

Article

Experimental Research on Interfacial Bonding Strength between Vertical Cast-In-Situ Joint and Precast Concrete Walls

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Abstract: In the monolithic precast concrete shear-wall structure, the bonding property of cast-in-situ joints to precast concrete walls is important to ensure the entire structural performance. Aiming to the vertical joint of precast concrete walls, an experimental study was carried out considering the factors including the strength of precast and joint concretes, as well as the interface processing and casting age of precast concrete. The micro-expansion self-compacting concrete was used for the cast-in-situ joints. The interfacial bonding strength between joint and precast concrete was measured by splitting tensile test. Results show that the interfacial bonding strength was benefited from the increasing strength of joint concrete and the spraying binder paste on the interface of precast concrete, and unbenefited from the overtime storage of precast concrete. The washed rough surface with exposed aggregates improved the interfacial bonding strength, which increased with the increasing roughness. Based on the test results, the limits of the strength grade of joint concrete and the roughness of washed rough surface are proposed to get the interfacial bonding strength equivalent to the tensile strength of precast concrete. Meanwhile, the spraying of binder paste on precast concrete is a good choice, the storage time of precast components is a better limit within 28 days.

Keywords: precast concrete wall; interfacial bonding strength; joint concrete; interface processing; washed rough surface; roughness; storage time



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1. Introduction

In recent years in China, the assembling of buildings with precast concrete structure has become an advanced construction technology with features of green, environmental protection and energy conservation for the building industry [1,2]. This produces an importance to the construction process of the cast-in-situ joint which relates to the entire performance and quality of monolithic precast concrete structure. In view of the monolithic precast shear-wall structures, great concerns have been made on how to safely anchorage of rebars in precast shear-walls. Methods for rebar splicing by grout-filled coupling sleeve, slurry anchor lap joints, closed-loop anchoring and their composites have been applied [3–6]. However, acting as the linking of the precast concrete walls together to subject the loads and seismic actions, the bonding performance of cast-in-situ concrete joints to precast concrete walls have not been studied sufficiently. This may affect the deformation and energy dissipation capacity of the structure. In practice, cracks along interfaces appear due to the weak bonding of cast-in-situ concrete to precast concrete. This forms a weak section of monolithic precast concrete structure. Meanwhile, the map cracking presents due to large drying shrinkage of the cast-in-situ concrete, and the cast quality problems of spongy surface and internal voids exist due to difficult compaction in narrow joint space.

To achieve the design criteria of equivalent cast-in-place for precast concrete shear-wall structures, the joint connection between precast concrete walls has been specified in China code JGJ 1 [3]. The strength grade of precast concrete should not be less than C30, and that of cast-in-situ concrete is better, one grade higher than precast concrete. Meanwhile, the interface of the precast concrete wall should be roughened or treated with groove keys. If a rough surface washed by pressure water is used, the rough area of the interface should be larger than 80%, and the roughness should not be less than 6 mm. However, by looking up the published literature, only a few studies were performed on the interface between cast-in-situ joint and precast concrete component [6–9].

Coming from the same bonding mechanism of concrete to concrete, studies on the bond of new to old concrete for the strengthening of existing concrete structures can be referenced to find the main influencing factors [10–13]. Firstly, the factors relate to the quality of the concrete interface. The interfacial bonding strength increases with the increasing strength of concrete, especially new concrete [10,14–16], and benefits from the spraying of cement paste on the original surface of precast concrete [10–13,17]. Secondly, the factors relate to the condition of the concrete interface. The roughening of old concrete surface is necessary to further improve the bonding strength of new to old concrete [18–20]. During the research process, several kinds of roughening methods have been applied, including indentation with steel bars, scraping with iron combs of different-shaped saw-teeth, artificial chipping, mechanical napping, sand blasting, washing to expose aggregates with pressure water, groove keys and rough formwork. This makes the interface zigzag with concrete protuberances or turns into a zone with certain thickness composited by the cohesive layer of binder paste and the permeable layer of interaction [13,17,21]. The bonding strength increases with the increase in the roughness of the old concrete. Comparatively, the best effect can be obtained with an exposed aggregate surface and mechanical napping surface [7–9,22–24]. Meanwhile, the interfacial bonding strength is also affected by the degradation of surface condition depended on the environmental actions such as carbonation, freezing and thawing, and chemical erosion. Even in a short time after casting (within 90 days), the bonding strength of new to old concretes decreases whatever the surface of old concrete is processed with different methods [24–26].

Therefore, the three kinds of factors mentioned above should be considered for the experimental study on interfacial bonding strength of cast-in-situ concrete to precast concrete. Differing from the artificial post-roughening of existing concrete surface for strengthening purpose, the interface roughening of precast concrete components should be industrialized in the precast factory. Therefore, the joint surface of precast concrete is always roughened by using the methods of mechanical napping, rough formwork, key groove or washing to expose aggregates by pressure water [7,8]. Meanwhile, a storage time after casting of precast concrete components is always created due to the out-of-sync of production and installation.

To make up for the lack of systematical evaluation of the bonding rationale for cast-in-situ joint to precast concrete walls, an experimental study was carried out in this paper. The precast concrete specimens were prepared in strength grade of C30 and C40, the micro-expansion self-compacting concrete was used for cast-in-situ joints in strength grade of C30, C35, C40 and C45. Three kinds of interfaces of precast concrete were made: the original, the closing net formed and the washed rough to expose aggregates. The interface of washed rough to expose aggregates was made with four levels of roughness. The storage time of precast concrete after demolding was considered at 14, 28, 56 and 90 days. The interfacial bonding strength of joint to precast concretes was experimentally studied for 32 groups of specimens by using the splitting tensile test. Results are analyzed, and the measures to satisfy the interfacial bonding strength equivalent to tensile strength of precast concrete are suggested.

