Research Article

Effect of Internal Curing with Superabsorbent Polymers on Bond Behavior of High-Strength Concrete

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High-strength concrete (HSC) is widely used in engineering due to its high strength and durability. However, because of its low water-to-cement ratio, external curing water hardly enters the dense internal structure of HSC so that high self-desiccation shrinkage often takes place. As a result, superabsorbent polymers (SAP) are added as an internal curing material to effectively reduce the shrinkage of high-performance concrete. Meanwhile, the bond performance between reinforcing steel and SAP HSC concrete remains unknown. In this paper, the bond performance of HSC mixed with SAP is studied by pull-out tests, and the results were obtained as follows: (1) the bond strength of HSC mixed with SAP increased first and then decreased with the increase of SAP content; (2) the slip at ultimate bond strength of HSC with SAP decreased with the increase of compressive strength; (3) a prediction model of the stress-slip relationship between steel rebars and HSC was established.

1. Introduction

High-strength concrete has higher strength and durability than conventional concrete due to its low water-to-cement ratio, denser internal structure, and low permeability [1]. However, autogenous shrinkage may take place when the water-to-cement ratio is below the critical level, resulting in cracking and reduction of the structure's serviceability [2–5]. Hence, internal curing has been employed to prevent autogenous shrinkage in high-strength concrete by replacing a percentage of normal-weight aggregates with lightweight-weight aggregates [6, 7], superabsorbent polymer (SAP), or other expansive materials [8, 9]. SAP has been extensively studied due to its advantages of being able to mitigate autogenous shrinkage and prevent self-desiccation [10–15]. Multiple studies have proved that SAP can effectively reduce the self-shrinkage of HSC [16–18] while there is no consensus on the influence of SAP on the compressive strength of HSC. Some tests found that SAP would reduce the compressive strength of HSC [19–22], but some other tests

found that SAP would increase the compressive strength of HSC [23–26]. It is reported that SAP content is one of the factors that affect HSC's compressive strength [27]. While there are many factors that influence compressive strength of HSC such as the amount of compensated water, type and SAP particle size, the absorption, desorption kinetic of SAPs, and the interfacial properties between cement matrix and SAPs, the authors only focus on the effect of SAP content on compressive strength of HSC in this study.

Meanwhile, as a key parameter for structural design, bond strength for HSC with SAP added has not been studied yet. Although there were many studies published on the bond strength of normal reinforced concrete [28–36] as well as high-strength concrete [37–42], the law of bond strength and the stress-slip relationship between HSC mixed with SAP and reinforcing steel remain unclear. The stress-slip relationship of concrete is usually obtained from pull-out tests. Various stress-slip models for normal concrete and high-performance concrete have been developed in many studies [41–51]. However, the stress-slip response for high-

strength concrete mixed with SAP is still unknown. In this paper, an experimental study has been carried out aimed at establishing SAP content and compressive strength relationship, SAP content and HSC bond strength relationship, and the stress-slip model for HSC with SAP.

2. Experimental Investigation

2.1. Material Properties. The cement used in this test is P.O. 42.5 Portland cement with chemical composition shown in Table 1. Medium coarse sand and 5–16 mm continuous graded gravel were mixed with the cement to create concrete with a compression strength of 50 MPa. High efficiency polycarboxylate superplasticizer was added as a water reducing agent. Drying and absorbing states of SAP are shown in Figure 1. Standard structural rebars are 16 mm in diameter, shown in Figure 2. In Theory, the internal curing water should be the same for same water-to-cement ratio. However, when SAP is added, water is partially absorbed such that more water is needed in addition to that for internal curing. Therefore, the internal curing water is set to be 20 times of the SAP content.

The mixture proportions of concrete used in the test are shown in Table 2.

2.2. Required Internal Curing Water. In order to ensure that the cement can reach the maximum hydration level, the internal curing water amount can be calculated according to the following equation [52] :

$$M_{ic} = C_f \times CS \times \alpha_{\max}, \quad (1)$$

where M_{ic} is internal curing water mass required for complete hydration of cement; C_f is the cement mass (kg/m^3); CS is the shrinkage of cement when it reaches 100% hydration; for general cement, it is 0.07; and $\alpha_{\max}$ is the maximum hydration degree when all water in SAP is used for cement hydration without evaporation loss; generally, it is $[W/C]/0.36$ (when $W/C \leq 0.36$).

According to the theoretical calculation, the internal curing water amount is $33.12 \text{ kg}/\text{m}^3$, but considering that different SAP contents were designed in the test, the final internal curing water amount of S0, S1, S2, S3, and S8 was determined to be 0, 10.2, 20.4, 30.6, and $81.6 \text{ kg}/\text{m}^3$, respectively.

