INFLUENCE OF CONCRETE UNIT WEIGHT ON THE INTERFACE SHEAR TRANSFER OF CONCRETES CAST AT DIFFERENT TIMES

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ABSTRACT

This study examines the influence of concrete unit weight on the direct shear transfer across an interface of concretes cast at different times. This type of interface is common with structural precast concrete connections, such as corbels, for which shear friction design provisions are commonly used. Increasing use of lightweight aggregate concretes prompted this investigation to determine the appropriateness of current shear friction design provisions with respect to all-lightweight and sand-lightweight concrete. The experimental investigation includes thirty-six push-off specimens, each of which is constructed with a cold-joint along the shear plane. Test variables include concrete type (unit weight), compressive strength of concrete, and surface preparation of the shear interface. A constant amount of reinforcing steel is used to cross the shear plane. Applied shear force-slip relations are presented and discussed. Peak and residual shear strengths are also compared. Results are compared with current shear friction design provisions.

Keywords: All-lightweight concrete, Coefficient of friction, Connections, Sand-lightweight concrete, Shear friction

INTRODUCTION

The overall goal of this experimental study was to extend previous research and examine the applicability of the shear friction concept for lightweight aggregate concretes with a cold-joint condition at the shear interface. Lightweight aggregate concretes are being used increasingly in precast concrete construction to reduce member weight and shipping costs. Precast concrete elements commonly incorporate connections that are designed based on the shear friction concept to transfer forces across an interface. Previous studies have shown that interface surface preparation, reinforcement ratio, concrete strength, and concrete type (normalweight, sand-lightweight, or all-lightweight) have significant impacts on the shear transfer strength[1-7]. The shear friction design provisions presented in American Concrete Institute's Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI 318R-11)[8] and the PCI Design Handbook: Precast and Prestressed Concrete (7th edition)[9] are largely empirical and are based on physical test data, yet little data exist on specimens constructed with lightweight aggregate concretes, especially for conditions in which concretes are cast at different times (i.e., cold-joint conditions).

Current ACI 318 code[8] and PCI Design Handbook[9] shear friction design provisions present a similar approach in which the nominal shear strength V_n is computed as a function of the coefficient of friction μ, the area of shear reinforcement across the shear plane A_{vf} , and the yield stress of reinforcement f_y shown in Equation 1:

$$V_n = \mu A_{vf} f_y \qquad (1)$$

In Equation 1, the coefficient of friction μ is intended to account for friction between the surfaces of the crack interface and dowel action of the reinforcement. The value of μ is taken to be a function of the crack interface condition and the concrete type as summarized in Table 1. The modification factor λ for concrete type is intended to account for reduced values of the mechanical properties of lightweight aggregate concrete relative to normalweight concrete of the same compressive strength. The value of λ is taken as 1.0 for normalweight concrete, 0.75 for all-lightweight concrete, and may be taken as 0.85 for sand-lightweight concrete[8,9]. An alternative approach to designing the shear friction reinforcement is presented in the PCI Design Handbook[9] in which μ is replaced with an effective coefficient of friction μ_e. However, this alternative approach is not applicable for certain crack interface conditions, namely Cases 3 and 4 in Table 1, or when load reversals occur.

The nominal shear strength given by Equation 1 can also be expressed in terms of shear stress as shown in Equation 2:

$$v_n = \mu \rho f_y \qquad (2)$$

In Equation 2, the reinforcement ratio $\rho = A_{vf}/A_c$, where A_c is the area of the shear plane. Upper limits are placed on the nominal shear strength v_n depending on the concrete type and interface condition[8,9].

Table 1 Value of μ for Different Interface Conditions[8,9]

Case	Crack Interface Condition	μ
1	Concrete to concrete, cast monolithically	1.4λ
2	Concrete to hardened concrete, with roughened surface	1.0λ
3	Concrete placed against hardened concrete not intentionally roughened	0.6λ
4	Concrete to steel	0.7λ

As mentioned previously, the shear friction concept has been studied extensively by others, especially for normalweight concrete with various reinforcement ratios, compressive strengths, and interface conditions[1-7]. Relatively little work has been done, however, to investigate shear friction of lightweight aggregate concretes with a cold-joint condition. This condition can be the result of precast plant practices where a projecting element is cast in advance and then inserted into the fresh concrete when the supporting element is cast. For example, Figure 1 shows precast column corbels that have been cast in advance of the supporting precast column element, and two distinctly different shear interface conditions in terms of surface roughness. The PCI Design Handbook[9] also notes that the use of self-consolidating concrete (SCC) can lead to conditions in which projecting elements are cast against supporting elements after the concrete has partially hardened. The result may be a cold-joint condition with a relatively smooth interface. Accordingly, this study was aimed at studying the shear transfer of lightweight aggregate concretes across a cold-joint with a roughened or smooth interface (Cases 2 and 3 in Table 1). Results are compared to normalweight concrete of the same concrete strength and interface condition.