2. Experimental Work

2.1. Preparation of Concretes

The cement (PC) was ordinary silicate cement of grade 42.5 produced by Henan Xinxiang Mengdian Cement Co. Ltd., Xinxiang, China. As presented in Table 1, the properties of cement met the specification of China code GB 175 [27]. Class-II fly ash (FA) and ground limestone (GL) were used as mineral admixtures to improve the workability of fresh concrete, the properties presented in Table 2 met the specification of China codes GB/T 1596 and JGJ/T 318 [28,29]. The HEM-V expansive agent (EA) produced by Jiangsu Subote New Materials Co. Ltd., Nanjing, China, was used for cast-in-situ joint concrete, the properties are presented in Table 3. The chemical compositions of cement, fly ash, ground limestone and expansive agent are presented in Table 4. LOI is the loss on ignition.

Table 1. Physical and mechanical properties of cement.

Density (g/cm ³)	Water for Standard Consistency (%)	Specific Surface Area (m ² /kg)	Setting Time (min)		Compressive Strength (MPa)		Flexural Strength (MPa)	
			Initial	Final	3d	28d	3d	28d
3.09	27	360	170	215	27.8	58.4	5.2	8.3

Table 2. Physical properties of fly ash and ground limestone.

Material	Apparent Density (kg/m ³)	Specific Surface Area (m ² /kg)	Activity Index (%)	Water Demand Ratio (%)	Mobility Ratio (%)	Fineness: Residual on Sieve (%)	
						80 µm	45 µm
FA	2350	406	73.3	84	-	5.48	21.75
GL	2780	428	61.6	-	103	1.2	25

Table 3. Physical and mechanical properties of the expansion agent (HEM-V).

Fineness		Water of Standard Consistency (%)	Setting Time (min)		Restrained Expansion Rate (%)		Compressive Strength (MPa)	
Specific Surface Area (m ² /kg)	Residual on 1.18 mm Sieve (%)		Initial	Final	In Water 7d	In Air 21d	7d	28d
375	0.155	30	260	351	0.042	0.075	29.5	44.6

Table 4. Chemical compositions of cementitious materials (unit: %).

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	f-Cao	Na ₂ O	K ₂ O	LOI	Others
PC	20.81	5.99	3.28	60.12	2.13	2.23	0.67	0.11	0.55	3.52	0.59
FA	55.92	17.31	5.91	6.95	3.82	1.93	0.26	0.48	1.96	2.63	2.83
GL	0.89	0.51	0.29	47.56	4.45	0.06	0.02	0.67	0.27	40.71	4.57
EA	3.48	9.27	1.44	42.78	0.48	27.38	6.65	0.62	0.47	5.51	1.92

The crushed limestones in continuous grading with particle size of 5–20 mm and 5–16 mm were used for precast concrete and cast-in-situ joint concrete, respectively. The fine aggregate was manufactured sand with fineness modulus of 2.85, stone powder of 8.8% and Methylene Blue value of 1.3. The properties are presented in Table 5.

Table 5. Physical properties of crushed limestone and manufactured sand.

Particle Size (mm)	Apparent Density (kg/m ³)	Bulk Density (kg/m ³)	Closed-Compact Density (kg/m ³)	Moisture Content (%)	Water Absorption (%)	Porosity (%)
5~20	2730	1548	1613	0.30	1.17	42
5~16	2760	1554	1678	0.23	1.05	41
Sand	2689	1583	1726	0.6	2.0	

The water reducer was PCA-I high-performance polycarboxylic acid type with a water reduction of 30%, which was produced by Jiangsu Subote New Materials Co. Ltd., Nanjing, China. The mix water was tap water of Zhengzhou city.

The mix proportions of concrete were designed by the absolute volume method [30,31], and results are presented in Table 6. The conventional concrete was used for precast concrete with two strength grades. The slump of fresh mixture was kept at 80–100 mm. Due to operating in a limited narrow space for the cast-in-situ concrete of joints with disturbing of reinforcements, the self-compacting concrete was used to ensure the compactness without vibration. Four strength grades of self-compacting concrete were prepared with the slump extension of fresh mixture kept at 650–750 mm [32,33]. Based on previous study, the EA content was 10% of total weight of cementitious materials [34,35].

Table 6. Mix proportions of concrete for precast components and cast-in-situ joints.

Concrete	Water to Binder Ratio	Dosage of Raw Materials (kg/m ³)							
		Water	Cement	FA	GL	Crushed Limestone	Sand	Water Reducer	EA
Precast components	0.47	175	335	37	-	1086	786	3.7	-
	0.57	185	292	32	-	1060	831	3.2	-
Cast-in-situ joints	0.37	190	308	51	103	885	816	5.6	51.4
	0.34	185	326	54	109	873	806	5.4	54.4
	0.31	185	358	60	119	851	786	7.2	59.7
	0.28	185	396	66	132	816	754	7.3	66.1

2.2. Mechanical Properties of Concretes

The mechanical properties of conventional concrete and self-compacting concrete were measured by using the test methods specified in China code GB/T50081 [36]. Six cubes with a dimension of 150 mm, with three of them as a group, were used for each concrete to measure the cubic compressive strength and the splitting tensile strength. Six cylinders, with a diameter of 150 mm and height of 300 mm, with three of them as a group, were used for each concrete to measure the axial compressive strength and the modulus of elasticity. Tests were carried out for concretes at a curing age of 28 days. The loading speed was controlled at 0.5 MPa/s for testing of cubic and axial compressive strengths, while that was 0.05 MPa/s for testing of splitting tensile strength.

Test results are presented in Table 7. The test values met the requirement of a corresponded strength grade, and tended the common regularity increasing with the decrease in the water to binder ratio [30,31].

Table 7. Mechanical properties of precast concrete and cast-in-situ concrete.

