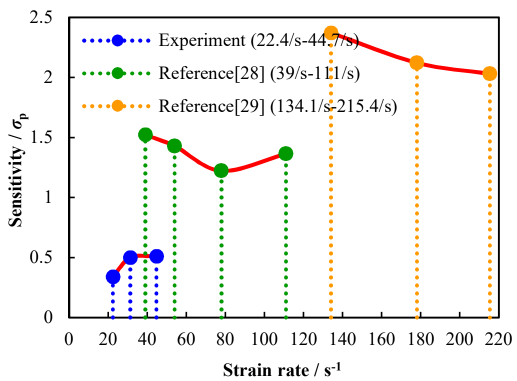

Fig. 8 Strain rate-sensitivity to peak stress

According to Table 15, the plot of strain rate versus peak strain was shown in Fig.9. It can be seen that the peak strain of the experimental test increases with the increase of the strain rate. However, no obvious concomitant relationship between peak strain and strain rate was found in [28]. After sorting the above strain rates and corresponding peak strains in order, the same conclusion as in the literature [28] was obtained. This may be related to the structural size of the impactor [31], or it may be the result of the combined effect of inertial effects and crack propagation effects [28, 29].

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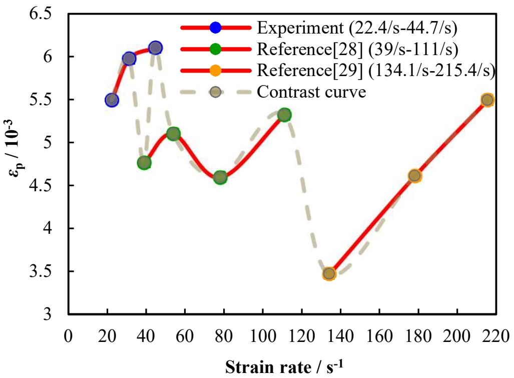

Fig. 9 Influence of strain rate on peak strain

5.2 Influence of Replacement Percentage

The replacement percentage of recycled coarse aggregate was 30%, 50%, 70% and 100%, and the average peak stress and peak strain of ordinary concrete at each strain rate were taken as the reference value. Table 17 shows the influence of substitution rate on peak stress and peak strain, and the sensitivities of recycled aggregate concrete peak stress and peak strain were shown in Table 18.

Table 17. Influence of replacement percentage on peak stress and peak strain

Data Sources	Experiment test			Reference[28]				
Replacement percentage / %	0	30	100	0	30	50	70	100
σ_p / MPa	50.82	43.88	43.52	56.01	54.32	55.73	50.78	49.78
ε_p / 10^{-3}	5.263	5.423	5.856	4.448	4.753	4.543	4.911	4.945

Table 18. Replacement percentage-sensitivity to peak stress and peak strain

Content (%) / Index Sensitivity	30	50	70	100	$\sum \mid S_i \mid / n$
Sensitivity to peak stress	-0.2782	-0.0010	-0.1334	-0.1274	0.1350
Sensitivity to peak strain	0.1650	0.0427	0.1487	0.1122	0.1172

It can be seen from Fig.10(a) that the replacement percentage of recycled coarse aggregate has a negative effect on the dynamic peak stress of recycled aggregate concrete, and the absolute value of its sensitivity decreases as the replacement percentage increases. It shows that the addition of recycled coarse aggregate reduces the peak stress of recycled aggregate concrete, the significance of the effect on the peak stress was reduced, and the peak stress change caused by the quality of recycled coarse aggregate will be weakened. However, when the replacement percentage was 50%, the sensitivity reaches the minimum, indicating that when the replacement percentage was 50%, the peak stress change amplitude of the recycled aggregate concrete was small, which was consistent with the conclusion obtained from the static analysis.

It can be seen from Fig.10(b) that the replacement percentage of recycled coarse aggregate has a positive effect on the dynamic peak strain of recycled aggregate concrete. It shows that the increase of the replacement percentage was beneficial to the improvement of the peak strain of recycled aggregate concrete. The change trend of peak strain sensitivity was opposite to the change of its sensitivity to peak stress.