2.3. Concrete Preparation for Compressive Strength and Pull-Out Test. A total of 6 specimens for pull-out test were made as shown in Figure 3. The rebar was embedded centrally in the $150 \text{ mm} \times 150 \text{ mm} \times 150 \text{ mm}$ concrete cube. The standard 28-day strength of the concrete is 50 MPa. The embedment length of the rebar in the concrete block is 3 times of rebar diameter (48 mm). The rebar was sheathed with PVC pipes for debonding on both ends of the concrete block at a length of 34 mm and 68 mm, respectively. A shorter bond length 3 times rebar diameter instead of typically used 5 times rebar diameter [53] was adopted in order to obtain a complete stress-slip curve and prevent splitting.

Three 150 mm concrete cubes were set for the compressive strength test. The concrete mixing is followed in a sequence. First of all, cement, coarse and fine aggregate, and dry SAP were put together and mixed for 30 s; then half of the water and the water reducing agent were added and mixed for another 2 min; after that, the remaining half of the water and the water reducing agent were poured and mixed for additional 2 min. Once the mixing was completed, the mixture was immediately poured into molds. The specimens have been cured for 28 days to achieve desirable strength.

2.4. Experimental Process. A hydraulic universal testing machine was used for the test, and an LVDT sensor was set on the specimen to measure the relative slip of steel bar and concrete, as shown in Figure 4(a). The test was controlled by displacement, and the loading rate was $0.3 \text{ mm}/\text{min}$. The test ended when the steel bar was pulled out or broken, the concrete specimen was damaged or reaches the specified displacement. Dynamic data collection was used to record the load value and the reading of the LVDT. The failure mode of all tests is deemed to be split failure from the visual inspection shown in Figure 4(b).

3. Experiment Results

3.1. Effect of SAP on Compressive Strength of HSC. The compressive strength of HSC with different content of SAP is shown in Figure 5. It indicates that a small amount of SAP can increase the compressive strength of HSC, but when the content exceeded the peak value, the compressive strength was reduced. When the SAP content was 0.1% of cement mass, the compressive strength of concrete increases by 4.55%; when the SAP content was 0.2%, 0.3%, and 0.8% of cement mass, the compressive strength of concrete decreased by 9.84%, 20.91%, and 33.33%, respectively. The amount of SAP needed to achieve maximum compressive strength is a trade-off analysis. SAP reduces the shrinkage in concrete and improves cement hydration which helps increase the compressive strength. Meanwhile, the addition of SAP increases water diversion and porosity and therefore results in decreased compressive strength. This experiment showed that the peak of compressive strength had been achieved with 0.1% SAP addition.

The following equation was created to best fit the data points in Figure 5 with the goodness of fit $R^2 = 0.99$:

$$f_{cu} = f_{c,28d} \cdot \frac{63.89x^2 - 7.01x + 3.07}{100x^2 - 11.93x + 3.07}, \quad (2)$$

where f_{cu} is the compressive strength of SAP concrete, MPa; $f_{c,28d}$ is the 28-day compressive strength of ordinary concrete, MPa; x is the SAP content, %.

The calculated and measured compressive strength of SAP concrete are listed in Table 3. It shows that the differences between the calculated and measured values are minimal so that equation (2) can be adopted to represent the SAP content-compressive relationship.

TABLE 1: Chemical composition of cement.

Chemical composition	Content (%)
SiO ₂	19.9
Al ₂ O ₃	4.6
Fe ₂ O ₃	3.0
CaO	64.6
SO ₃	2.37
Na ₂ O	0.06
K ₂ O	0.65
MgO	0.78
Cl ⁻	0.01

(a)

(b)

FIGURE 1: Superabsorbent polymer (SAP): collapsed (a); swollen (b).

FIGURE 2: Rebars used in the experiments.

TABLE 2: Mixture proportions of concrete.

Serial number	S0	S1	S2	S3	S8
W/C	0.334	0.334	0.334	0.334	0.334
Cement (kg/m ³)	510	510	510	510	510
Water (kg/m ³)	170	170	170	170	170
Internal curing water (kg/m ³)	0	10.2	20.4	30.6	81.6
Coarse aggregate (kg/m ³)	1131	1131	1131	1131	1131
Fine aggregate (kg/m ³)	636	636	636	636	636
Water reducing agent (kg/m ³)	2.6	2.6	2.6	2.6	2.6
SAP (kg/m ³)	0	0.51	1.02	1.53	4.08

"S" in the serial number stands for SAP content.