Fig. 1 Precast facility #1 corbel (left), corbel in place (center), precast facility #2 corbel (right).

EXPERIMENTAL PROGRAM

The experimental program included 36 push-off specimens used to investigate the direct shear transfer across an interface of concrete cast at different times. The test variables included concrete type, compressive strength of concrete, and shear interface surface preparation. In this paper, the term "concrete type" refers to normalweight, sand-lightweight, or all-lightweight concrete, where each type is designated by its unit weight in accordance with the ACI 318 code[8]. The test matrix is shown in Table 2. Target unit weights (densities) of fresh concrete were 145, 120, and 108 lb/ft^3 to represent normalweight, sand-lightweight, and all-lightweight concrete types, respectively. As discussed in the next paragraph, the different types of concrete were achieved using normalweight and/or lightweight aggregates. Target compressive strength of concrete was either 5000 or 8000 psi. Interface condition was either "roughened" (0.25 in. amplitude) or "smooth." These interface conditions represented a Case 2 condition and a lower bound condition of Case 3 in Table 1, respectively. Three replicate specimens were tested in each series. The specimens were designed to be similar to those by Hofbeck et al.[2], Mattock and Hawkins[3], Mattock[4], Mattock et al.[5], and Kahn and Mitchell[7] so that results could be compared to previous tests. The shear plane was 11.0 in. long and 4.5 in. wide, with an area of shear plane A_c = 49.5 in^2. Shear reinforcement consisting of three No. 3 closed tie deformed reinforcing bar stirrups was provided normal to the shear plane for all specimens. The resulting reinforcement ratio ρ was 1.33%. The stirrups were ASTM A615[10] Grade 60 with a measured yield strength f_y of 66.2 ksi. Test specimen dimensions and reinforcement are shown in Figure 2.

All concrete mixtures were designed with a similar nominal maximum aggregate size. The normalweight concrete included crushed dolomitic limestone and natural sand that met or exceeded ASTM C33[11] specifications. The coarse aggregate gradation used was selected to consist of 100% passing a 1/2 in. sieve and less than 5% passing a No. 8 sieve. The sand-lightweight concrete was comprised of a lightweight expanded shale coarse aggregate with a ASTM C330[12] blended gradation with 100% passing a 1/2 in. sieve and less than 10% passing a No. 8 sieve. Fine aggregate was the same natural sand used in the normalweight concrete. The all-lightweight concrete consisted of an ASTM C330[11] structural aggregate gradation containing lightweight expanded shale aggregate with 100% passing a 1/2 in. sieve with 100% retained on the pan. No normalweight sands were used in the production of the all-lightweight concrete in this study. In producing the sand-lightweight and all-lightweight concretes, the lightweight aggregates were saturated for a minimum of 48 hours prior to casting of specimens. Lightweight aggregate gradations and properties are presented in Tables 3 and 4, respectively. For each concrete type, Type I/II portland cement was used with water-cement ratios ranging from 0.40-0.60. A high range water reducer (HRWR) was used in the 8000 psi concrete mixtures to reduce the water demand. Plastic and hardened concrete properties are presented in Tables 5 and 6, respectively. Values of concrete density reported in Table 5 correspond to the unit weights measured on the fresh concrete. Hardened concrete properties presented in Table 6 include the 28-day compressive strength f'_c, splitting tensile strength f_t, and modulus of elasticity E_c.

Table 2 Test Matrix and Series Designation

Concrete Type and Target Unit Weight	Target Concrete Compressive Strength	Shear Interface Condition	Series Designation
Normalweight (145 lb/ft^3)	5000 psi	Roughened	N-5-R
		Smooth	N-5-S
	8000 psi	Roughened	N-8-R
		Smooth	N-8-S
Sand-lightweight (120 lb/ft^3)	5000 psi	Roughened	S-5-R
		Smooth	S-5-S
	8000 psi	Roughened	S-8-R
		Smooth	S-8-S
All-lightweight (108 lb/ft^3)	5000 psi	Roughened	A-5-R
		Smooth	A-5-S
	8000 psi	Roughened	A-8-R
		Smooth	A-8-S