Concrete	Water to Binder Ratio	Strength Grade	Cubic Compressive Strength (MPa)	Axial Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Modulus of Elasticity (GPa)
Precast	0.57	C30	33.1	28.7	2.38	30.5
	0.47	C40	48.4	35.5	3.18	31.7
	0.37	C30	37.5	28.7	2.08	28.9
Cast-in-situ	0.34	C35	43.6	30.1	2.77	30.5
	0.31	C40	47.0	32.4	2.94	31.3
	0.28	C45	54.7	35.7	3.71	33.3

2.3. Formation of Interface

Three kinds of interface of precast concrete were made in this study. The first was the original surface. As exhibited in Figure 1a, the original surface was flat with some small pores after demolding.

The second was the washed rough surface with exposed aggregates by pressure water washing, as exhibited in Figure 1b. An agent was brushed on the interface formwork. After demolding, the interface of concrete was washed by pressure water to expose aggregates.

The agent produced by Henan Meilitong New Materials Co. Ltd., Zhengzhou, China, was a water-soluble homogeneous viscous substance composited by non-toxic organic matter; the density was 1.10 g/cm^3 .

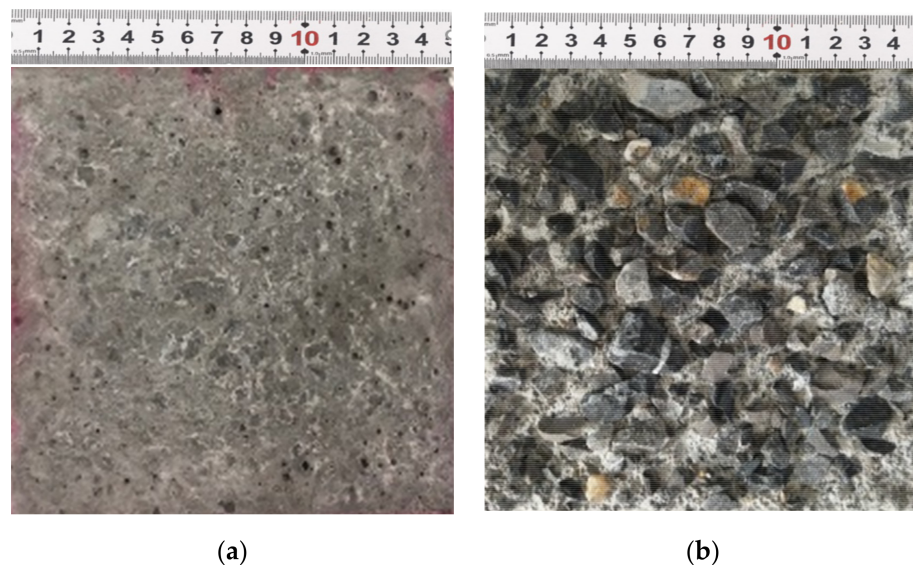


Figure 1. Two kinds of interface in sectional dimension of $150 \text{ mm} \times 150 \text{ mm}$: (a) original surface; (b) washed rough surface.

The third was a rough surface formed with a fast-ribbed closing net, which was used as an interface formwork of precast concrete. As presented in Figure 2, the fast-ribbed closing net is a sheet steel plate rolled from thin galvanized steel with depth of 0.2 mm and swelling of 5 mm , which could be cut into the size used. The rough surface was formed with concrete protuberances after demolding of the fast ribbed closing net.

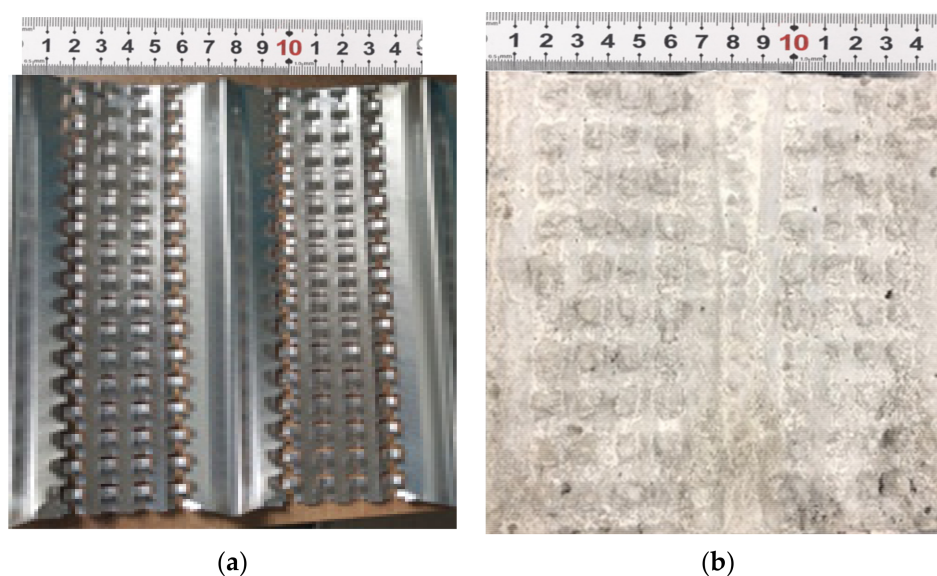


Figure 2. The third interface: (a) fast-ribbed closing net cut to be $150 \text{ mm} \times 150 \text{ mm}$ when used for interface; (b) rough surface in sectional dimension of $150 \text{ mm} \times 150 \text{ mm}$.

The surface roughness of precast concrete was determined by using a sand patch test [13,23,37]. As presented in Figure 3, the precast specimen with dry surface was placed in a salver, and enveloped with transparent plastic sheets. The top surface of plastic sheets was taken at the highest point of protuberances. The sand weighted as m_1 was filled on

the rough surface and finished flat by a ruler along the surface of the plastic sheet. The residual sand scraped into the salver was weighted as m_2 , where the mass of patched sand is $M = m_1 - m_2$. The roughness expressed by the average sand depth can be computed as,

$$\bar{y} = \frac{M}{\rho A} \quad (1)$$

where, $\bar{y}$ is the average sand depth, mm; M is the mass of patched sand, g; ρ is the density of sand, g/cm³; A is the sectional area of rough surface, mm².

