The Effect of Expansive Agent and Hybrid Fiber on the Workability of Self-compacting Concrete for Modular Building Construction Connection

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Abstract. Modular construction is a green and low-carbon construction method. In this paper, the effect of expansive agent (EXP), mixed steel fiber (SF) and polyvinyl alcohol fiber (PVA) on the workability of self-compacting concrete (SCC) were studied. The filling performance, passing capacity and anti-segregation performance of SCC with different mix ratios are investigated. It is found that the workability can be improved by adding EXP and reduced by adding hybrid fiber. The formula of the relationship between slump flow and the amount of EXP, SF and PVA is obtained by correlation analysis simultaneously. When the EXP content constitutes 7%-10% of the cementing material, the workability of the freshly mixed SCC is optimized. Additionally, to ensure proper filling performance at an EXP content of 7%, the volume content of total fiber in concrete should not exceed 0.25%. At an EXP content of 10%, this volume content should not exceed 0.29%.

Keywords: Expansive agent, Modular building, Polyvinyl alcohol fiber, Self-compacting concrete, Steel fiber, Workability

1 Introduction

Modular building has been widely concerned and affirmed for its superior production and construction efficiency, good building quality in sustainable development and other aspects. The interconnection between modules in a modular building has a great impact on the integrity of the structure, and the connected structure design should meet the requirements of safety and reliability, clear force transmission, reasonable structure, good durability and easy construction[9]. Therefore, in the connection design of modular buildings, the choice of materials is particularly important.

Self-compacting concrete SCC refers to the concrete that has a certain flow and compaction ability by adding admixtures relying on its own gravity without external vibration. Compared with ordinary concrete, SCC has better fluidity, filling performance and passing capacity[9], so that it can be better filled in dense steel bars, so as to effectively save the construction labor force at the joint of modular buildings

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and reduce the construction difficulty. SCC has been currently recognized and used by countries around the world with its good economic benefits.

There have been studies on the application of expansive agent EXP and fiber to SCC. Zhang[9] found that the strength of SCC decreased significantly when the content of EXP was greater than 10%. Both self-shrinkage and drying shrinkage of SCC decrease continuously with the increase of EXP content. Li[9] used HCSA, a double expansion source of Calcium-sulphoaluminate and calcium oxide, to prepare SCC, which effectively solved the problems of large shrinkage performance, poor volume stability and easy cracking of SCC, and achieved good engineering benefits. Zhu[9] found in the test that when the content of EXP is greater than 10%, freshly mixed SCC will lose fluidity too quickly due to too fast hydration reaction. Ganga[9] proposed that the addition of Calcium-sulphoaluminate-portland cement has a positive impact on the flow and filling capacity of SCC, and also has a significant impact on the expansion mechanism.

The effect of fiber on SCC is mainly reflected in improving the early age shrinkage, self-shrinkage and drying shrinkage, and improving the splitting tensile strength of SCC. Zhang9 found that the inclusion of fiber can reduce the early-age shrinkage rate and improve the crack resistance of SCC, and the effect of hybrid fiber is better than that of single fiber. Li[9] proposed that steel fiber SF has obvious inhibition on dry shrinkage, among which micro-fine SF has the best inhibition on dry shrinkage, and the addition of micro-fine SF can greatly improve the compressive and splitting tensile properties of SCC. Jia[9] found that proper incorporation of Polyvinyl alcohol fiber PVA could improve the flexural strength of concrete. Zheng[9] found that mixed SF and PVA fiber will form a fiber network structure. As a hybrid carrier of SF, PVA can evenly disperse SF in the matrix so that the problems of high elastic modulus steel fiber such as high cost, poor durability and low elastic modulus PVA fiber affecting the strength of matrix are effectively remedied. Ganesh[10] summarized the effects of single and mixed mixtures of several fibers as admixtures on SCC. It is found that the single mixing of all kinds of fibers has a positive effect on the mechanical properties of SCC, and the effect is better when the double mixing of different fibers. In addition, the orthogonal and uniform distribution of fibers effectively establishes a "Bridge effect" on the internal structure of SCC, effectively hindering the development of cracks.

The above research shows that the application of EXP, SF and PVA fiber to SCC is feasible, but at present, domestic and foreign scholars have little research on the simultaneous application of EXP and mixed SF and PVA fiber. How to improve the workability of SCC on the basis of ensuring its mechanical properties and making it more convenient and faster in the construction and pouring process is still valuable. Therefore, this paper mainly explores the influence of the inclusion of EXP, SF and PVA fiber on the workability of SCC, so as to obtain an optimal mix ratio that can be applied to actual construction.