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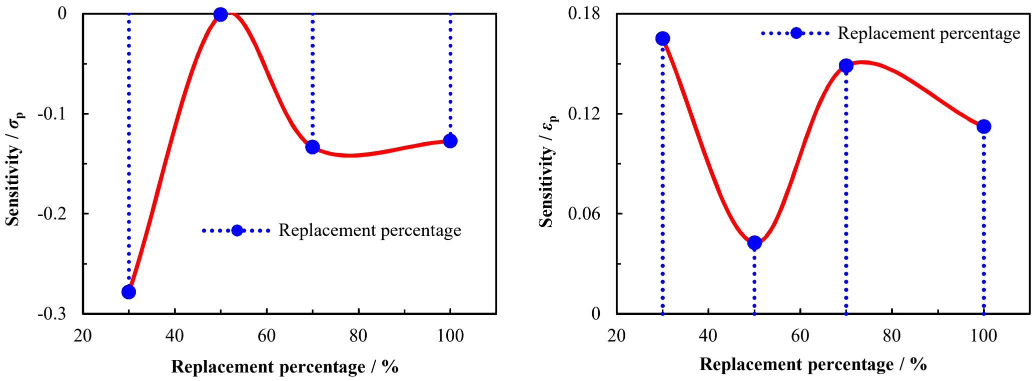

(a)Sensitivity to peak stress (b)Sensitivity to peak strain

Fig. 10 Replacement percentage-sensitivity to peak stress and peak strain

5.3 Influence of nano-SiO2 and PVA Fibers

The dynamic peak stress and peak strain of the fully recycled aggregate concrete without nano-SiO2 and PVA fibers were selected as the reference values. Table 19 shows the value of each level of the influencing factors, and Table 20 shows the sensitivity of nano-SiO2 and PVA fibers to the peak stress and peak strain of recycled aggregate concrete.

Table 19. Influence of nano-SiO2 and PVA fiber on peak stress and peak strain

Data sources	Factors	Factor level	σ_p / MPa	ε_p / 10^{-3}
Experiment test	Nano-SiO_2 (by pre-soaking)	0	43.52	5.856
		2%	46.65	5.965
Reference [29]	Nano-SiO_2 (by direct)	0	72.24	4.524
		1%	77.86	4.724
		2%	75.07	4.659
Experiment test	PVA fiber	0.05%	43.09	6.286
		0.10%	39.48	6.630

Table 20. Nano-SiO2 and PVA fiber-sensitivity to peak stress and peak strain

Data sources	Factors	Factor level	Sensitivity /σ_p	Sensitivity /ε_p	$\sum \lvert S_i \rvert$ / n (σ_p)	$\sum \lvert S_i \rvert$ / n (ε_p)
Experiment test	Nano-SiO_2 (by pre-soaking)	2%	0.07192	0.0186	0.0719	0.0186
Reference [29]	Nano-SiO_2 (by direct)	1%	0.1556	0.0884	0.0974	0.0591
		2%	0.0392	0.0298		
Experiment test	PVA fiber	0.05%	-0.0198	0.1469	0.0563	0.1396
		0.10%	-0.0928	0.1322		

Fig.11(a) shows that the incorporation of nano-SiO2 has a positive effect on the peak stress of recycled aggregate concrete, while the incorporation of PVA fibers has a negative effect on the peak stress. It is shown that the incorporation of nano-SiO2 was beneficial to the increase of the peak stress, while the PVA fiber has a detrimental effect on the peak stress. Fig.11(b) shows that the incorporation of both nano-SiO2 and PVA fibers positively affects the peak strain sensitivity of recycled aggregate concrete. It shows that the incorporation of nano-SiO2 and PVA fibers was beneficial to the increase

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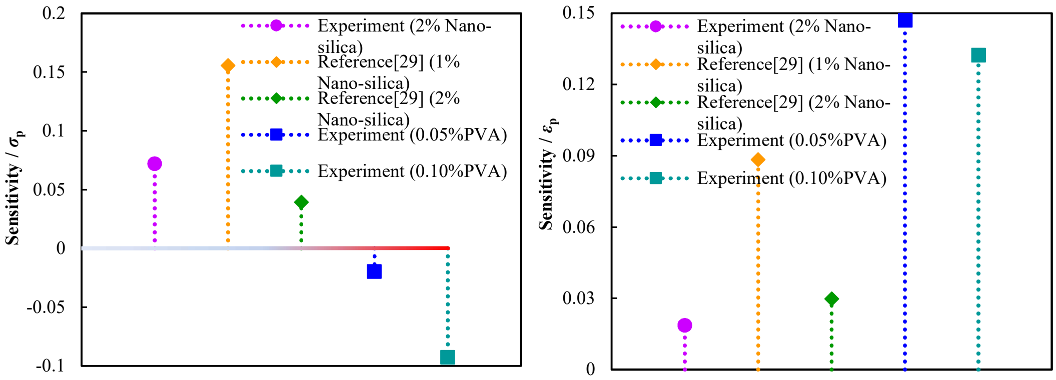
of the peak strain of recycled aggregate concrete. Compared with the incorporation of nano-SiO2, the effect of PVA fibers on the peak strain was more significant.