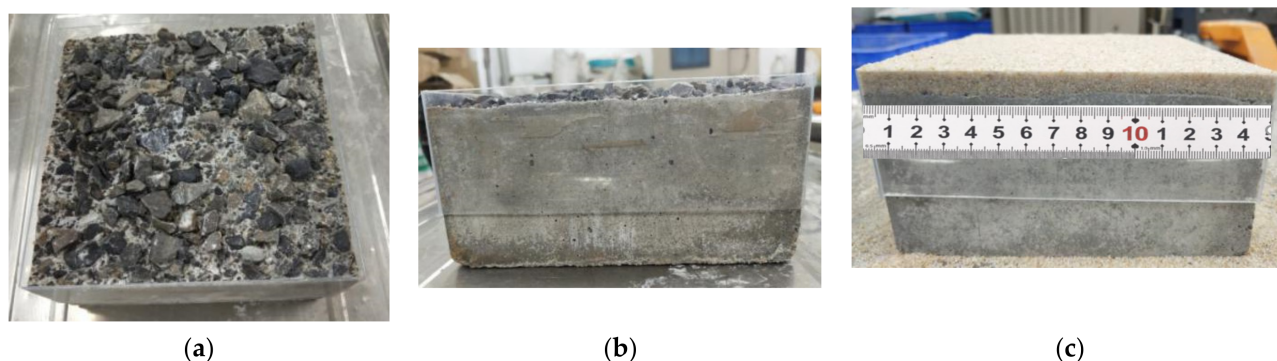


Figure 3. Roughness measuring of surface in sectional dimension of 150 mm × 150 mm: (a) specimen preparation; (b) fit to plastic board; (c) sand replacement.

2.4. Preparation of Bond Specimens and Test Method

Based on previous studies, splitting tensile test is always applied for the bonding performance of new to old concrete [12–14,22–26,38]. In this study, the splitting tensile test was in accordance with the specification of China code GB/T50081 [36]. The composite cubic specimens with a single interface between precast concrete and cast-in-situ concrete was made in a dimension of 150 mm. Along sides of the interface was precast concrete and cast-in-situ concrete, respectively. The interface was 150 mm × 150 mm. Three specimens were made as a group.

The precast concrete in dimension of 75 mm × 150 mm × 150 mm was first cast and cured in standard curing room at a temperature of (20 ± 2) °C and relative humidity of 65% for the required curing age. The interface of precast concrete was pretreated according to the requirement. Except the six groups of precast concrete used for the research of the effect of casting age at 14, 56 and 90 days, others were cured for 28 days. As presented in Figure 4, the precast concrete was first placed into the cube mold, then the cast-in-situ concrete was poured into the mold, covered by plastic after finishing smooth of surface, and cured in a standard curing room for 28 days. Before testing, the load surface needed to be polished for the uniform loading.

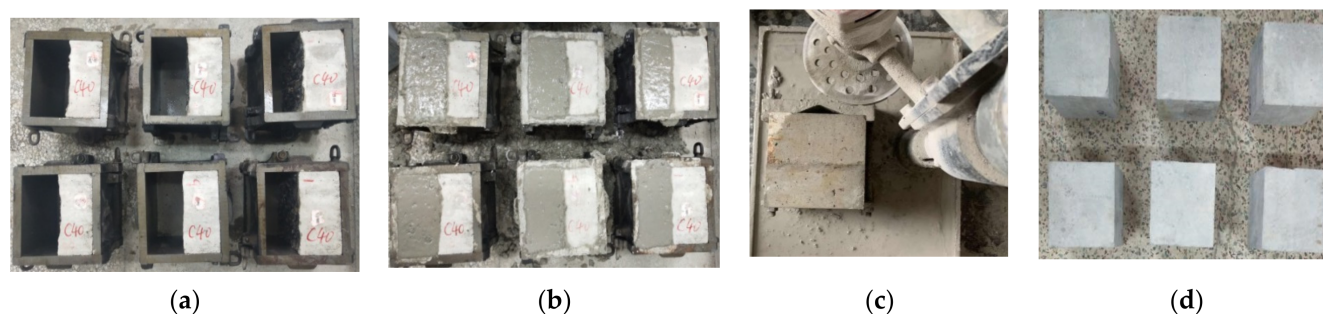


Figure 4. Main process of specimen formation: (a) precast concrete placed into module; (b) cast-in-situ concrete poured into mold; (c) polishing load surface; (d) prepared specimens in dimension of 150 mm.

As shown in Figure 5, the load was directly exerted along the interface section with steel strips at bottom and top surfaces on the universal testing machine produced by SNS Testing Machine Co. Ltd., Shanghai, China. The capacity of the testing machine is 600 kN, and the loading speed was 0.05 MPa/s. The interfacial bonding strength is computed as [36],

$$f_b = 0.637 \frac{P}{A} \quad (2)$$

where, f_b is the interfacial bonding strength, MPa; P is the peak load at failure, N; A is the area of splitting section, mm².

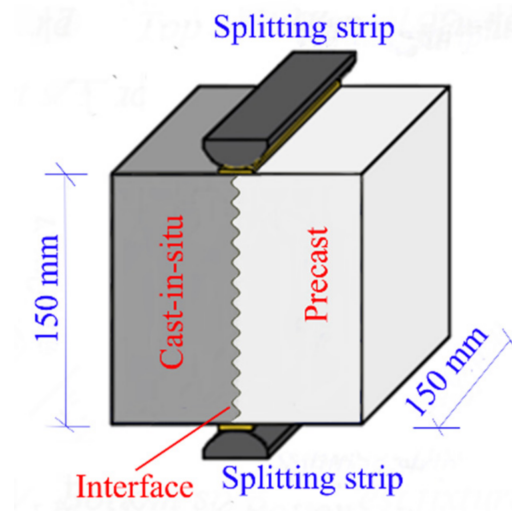


Figure 5. Loading diagram for bond strength of interface in sectional dimension of 150 mm × 150 mm.