2 Experiment

2.1 Experimental materials

PO42.5R cement and fly ash were selected as cementing materials. Medium sand is selected for fine aggregate, and two graded stones of 5-10mm and 10-16mm are selected for coarse aggregate. The matching ratio of the two graded coarse aggregates is 1:1.

A high performance expansive anti-cracking agent is selected as EXP, which the main chemical components are Calcium thiophosphate and Calcium hydroxide. The micro-fine SF with a length of 13mm and the PVA fiber with a length of 9mm are selected.

Due to the unique molecular structure of Polycarboxylate superplasticizer, it has the advantages of low dosage, high water reduction rate, fast growth of concrete strength, small slump loss and small viscosity resistance of concrete mix. Moreover, it contains PCE surfactant thus has air entraining function[10], which can introduce air in the concrete mixing process, significantly improving the shrinkage performance of concrete. Therefore, Polycarboxylate superplasticizer was selected as water reducing agent in this experiment, which was determined to be 2% of the total mass of cementing material.

2.2 Experimental method

The test of the workability of SCC was carried out according to the national code JGJ T283-2012[10], including filling performance, passing capacity and anti-segregation performance.

2.3 Experimental design

According to the national code[10], the basic mix ratio of SCC was designed by using the absolute volume method, as shown in Table 1. In order to explore the different influences of EXP, SF and PVA on SCC, three factors and three levels orthogonal test were used. From the relevant literature[14-18], determine the content of EXP, SF and PVA as the three factors, and the three levels were constituted by the content of 4%, 7% and 10% EXP, the content of 0.15%, 0.20% and 0.25% SF, the mixing ratio of SF and PVA were 3:1, 4:1 and 6:1. Based on the basic mix ratio, the orthogonal experimental design was conducted for this experiment, as shown in Table 2.

Table 1. Basic mix ratio of SCC

Strength graded	m_w/m_b	Cement (kg/m^3)	Fly ash (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
C40	0.33	389.0	166.7	846.7	783.0	181.0	11.1

Table 2. Orthogonal design of SCC

Design	Ratio	EXP (%)	SF (%)	PVA (%)	SF:PVA	Total fiber (%)
E4S15R3	P1	4	0.15	0.05	3:1	0.20
E4S20R6	P2	4	0.20	0.03	6:1	0.23
E4S25R4	P3	4	0.25	0.06	4:1	0.31
E7S15R6	P4	7	0.15	0.03	6:1	0.18
E7S20R4	P5	7	0.20	0.05	4:1	0.25
E7S25R3	P6	7	0.25	0.08	3:1	0.33
E10S15R4	P7	10	0.15	0.04	4:1	0.19
E10S20R3	P8	10	0.20	0.07	3:1	0.27
E10S25R6	P9	10	0.25	0.04	6:1	0.29

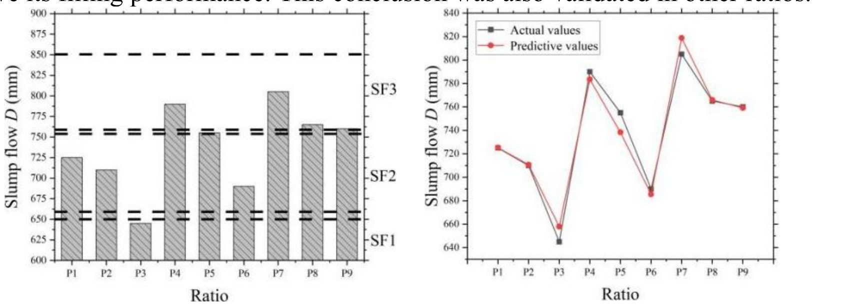
3 Effect of EXP, SF and PVA on the workability of SCC

3.1 Filling performance

The code[13] uses slump flow D and flow time T_{500} to measure the filling performance of SCC. Slump flow D is divided into three grades SF1, SF2 and SF3, of which SF3 is the best. T_{500} indicates the time when the slump flow reaches 500mm. When T_{500} is small, the freshly mixed SCC has good filling performance and self-leveling performance. T_{500} is divided into two levels: less than 2 seconds and greater than or equal to 2 seconds, of which less than 2 seconds is the best.

Final Slump flow *D*. According to national code, P4, P7, P8 and P9 fulfil the requirement of SF3. P1, P2, P5 and P6 fulfil the requirement of SF2. P3 fulfil the requirement of SF1, respectively, as shown in Figure 1a.