3.2. Effect of SAP on Bond Strength of HSC. The equation for calculating the bond strength is simply to use the pull-out force divided by the contact area around the rebar as shown in the following equation:

$$\tau_u = \frac{P_u}{\pi d l_d}, \quad (3)$$

where τ_u is the bond strength, MPa; P_u is the pull-out force, N; d is the diameter of the steel bar, mm; and l_d is the bond length, mm.

The bond strength for HSC with different SAP content is tested and shown in Table 4. It can be seen from the table that a small amount of SAP could increase the bond strength of HSC, but if adding more than 0.1% of SAP, the bond strength was reduced. When the SAP content was 0.1% of the cement mass, the bond strength of concrete increased by 8.92%; when the SAP content was 0.2%, 0.3%, and 0.8% of the cement mass, the bond strength of concrete decreased by 5.98%, 14.55%, and 25.24%, respectively.

The experimental results show that the bond strength variations with SAP content in HSC is similar to that of compressive strength. It is worth noting that the addition of SAP made the bond strength of concrete increase more than compressive strength (Figure 6). For example, adding 0.1% of SAP caused 4.55% increase in compressive strength and 8.92% in bond strength. Similarly, adding 0.2%, 0.3%, and 0.8% SAP caused 9.84%, 20.91%, and 33.33% drawdown in

FIGURE 3: Pull-out test specimen (all units in millimeters, d is the rebar diameter).

FIGURE 4: Pull-out test device. (a) Test instrument. (b) Split at failure.

compressive strength and 5.98%, 14.55%, and 25.24% decrease in bond strength. The correlation between bond strength and compressive strength is discussed in Section 3.3.

3.3. Relationship between Compressive Strength and Bond Strength of Concrete Mixed with SAP. There have been a number of studies carried out on the relationship between bond strength and compressive strength of concrete and rebar. In these studies, bond strength is expressed in terms of the exponent of compressive strength [29, 33–35, 39–42]:

$$\tau_b = a(f'_c)^b, \quad (4)$$

where τ_b is the bond strength in MPa, f'_c is the cylinder compressive strength in MPa, and a and b are the constants.

The authors of the literature [29, 33] studied the relationship between cylinder compressive strength and bond

strength accounting for factors such as the minimum thickness of protective layer, diameter of steel bars, and bond length of steel bars. The empirical equation and value for parameters a and b were given:

$$a = A + B \frac{c_{\min}}{d_b} + C \frac{d_b}{l_d}, \quad (5a)$$

$$b = 0.5, \quad (5b)$$

where $c_{\min}$ is the minimum thickness of protective layer, mm; d_b is the diameter of steel bars, mm; l_d is the bond length, mm; and A , B , and C are the constants.

The research results of literature [29, 33] are shown in Table 5.

In literature [34, 35, 39], the relationship between cylinder compressive strength and bond strength under the influence of minimum thickness of protective layer,

FIGURE 5: Relationship between SAP content and compressive strength.

TABLE 3: Theoretical and experimental results of compressive strength of SAP concrete.

SAP dosage (%)	Test compressive strength (MPa)	Theoretical compressive strength (MPa)	Error
0	49.27	49.27	0
0.1	51.51	51.51	0
0.2	44.42	44.43	0.02
0.3	38.97	38.98	0.03
0.8	32.85	32.85	0

TABLE 4: Bonding strength of specimens.

SAP dosage (%)	Bond strength (MPa)	Slip corresponding to bond strength (mm)
0	36.76	0.833
0.1	40.04	0.836
0.2	34.56	0.986
0.3	31.41	1.005
0.8	27.48	1.126

maximum thickness of protective layer, diameter of steel bars, bond length of steel bars, and area of steel bars was studied; a different function and value for a and b were derived and shown in the following equations:

$$a = [Al_d(c_{\min} + 0.5d_b) + BA_b] \left(0.1 \frac{c_{\max}}{c_{\min}} + 0.9 \right) (\pi d_b l_d)^{-1}, \quad (6a)$$

$$b = 0.25, \quad (6b)$$

where l_d is the bond length, mm; $c_{\min}$ is the minimum thickness of protective layer, mm; d_b is the diameter of steel bars, mm; A_b is the area of steel bars; $c_{\max}$ is the maximum thickness of protective layer, mm; and A and B are the constants.

The research results of literature [34, 35, 39] are shown in Table 6.