According to the specification of China code GB/T50081 [36], test data of bonding strength for three specimens are dealt with the following criteria: (1) The arithmetic mean value of three test data is taken as the group strength; (2) If the difference between one of the maximum or minimum values and the median value exceeds 15% of the median value, the maximum and minimum values are discarded together, and the median value is taken as the group strength; (3) If the difference between the maximum and minimum values and the median value is over 15% of the median value, the test results of this group are invalid.

To evaluate the bond efficiency of interface, the interfacial bonding strength divided by the tensile strength of precast concrete was defined as the equivalent coefficient of bonding strength, that is,

$$\beta_e = \frac{f_b}{f_{t,p}} \quad (3)$$

where, β_e is the equivalent coefficient of bonding strength; $f_{t,p}$ is the tensile strength of precast concrete, MPa.

3. Analyses of Test Results

3.1. Effect of Cast-In-Situ Concrete Strength

The strength matching of cast-in-situ concrete to precast concrete was explored. The precast concrete was fixed at strength grade of C40, the cast-in-situ concrete was changed with strength grade of C30, C35, C40 and C45, the interface was the original surface of precast concrete with roughness of 1.55 mm.

All specimens broke at the interface section with smooth splitting, a peeling of precast concrete took place on the splitting section of some specimens with the original surface of precast concrete. The entrance of binder paste into the pores of precast concrete was observed on some splitting interface. As presented in Figure 6, the interfacial bonding strength increased with the increasing strength of cast-in-situ concrete. This is the macro-

scopic response of the meshing forces due to the interlaced crystals formed by the hydration of cast-in-situ concrete and precast concrete. As in previous studies [10–13,17], the hydration products $\text{Ca}(\text{OH})_2$, Aft and C-H-S of new concrete grow in the holes or defects of old concrete, the skin needling of C-H-S and thinner needle-like Aft enter into the pores of old concrete, and the unhydrated and incomplete hydration composites of old concrete continuously hydrate in the new concrete. Due to the domination of mix proportion of concrete to the hydration process, the microscopic effect is directly represented by the strength of concrete in macroscopic. With the increasing strength of cast-in-situ concrete, the binder paste was higher of strength with fewer pores adhered to the interface to improve the bonding behavior of cast-in-situ concrete with precast concrete. However, the equivalent coefficient of bonding strength β_e was only 0.32~0.45. In this condition, the bonding strength of the joint interface has a large gap to the tensile strength of precast concrete. This could not meet the requirement of equivalent monolithic concrete [3,5]. Therefore, other measures should be adopted to improve the bonding strength.

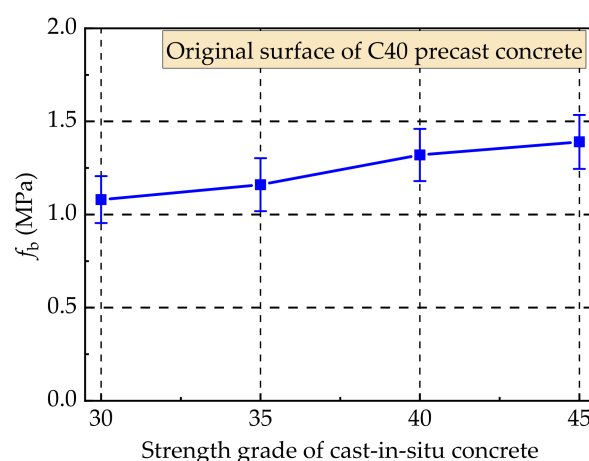


Figure 6. Bonding strength of interface changed with different strength of cast-in-situ concrete.

3.2. Effect of Interface of Precast Concrete

In this trial of testing, the effect of interfaces of the original, the closing net formed and the washed rough of precast concrete was examined. The roughness of the interfaces was 1.55 mm, 5.25 mm and 6.60 mm respectively. All specimens failed in splitting at the interface section. For specimens with closing net formed interface, some of the concrete protuberances were scraped to expose aggregates due to the binder paste peeled off. In this condition, except the meshing forces of interlaced crystals formed by the hydration of cast-in-situ concrete and precast concrete, the built-in effect of precast concrete protuberances to the cast-in-situ concrete takes part in the bond of interface [18–20]. This further promotes the interfacial bonding strength of cast-in-situ to precast concrete.

For specimens with washed rough interface, the interlocked coarse aggregates of cast-in-situ and precast concretes broke on the splitting section, the failure mode of interface was similar to the splitting of monolithic concrete. In this condition, the aggregates of cast-in-situ concrete interlocked with the aggregates exposed on the interface of precast concrete and bonded by the binder paste into entirety. The meshing force and the interlock force work together on the interface, which participates in the main function of enhancing the interfacial bonding strength [13,17,21,22].

With the above interfacial bonding mechanisms, the interfacial bonding strength increased in the order of the original interface, closing net formed interface and washed rough interface. As presented in Table 8, compared to the specimens with original interface, the bonding strength of specimens with closing net formed interface increased by 19.4% and 26.5%, respectively, accompanied by a strength grade of C30 and C40 for cast-in-

situ concrete, while that of specimens with washed rough interface increased by 87.0% and 125.8%.

Table 8. Bonding strength of interface with different surface of precast concrete.

Surface of Precast Concrete	Strength Grade of Concrete		f_b (MPa)	β_e
	Precast	Cast-In-Situ		
Original surface	C40	C30	1.08	0.34
		C40	1.32	0.41
Closing net formed surface	C40	C30	1.29	0.40
		C40	1.67	0.53
Washed rough surface	C40	C30	2.02	0.64
		C40	2.98	0.94

Meanwhile, a higher interfacial bonding strength was provided with the higher strength of cast-in-situ concrete, whatever the interfaces of precast concrete. With the strength grade of cast-in-situ concrete increased from C30 to C40, the increments of interfacial bonding strength are 22.2%, 29.4% and 47.5% respectively corresponded to the original, closing net formed and washed rough surfaces of precast concrete. This once again indicates the effect of cast-in-situ concrete strength on the interfacial bonding strength [10,14–16].