From Figure 1a, for P1, P4, and P7 with similar total fiber content but different EXP content, it was found that when the EXP content increased in the range of 4% to 10%, the filling performance of freshly mixed SCC was greatly improved. This is because both EXP and fly ash have the characteristics of small and regular particles, which can reduce the friction force during the flow process of SCC mixture and improve its filling performance. This conclusion was also validated in other ratios.



(a) Slump flow of each ratio (b) Actual values and predictive values

Fig. 1. Final Slump flow

For P1, P2, and P3 with the same EXP content but different total fiber content, it was found that when the fiber content increased in the range of 0.18% to 0.33%, the filling performance of freshly mixed SCC significantly decreased. Since the fiber and SCC mixture have good cohesion, thereby reducing the filling performance of freshly mixed SCC. This conclusion was also validated in P4, P5, P6, and P7, P8, and P9.

Tests show that in order to meet the SF3 filling performance grade, the content of EXP should be between 7% and 10%, and the total fiber content should not be too high. When the EXP content is 7%, the total fiber content should not exceed 0.25%. When the EXP content is 10%, the total fiber content should not exceed 0.29%.

In order to investigate the specific effects of EXP, SF, PVA and total fiber content on the filling performance of freshly mixed SCC, a linear regression correlation analysis was conducted, and the results are shown in Table 3.

Table 3. Correlation analysis results

Linear regression analysis results n=9								
	Non standardized coefficient		Standardized coefficient	*t*	*P*	*VIF*	R^2	*F*
	B	*σ*	*Beta*					
Constant value	795.794	22.754	-	34.974	0.000***	-		
EXP (%)	14.315	1.616	0.733	8.859	0.000***	1.009	0.966	*F*=47.488 *P*=0.000***
SF (%)	-142.368	145.597	-0.121	-0.978	0.373			
PVA (%)	-311.994	207.753	-0.106	-1.502	0.193			
Total fiber (%)	-454.361	81.273	-0.484	-5.591	0.003***			
dependent variable: Slump flow (mm)								

Note: *** represent significance levels of 1%, 5%, and 10%.

The fitting formula is shown in formula (1), where *Y* is the value of slump flow, *A*, *B*, *C* and *D* are the content of EXP, SF, PVA and total fiber content, respectively. The fitting is predicted and compared with the measured values. It is found that the fitting effect is ideal, as shown in Figure 1b.

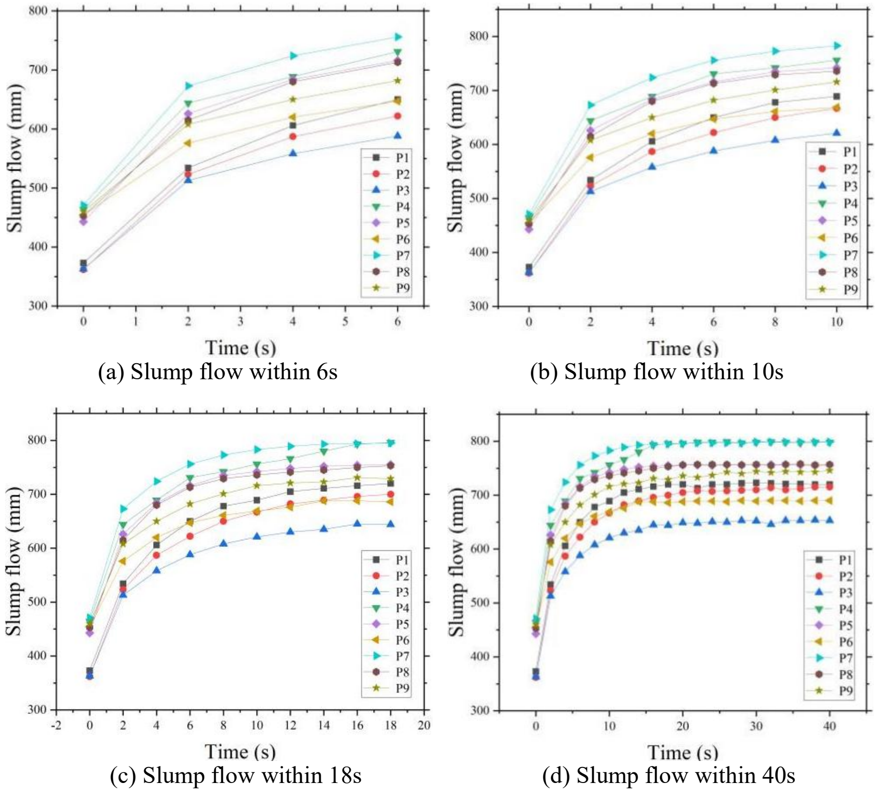
$$Y = 795.794 + 14.315A - 142.368B - 311.994C - 454.361D \tag{1}$$