In literature [39], experimental studies were conducted on concrete specimens with strength up to 90 MPa, and the expressions of a and b values were obtained as shown below:

$$a = 4.1, \quad (7a)$$

$$b = 0.5, \quad (7b)$$

In literature [41], bond strength of high-strength concrete was studied, and the expressions of a and b values obtained are shown in the following equation:

$$a = 1.65, \quad (8a)$$

$$b = 0.7. \quad (8b)$$

FIGURE 6: Comparison of bond strength and compressive strength of concrete mixed with SAP.

TABLE 5: Values of A, B, and C in different tests.

Serial number	A	B	C
Orangun [33]	0.10	0.25	4.15
Chapman [29]	0.29	0.282	4.734

TABLE 6: Values of A and B in different tests.

Serial number	A	B
Darwin [34]	1.5	51
Zuo [39]	1.43	56.2
ACI [35]	1.43	57.4

According to literature [44], the ratio of compressive strength of the 150 mm cube to that of the standard cylinder is 0.8, so the cylinder compressive strength f'_c of the concrete with 0, 0.1%, 0.2%, 0.3%, and 0.8% SAP content in this test is 39.42, 41.21, 35.54, 31.18, and 26.28 MPa, respectively.

The relationship between the cylinder compressive strength and bond strength obtained from the above calculation results and this test is shown in Figure 7.

As seen in Figure 7, the models from the listed literatures are not consistent with testing data for concrete mixed with SAP. Equation (4) was used to best fit the data, and the values for a and b were obtained ($a=2.03$, $b=0.8$) with $R^2=0.97$. Hence, the bond strength and the cylinder compressive strength relationship of SAP concrete can be expressed as

$$\tau_b = 2.03 (f'_c)^{0.8}, \quad (9)$$

where τ_b is the bond strength, MPa; f'_c is the cylinder compressive strength, MPa.

The calculated and measured bond strengths for concrete specimens with various SAP content are shown in

Table 7. Since the difference between the two is within 5%, equation (9) is suitable for bond strength evaluation.

Substituting equation (2) into equation (9), the bond strength can be written as

$$\tau_b = 2.03 \cdot \left[0.8 \cdot f_{c,28d} \cdot \frac{63.89x^2 - 7.01x + 3.07}{100x^2 - 11.93x + 3.07} \right]^{0.8}, \quad (10)$$

where τ_b is the bond strength, MPa; $f_{c,28d}$ is the 28-day compressive strength of ordinary concrete (MPa); and x is the SAP content, %. The factor of 0.8 in the bracket is to convert cylinder strength to cube strength.

3.4. Slip and Compressive Strength Relationship. Shen et al. [42] proposed a nonlinear relationship between slip at ultimate bond stress and compressive strength based on their test data. Similar trend was observed in the experiment with SAP concrete. Hence, the nonlinear model in literature [42] is adopted in this study as shown below:

$$s_0 = \frac{m}{f'_c + n}, \quad (11)$$

where s_0 is the slip at ultimate bond stress, mm; f'_c is the cylinder compressive strength, MPa; m and n are the constants.

The slip at ultimate bond stress of concrete mixed with SAP in this test is shown in Figure 8. The factors of m and n in equation (11) were found to be $m=48.74$ and $n=16.79$ through data fitting with goodness of fit $R^2=0.93$. Then the relationship between the slip at ultimate bond stress s_0 and cylinder compressive strength f'_c can be written as

$$s_0 = \frac{48.74}{f'_c + 16.79}. \quad (12)$$

FIGURE 7: Relationship between bond strength and cylinder compressive strength of different models.

TABLE 7: Theoretical and experimental results of bond strength of SAP concrete.

SAP content (%)	Test bond strength (MPa)	Theoretical bond strength (MPa)	Error
0	36.76	38.37	4.38
0.1	40.04	39.76	0.70
0.2	34.56	35.33	2.23
0.3	31.41	31.82	1.31
0.8	27.48	27.75	0.98

Then the tested and theoretical slip from equation (12) at ultimate bond stress for HSC with various SAP contents are listed and compared in Table 8.

3.5. The Prediction Model of Stress-Slip Relationship between Steel Bars and HSC Mixed with SAP. Various stress-slip models have been developed in the past two decades [41–51] showing that there is a clear relationship between bond stress and slip. In this study, the BPE model [51] was used:

$$\tau = \tau_{\max} \left(\frac{s}{s_0} \right)^\alpha \quad (13a)$$

It can also be expressed as

$$\frac{\tau}{\tau_{\max}} = \left(\frac{s}{s_0} \right)^\alpha, \quad (13b)$$

where τ is the bond stress value, MPa; s is the slip corresponding to bond stress, mm; $\tau_{\max}$ is the ultimate bond strength, MPa; s_0 is the slip at ultimate bond strength, mm; and α is a constant.