In this study, an equivalent coefficient β_e was 0.94 only for the specimens with washed rough surface of precast concrete and C40 cast-in-situ concrete. This means that the washed rough surface is optimum to enhance the interfacial bonding strength, other interfaces were difficult to have an equivalent tensile strength of precast concrete.

3.3. Effect of Interface Adhesion Agent

Accompanied by the trials of test for specimens in Section 3.2, a parallel trial of test was carried out on specimens with spraying adhesion agent on the surface of precast concrete. For the specimens of this trial, the adhesion agent was sprayed on the surface of precast concrete before cast-in-situ concrete was poured into mold. The adhesion agent was the cement paste with the same water to binder ratio of cast-in-situ concrete, the binder was composite of 60% cement, 20% GL, 10% FA and 10% EA. Test results of interfacial bond strength are comparatively presented in Figure 7.

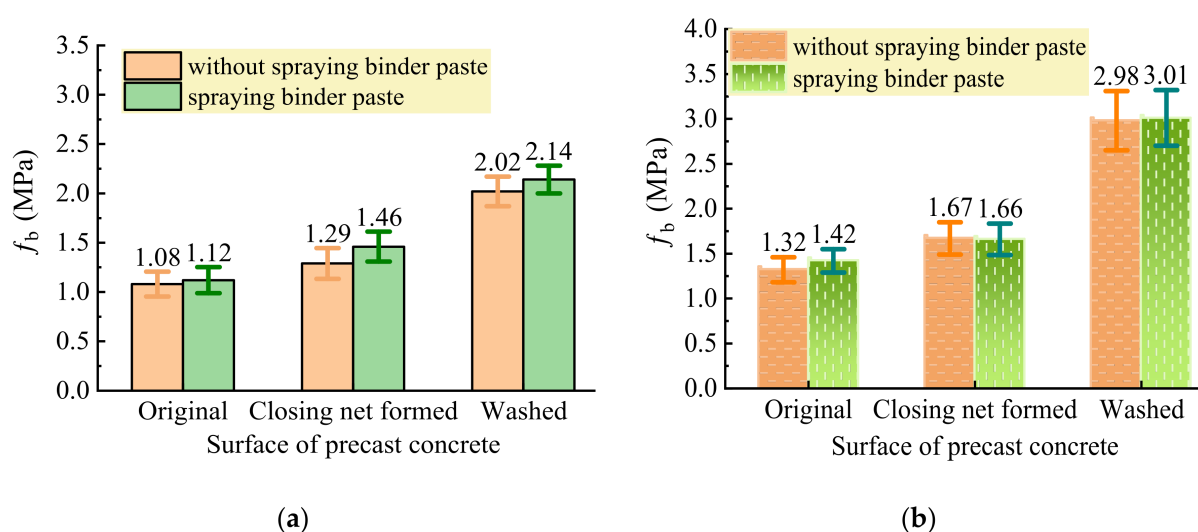


Figure 7. Comparison of bond strength of interface with or without adhesion agent: (a) C30 cast-in-situ concrete; (b) C40 cast-in-situ concrete.

Due to only three specimens as a group for each trial, the statistical result of test data has limitation to clarify the changes of bonding strength for interfaces with and without spraying adhesion agent. This leads the difference of bonding strength for specimens with and without spraying adhesion agent, which may be less than the error bar, which indicates the dispersion of test data of a group of specimens. However, due to almost equal error bars for specimens with and without spraying adhesion agent, the test results are comparable between these two kinds of specimens by using the statistical results. Compared with the specimens without spraying adhesion agent, the specimens sprayed adhesion agent had a higher bond strength, and the more beneficial effect appeared on the interface with C30 than C40 cast-in-situ concrete. With C30 cast-in-situ concrete, the interfacial bond strength with original, closing net formed and washed rough surfaces of precast concrete increased by 3.7%, 13.2% and 5.9%, while that with C40 cast-in-situ concrete increased by 7.6%, 0% and 1.0%. This indicates a favorable effect of the sprayed interface agent on the formation of interlaced crystals in hydration of cast-in-situ concrete with adequate humidity on the surface of precast concrete [17,21,23]. At the same time, spraying cement paste containing fly ash can improve the chemical force due to the rehydration of active SiO_2 of fly ash with Ca(OH)_2 of old concrete [10,17,39].

3.4. Effect of Roughness of Washing Exposed Aggregates

The formation of washed rough surface depends on the amount of agent that was brushed on the interface formwork, the curing age of precast concrete, the pressure of washing water and the washing time. Based on practice, the roughness measured by sand patch test is better to limit within 8 mm [6,7]. Therefore, a research was pointed on the roughness from 4 mm to 8 mm. The amount of water washing rough agent was 0.2~0.4 kg per square-meter of surface. The washing began at 24 h after demolding at a room temperature of 20 ± 5 °C. The working pressure of jetting machine was 8~10 MPa, the washing time was 12~15 min per square-meter of surface. Table 9 presents the test results of roughness of washed rough surface for precast concrete specimens. The roughness can be controlled by the washing technique. Four zones of roughness were divided into 4~5 mm, 5~6 mm, 6~7 mm and 7~8 mm. The photos are exhibited in Figure 8.

Table 9. Test results of roughness of washed rough surface of precast concrete.