According to the correlation analysis, the standardized coefficient of the EXP dosage is 0.733, indicating that the EXP dosage will have a significant positive impact on the filling performance of freshly mixed SCC. The standardization coefficient of the total fiber content is -0.484, indicating that the total fiber content will have a significant negative impact on the filling performance of freshly mixed SCC. The significance *P*-value represents the probability of more extreme situations occurring in the observed sample data under the premise of the original hypothesis being true. That is, the smaller the *P*-value, the greater the significance of the result, and the greater the confidence of the independent variable's influence on the dependent variable. Base on the correlation analysis, the *P*-values of both the EXP content and the total fiber content on slump flow are less than 0.01, indicating a significant impact of the two on slump flow.

Analysis shows that the specific content of SF and PVA in the fiber is not significantly related to the filling performance of freshly mixed SCC. However, the addition of both types of fiber will reduce their filling performance.

Slump flow process. Recorded the slump flow process of freshly mixed SCC within 40 seconds of lifting the slump cylinder to observe the flow rate of freshly mixed SCC within different time periods, the results are shown in Figure 2 and Table 4.

Figure 2 found that after lifting the slump cylinder to allow the freshly mixed SCC to flow for 18 seconds, the process of slump propagation basically ended, and the slump propagation remained basically unchanged from 18 seconds to 40 seconds.



(a) Slump flow within 6s (b) Slump flow within 10s

(c) Slump flow within 18s (d) Slump flow within 40s

Fig. 2. Slump flow process

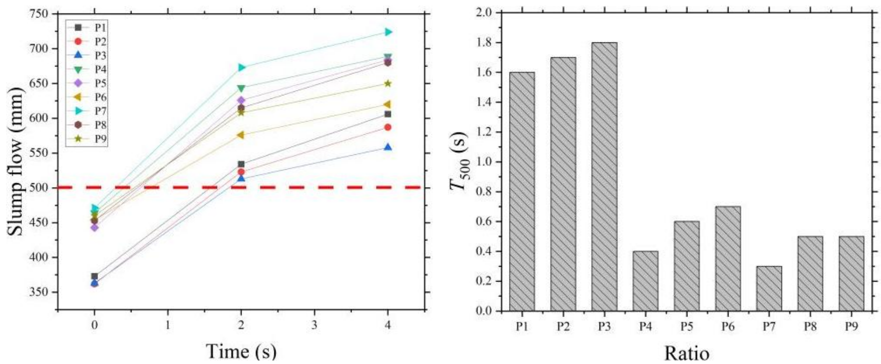
From Table 4, the ratios P4 and P7 have higher flow rate within 6s and 10s, while P7 has the highest flow rate and P3 has the lowest flow rate; Within 18 seconds, the flow rates of P4 and P7 are consistent and both are the highest values, while P3 having the lowest flow rate; The ratios P4, P5, P7, P8, and P9 have higher flow rate within 40 seconds. Among them, P4 and P7 have the same highest flow rate, while P3 has the lowest flow rate as well.

Test found the flow rate of each ratio is basically consistent with the final slump flow. In modular building connections, the application of SCC with better filling performance and faster filling rate can not only better fill the connection and improve its strength, but also achieve faster self-compacting effect, shorten the construction period, thus saving time and labor.

Table 4. Flow rate within different time periods

Ratio	Within 6s (mm/s)	Within 10s (mm/s)	Within 18s (mm/s)	Within 40s (mm/s)
P1	108	69	40	18
P2	104	67	39	18
P3	98	62	36	16
P4	122	76	44	20
P5	119	74	42	19
P6	108	67	38	17
P7	126	78	44	20
P8	119	74	42	19
P9	114	72	41	19

Flow time T_{500}. Figure 3 shows the T_{500} of all ratios. The value of T_{500} is inversely proportional to the final slump flow and flow rate, and the flow time T_{500} of all ratios are less than 2 seconds. It can be used for structures with more reinforcement or structures with higher requirements for concrete appearance performance.