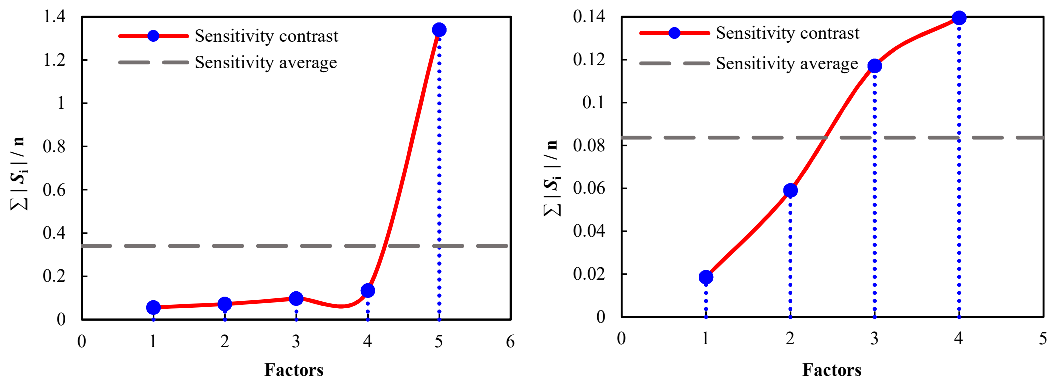


(a)Sensitivity to peak stress (b)Sensitivity to peak strain

Fig. 11 Nano-SiO2 and PVA fiber-sensitivity to peak stress and peak strain

To sum up, the horizontal axes 1, 2, 3, 4, and 5 in Fig.12 represent the PVA fiber incorporation, nano-SiO2 pre-soak method, nano-SiO2 direct incorporation method, the replacement percentage of recycled coarse aggregate and the strain rate, respectively. It can be seen from Fig.12(a) that the influence of strain rate on the peak stress of recycled aggregate concrete was the main factor, and its influence degree was much higher than that of the other four factors. The sensitivity of PVA fiber incorporation was the lowest, indicating that peak stress was not sensitive to changes in PVA fiber incorporation. Compared with the nano-SiO2 pre-soak method, the direct incorporation method was more sensitive to the peak stress and has a more significant impact.

Fig.12(b) shows that the incorporation of PVA fibers and the replacement percentage of recycled coarse aggregate were the main controlling factors affecting the peak strain of recycled aggregate concrete. Compared with the nano-SiO2 pre-soak method, the direct incorporation method was more sensitive and has a more significant impact on the peak strain. It can also be seen that no matter the index was the peak stress or peak strain of the impact specimen, the index sensitivity value of the replacement percentage of recycled coarse aggregate was in the top two.



(a)Sensitivity to peak stress (b)Sensitivity to peak strain

Fig. 12 Comprehensive comparison of dynamic mechanical properties sensitivity

6. Conclusion

(1) The increase of the water-cement ratio of the pre-slurry improves the water absorption rate of the recycled coarse aggregate and reduces the crushing index. The pre-soaking concentration and time of nano-SiO2 increased, and the crushing index and water absorption rate of recycled coarse aggregate

decreased. The pre-soaking concentration of nano-SiO2 is the main sensitive factor for the apparent density and crushing index of recycled coarse aggregate, and the pre-soaking time is the main controlling factor for water absorption.

(2) The addition of nano-SiO2 is beneficial to increase the static cube compressive strength of recycled aggregate concrete, while the addition of recycled coarse aggregate reduces the compressive strength of recycled aggregate concrete. The replacement rate of recycled coarse aggregate was the main controlling factor affecting the compressive strength, while the PVA fiber content had no significant effect on the compressive strength. Compared with the nano-SiO2 pre-soak method, the direct incorporation method has a more significant effect on the compressive strength of recycled aggregate concrete.

(3) Incorporating nano-SiO2 and increasing the impact strain rate are beneficial to the growth of the dynamic peak stress of recycled aggregate concrete, while the increase of the replacement percentage and PVA fiber content reduces the peak stress. The main controlling factor for the dynamic peak stress of recycled aggregate concrete is the strain rate, while PVA fibers are less sensitive to the peak stress.

(4) The addition of recycled coarse aggregate, nano-SiO2 and PVA fibers has a positive effect on the dynamic peak strain of recycled aggregate concrete. The incorporation of PVA fibers is the main controlling factor for the dynamic peak strain of recycled aggregate concrete, while the nano-SiO2 pre-soak method is less sensitive to the peak strain.

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