Roughness Range	Average Depth of Filled Sand (mm)					
	C40 Precast Concrete			C30 Precast Concrete		
	1	2	3	1	2	3
4~5 mm	4.57	4.73	4.81	4.20	4.44	4.73
5~6 mm	5.04	5.36	5.73	5.14	5.33	5.95
6~7 mm	6.30	6.73	6.94	6.13	6.36	6.92
7~8 mm	7.02	7.24	7.46	7.31	7.33	7.96

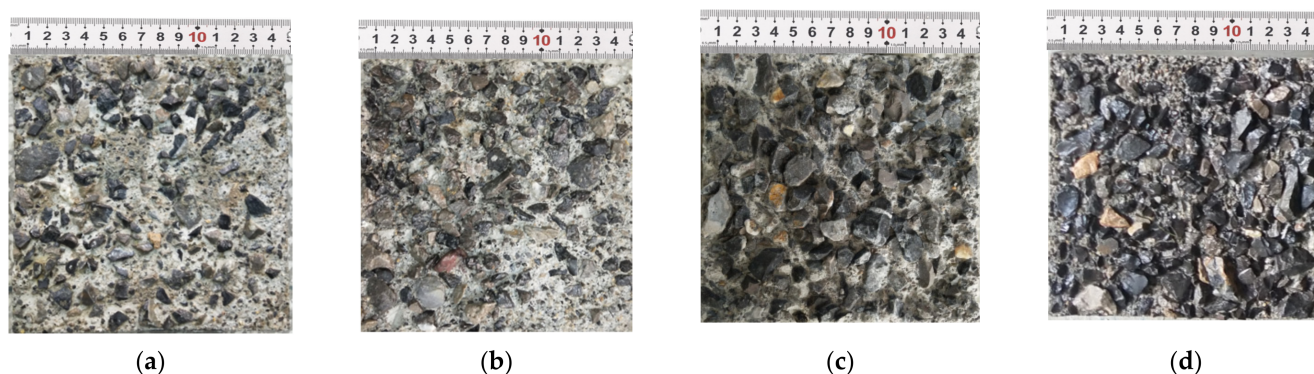


Figure 8. Washed rough surfaces of specimens in sectional dimension of 150 mm × 150 mm with different roughness: (a) 4~5 mm; (b) 5~6 mm; (c) 6~7 mm; (d) 7~8 mm.

Figure 9 presents the failure mode of eight group specimens with different roughness of washed rough surface of precast concrete. Four groups were made with C40 precast concrete and C45 cast-in-situ concrete, others were made with C30 precast concrete and C35 cast-in-situ concrete. Most specimens failed along the interface with the interlaced mortar among exposed aggregates and part fractured aggregates. Some specimens appeared two cracks on the compression zone of the loading surface, one crack was along the interface, another was near the interface. This indicates that with the increase in interface roughness, the possibility increased that the bond failure of interface transfer to the weak side of precast or cast-in-situ concrete. In this study, the test result of larger splitting load without along the interface was discarded.