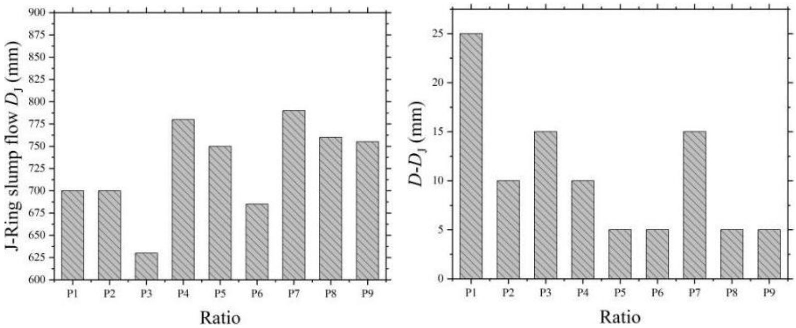


(a) Flow curve within 4s and 500mm slump flow line (b) Flow time T_{500} of each ratio

Fig. 3. Flow time

3.2 Passing capacity

The code[13] uses the difference of Slump flow and J-Ring slump flow (D-D_J) to measure the clearance permeability of SCC. It divides (D-D_J) into two levels: less than or equal to 25 mm and greater than 25mm but less than or equal to 50mm, of which the former is better. The results of J-Ring slump flow D_J and (D-D_J) are shown in Figure 4.



(a) J-Ring slump flow (b) D-D_J

Fig. 4. Passing capacity of each ratio

Compared to the ratios P1, P2, and P3 with 4% EXP content, the J-Ring slump flow of ratios P4, P5, and P6 with 7% EXP content have significantly increased; Similarly, compared to the ratios P4, P5, and P6 with 7% EXP content, the J-Ring slump flow of P7, P8, and P9 with 10% EXP content have also been significantly improved. And it was found that J-Ring slump flow is also roughly negatively correlated with the total fiber content, and positively correlated with the EXP content. The above conclusions are consistent with the conclusion of slump flow of freshly mixed SCC.

(D-D_J) of all ratios are less than or equal to 25mm, which can be applied to structures with more densely distributed steel bars, usually suitable for steel bars with a clear distance of 60mm~80mm.

3.3 Anti-segregation performance

The code[13] uses segregation rate SR to measure anti-segregation performance of SCC, which is calculated by formula (2), where m_0 indicates the mass of square hole sieve, m_1 indicates the mass of the SCC sample and m_2 indicates the mass of the mass of slurry flowing from the sieve to the weighing barrel.

$$SR = \frac{m_0 + m_2}{m_1} \times 100\% \tag{2}$$

Table 5 shows the SR of each ratio. From Table 5, the SR of all ratios are less than 15%, which can ensure the uniformity and pouring quality of SCC.

Table 5. Segregation rate of each ratio

Ratio	m_0 (kg)	m_1 (kg)	m_2 (kg)	Segregation rate SR (%)
P1	0.605	4.812	-0.137	9.7
P2	0.607	4.894	-0.363	5.0
P3	0.605	5.105	-0.329	5.4
P4	0.606	4.771	-0.164	9.3
P5	0.616	5.005	-0.273	6.9
P6	0.628	4.923	-0.366	5.3
P7	0.608	4.943	-0.163	9.0
P8	0.611	4.881	-0.296	6.5
P9	0.642	4.719	-0.307	7.1

4 Conclusion

The influence of EXP, SF and PVA fiber on the workability of freshly mixed SCC, including filling performance, passing capacity and anti-segregation performance are studied. The experimental conclusions are as follows.

(1) The addition of EXP can increase the slump flow and reduce the flow time T_{500}, thereby improving the filling performance of freshly mixed SCC, while the addition of SF and PVA fiber generally reduces the slump flow and increases the flow time T_{500}, thereby reducing the filling performance of freshly mixed SCC.

(2) To ensure that the slump flow of freshly mixed SCC meet the SF3 performance level (760mm-850mm) specified in the specifications, the content of EXP should be 7%-10%. When the content of EXP is 7%, the total content of fiber should not exceed 0.25% (SF content 0.2% with PVA content 0.05% in this experiment). When the content of EXP is 10%, the total content of fiber should not exceed 0.29% (SF content 0.25% with PVA content 0.04% in this experiment).

(3) Compared to other ratios, ratios P4 and P7 are more optimal, with the maximum slump flow, maximum flow rate, and minimum T_{500}. Therefore, these two ratios of freshly mixed SCC have excellent filling performance. In addition, the passing capacity and anti-segregation performance also meet the specification requirements.

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