Performing best fitting analysis, α values for SAP content of 0, 0.1%, 0.2%, 0.3%, and 0.8% were found to be 0.2477, 0.1367, 0.19, 0.2101, and 0.1615, respectively, as shown in

Figure 9. Then the mean of the five numbers 0.1892 was taken for the finalized stress-slip relationship of SAP concrete as shown in the following equation:

$$\tau = \tau_{\max} \left(\frac{s}{s_0} \right)^{0.1892} \quad (14)$$

Combined with equation (2), equation (9), equation (10), and equation (13), bonding performance of UPC with SAP can be expressed as follows:

$$f_{cu} = f_{c,28d} \cdot \frac{63.89x^2 - 7.01x + 3.07}{100x^2 - 11.93x + 3.07}, \quad (15a)$$

$$f'_c = 0.8f_{cu}, \quad (15b)$$

$$\tau_{\max} = 2.03(f'_c)^{0.8}, \quad (15c)$$

$$s_0 = \frac{48.74}{f'_c + 16.79}, \quad (15d)$$

$$\tau = \tau_{\max} \left(\frac{s}{s_0} \right)^{0.1892}, \quad (15e)$$

FIGURE 8: Relationship between slip at ultimate bond stress and cylinder compressive strength.

TABLE 8: Theoretical and experimental results of slip at ultimate bond stress for HSC with various SAP contents.

SAP dosage (%)	Tested slip at ultimate bond stress (mm)	Theoretical slip at ultimate bond stress (mm) by equation (12)	Error (%)
0	0.833	0.867	4.08
0.1	0.836	0.840	0.48
0.2	0.986	0.931	5.58
0.3	1.005	1.016	1.09
0.8	1.126	1.132	0.53

(a)

FIGURE 9: Continued.

(b)

(c)

FIGURE 9: Continued.

FIGURE 9: Relationship between stress ratio and slip ratio of different SAP contents. (a) 0; (b) 0.1%; (c) 0.2%; (d) 0.3%; (e) 0.8%.

where f_{cu} is the compressive strength of SAP concrete, MPa; $f_{c,28d}$ is the 28-day compressive strength of ordinary concrete, MPa; x is the SAP content, %; f'_c is the cylinder compressive strength, MPa; $\tau_{\max}$ is the bond strength, MPa; s_0 is the slip at ultimate bond strength, mm; τ is the bond

stress value, MPa; and s is the slip corresponding to bond stress, mm.

The comparison between the theoretical value calculated according to formula (14) and the actual value in the test is shown in Figure 10.

FIGURE 10: Theoretical and practical comparison of bond behavior of concrete mixed with SAP.

4. Conclusions

In this paper, through relevant tests and theoretical derivation, the bond behavior of concrete mixed with SAP was systematically studied, and the following conclusions were obtained:

- (1) The compressive strength of HSC mixed with SAP first increases and then decreases with the increase of SAP content. The compressive strength of concrete with SAP content of 0, 0.1%, 0.2%, 0.3%, and 0.8% is 49.27, 51.51, 44.42, 38.97, and 32.85 MPa, respectively.
- (2) With the increase of SAP content, the bond strength of HSC with SAP content first increases and then decreases. The bond strength of concrete with SAP content of 0, 0.1%, 0.2%, 0.3%, and 0.8% are, respectively, 36.76, 40.04, 34.56, 31.41, and 27.48 MPa.
- (3) The bond strength of HSC mixed with SAP increases with the increase of its compressive strength, and a prediction model of the bond strength of SAP concrete is established.
- (4) The slip corresponding to bond strength of HSC mixed with SAP decreases with the increase of compressive strength, and the prediction model of slip corresponding to bond strength of concrete mixed with SAP is established.
- (5) A prediction model of stress-slip relationship between steel bars and HSC mixed with SAP was established, which was in good agreement with the

experimental data and could be used to estimate the stress-slip relationship of HSC mixed with different SAP content.

5. Future Work

In this paper, compression and bond strength for HSC with various SAP content were determined from pull-out tests. The results presented can be utilized for determining the amount of SAP addition in engineering applications. Also, the slip-stress relationship developed in this study can be incorporated into the finite element analysis for structures. In addition, the slip-stress curve was developed for 50 MPa compression strength HSC. The reason of not being able to obtain the descending portion after the ultimate bonding stress can be attributed to the high bond strength between HSC and the rebar. In the future, the bond strength for normal strength concrete should be compared with this study.

Data Availability

The research data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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