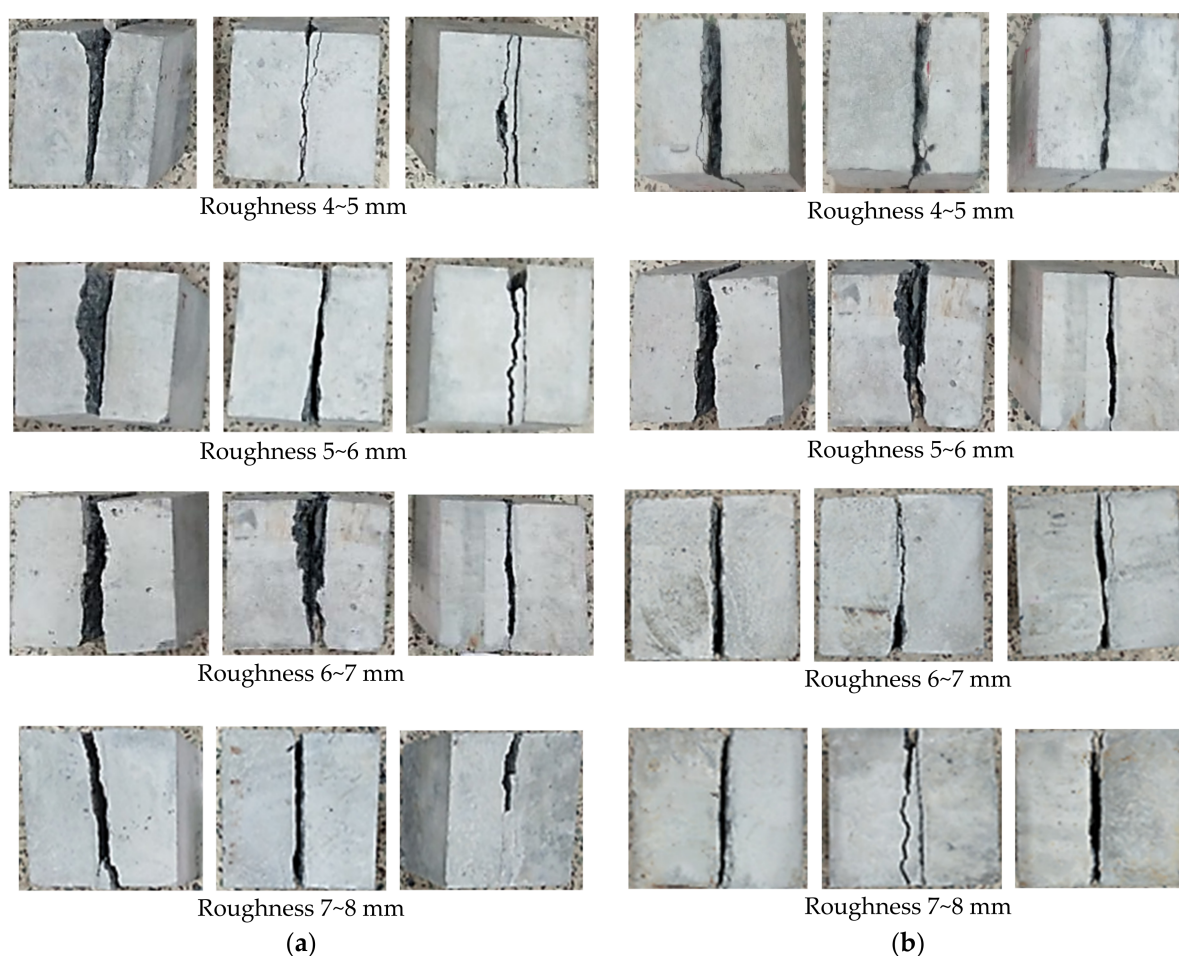


Figure 9. Failure mode of specimens with different roughness of precast concrete in dimension of 150 mm × 150 mm: (a) C45 cast-in-situ concrete to C40 precast concrete; (b) C35 cast-in-situ concrete to C30 precast concrete.

Test results of bonding strength of interface are presented in Table 10. The interfacial bonding strength increased obviously with the increasing roughness of washed rough surface of precast concrete. This is easy to be understood that the interlock effect of aggregates on interface became stronger with the increase in interface roughness [21–23]. When the roughness was over 6 mm, the equivalent coefficient of bonding strength was close to 1.00. In this condition, the exposed size of aggregate was about one-third to four-fifths of the maximum particle size of 20 mm for precast concrete. Therefore, the interfacial bonding strength equivalent to tensile strength of precast concrete can be provided by the washed rough interface of precast concrete at the roughness of 6~8 mm, accompanied by the strength grade of cast-in-situ concrete over precast concrete.

Table 10. Bond strength of interface with different roughness of precast concrete.

Strength Grade of Concrete	C40 Precast, C45 Cast-In-Situ		C30 Precast, C35 Cast-In-Situ	
Roughness of Precast Concrete	f_b (MPa)	β_e	f_b (MPa)	β_e
4~5 mm	2.69	0.85	1.99	0.84
5~6 mm	2.72	0.86	2.08	0.87
6~7 mm	3.09	0.97	2.32	0.97
7~8 mm	3.24	1.02	2.46	1.03

3.5. Effect of Storage Time of Precast Concrete

Table 11 presents the bonding strength of the interface at different storage time after casting of precast concrete. The washed rough surface of precast concrete was made with roughness of 7~8 mm. The specimens failed in splitting at interface with paste peeled off and aggregates fractured, except one failed in splitting inclined into the precast concrete. This indicates the interface was still weak without enough strength resisting the splitting tensile force. Due to the higher strength of cast-in-situ concrete than precast concrete, the possible failure may be happened in precast concrete.

Table 11. Bond strength of interface with different storage time of precast concrete (MPa).

Strength Grade of Concrete	C40 Precast, C45 Cast-In-Situ		C30 Precast, C35 Cast-In-Situ	
Age of Precast Concrete (d)	f_b (MPa)	β_e	f_b (MPa)	β_e
14	3.24	1.02	2.46	1.03
28	3.16	0.99	2.40	1.01
56	2.88	0.91	2.08	0.87
90	2.68	0.84	1.93	0.81

The interfacial bonding strength decreased with the increasing age of precast concrete. After the age of 28 days, the equivalent coefficient of bonding strength was lower than 1.00. Similar to those studies on bonding strength of new to old concrete [24–26], the unhydrated and incomplete hydrated binders on the surface of precast concrete has more activity to continuously hydrate with the binders of cast-in-situ concrete before the casting age of 28 days. However, the early-age carbonation of precast concrete consumes the hydrate product $\text{Ca}(\text{OH})_2$ and filled the interfacial pores and defects [40,41]. This is unbeneficial to the interlaced crystals formed by the hydration of cast-in-situ concrete and precast concrete [10]. Meanwhile, the hydration of cement and mineral admixtures is continuous to keep the time-dependent strength development of concrete [42–44]. This is also unbeneficial to the interaction of cast-in-situ concrete to precast concrete, due to the decrease in the amount of unhydrated and incomplete hydrated binders on the surface of precast concrete. Therefore, a largest storage time no more than 28 days should be considered for the production and installation cycle of precast concrete components.

4. Conclusions

The strength grades of precast and cast-in-situ concretes, the interface conditions and storage time of precast concrete were considered as the experimental factors in this paper. The interface roughness of precast concrete was measured by sand patch test. The interfacial bonding strength of cast-in-situ to precast concrete was measured by the splitting tensile test. The equivalent coefficient of bonding strength was computed with the interfacial bonding strength divided by the tensile strength of precast concrete. Based on the experimental research, conclusions can be drawn as follows:

- (1) With the premise of higher strength grade of cast-in-situ concrete than precast concrete, the interfacial bonding strength increased with the increasing strength of cast-in-situ concrete. In practice, the cast-in-situ concrete is better one strength grade higher than precast concrete.
- (2) The interfacial bonding strength increased with sequence of original interface, closing net formed interface and washed rough interface of precast concrete. The washed rough interface of precast concrete is a good choice in practice to ensure the interfacial bonding strength. When the roughness was over 6 mm that is about one-third of exposed aggregates with maximum particle size of 20 mm, the interfacial bonding strength can reach the tensile strength of precast concrete.
- (3) Spraying binder paste on surface of precast concrete has beneficial effect on the bond of interface. This can be considered as a choice for the quality promotion of joints in practice.
- (4) The interfacial bonding strength decreased with the increasing storage time of precast concrete. The bonding strength could be equivalent to the tensile strength of precast concrete when the casting age of precast concrete was not over than 28 days. In practice, the production and installation cycle of precast concrete components should limit within 28 days.
- (5) The research of this paper has limitations only in macroscopic phenomena and index of bonding strength. Due to the complexity of interfacial bonding performance influenced by multi factors, further systematical researches should be carried out combined the macroscopic with the microscopic indices to reveal the truth and accumulate research results.

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