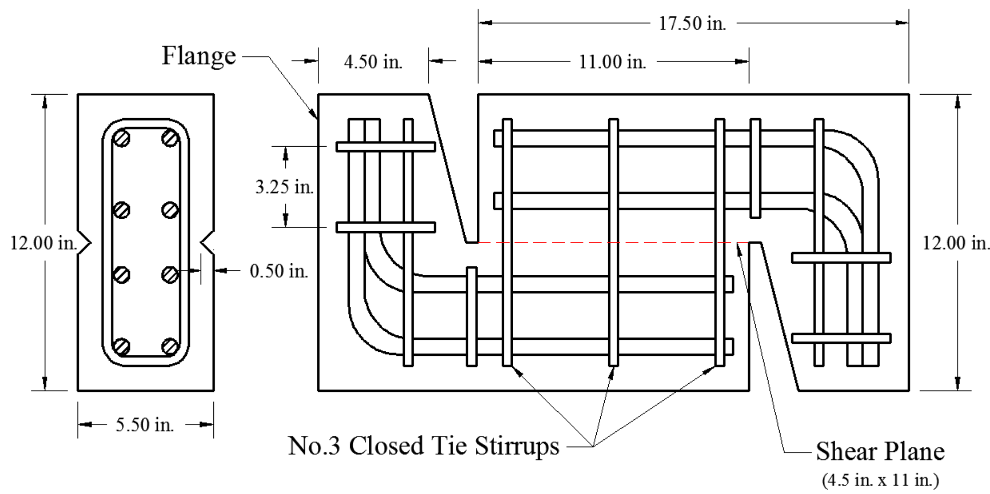

Fig. 2 Test specimen (dimensions shown in the figure are measured to the nearest 0.25 in.)

Table 3 Lightweight Aggregate Gradations

	Sieve Designation	Percent Retained		Percent Passing	
		Gradation	Specification (Note 1)	Gradation	Specification (Note 1)
3/8 in. x No. 8 Gradation	1/2 in.	0	0	100	100
	3/8 in.	1	0-20	99	80-100
	No. 4	82	60-95	18	5-40
	No. 8	99	80-100	1	0-20
	No. 16	99	90-100	1	0-10
3/8 in. x No. 0 Gradation	1/2 in.	0	0	100	100
	3/8 in.	0	0-10	100	90-100
	No. 4	13	10-35	87	65-90
	No. 8	49	35-65	51	35-65
	No. 16	67	-----	33	-----
	No. 30	79	-----	21	-----
	No. 50	86	75-90	14	10-25
	No. 100	93	85-95	7	5-15

Note: 1. ASTM C330[12]

Table 4 Lightweight Aggregate Material Properties

ASTM Gradation	Specific Gravity (Note 1)	Density (Note 2) (lb/ft^2)	Percent Absorption (Note 1) (%)	Saturated Density (Note 1) (lb/ft^2)
3/8 in. x No. 8	1.3	44	20	54
3/8 in. x No. 0	1.45	54	10	65

Notes: 1. ASTM C127[13] / ASTM C128[14], Bulk specific gravity
2. ASTM C29[15], Loose unit weight at 6% saturation

Table 5 Plastic Concrete Properties

Concrete Mixture	Density (lb/ft^3)	Air (%)	Slump (in.)
Normalweight - 5000 psi	145.0	1.5	5.0
Normalweight - 8000 psi	144.0	2.5	4.0
Sand-lightweight - 5000 psi	118.0	4.5	4.0
Sand-lightweight - 8000 psi	118.0	4.0	5.0
All-lightweight - 5000 psi	108.0	3.5	6.0
All-lightweight - 8000 psi	109.0	4.5	6.0

Table 6 Hardened Concrete Properties

Concrete Mixture	Target f'_c (psi)	f'_c (Note 1) (psi)	f'_c at test day (Note 1) (psi)	f_t (Note 2) (psi)	E_c (Note 3) (psi)
Normalweight - 5000 psi	5000	4860	4860	420	3.70×10^6
Normalweight - 8000 psi	8000	7550	7550	540	3.80×10^6
Sand-lightweight - 5000 psi	5000	4600	4600	320	3.65×10^6
Sand-lightweight - 8000 psi	8000	7200	7200	510	3.75×10^6
All-lightweight - 5000 psi	5000	6080	6080	510	2.90×10^6
All-lightweight - 8000 psi	8000	7840	7840	520	3.30×10^6

Notes: 1. ASTM C1231[16]
2. ASTM C496[17]
3. ASTM C469[18]

Specimens were constructed with custom-built formwork to facilitate production of the cold-joint along the shear plane. The concrete was placed with the cold-joint oriented horizontally as shown in Figure 3. To achieve the cold-joint, specimens were cast in two stages. After casting the first half of the specimen, the shear interface was trowelled smooth. Three hours after casting, the interface roughening was completed on specimens that were designated to have a roughened interface. Roughening was accomplished by scoring the surface of the shear interface in the direction perpendicular to the direction of loading as shown in Figure 4. The surface roughness was measured using a digital caliper at ten locations on the shear interface. The average value of measured scoring line depth, that is, its measure of roughness, ranged between 0.245-0.260 in. for all specimens with a roughened interface. After roughening was completed, the interface was cleaned with compressed air. The second half of the specimen was cast a minimum of eight hours after casting the first half of the specimen.

Fig. 3 Test specimen casting

Fig. 4 Interface roughening procedure (left) and measurement (right)

All specimens were tested 28 days after casting the concrete. Specimens were loaded concentric to the shear plane with a hemispherical head at the top of the specimen to allow rotational freedom and a fixed platen at the base of the specimen. All specimens were tested under displacement control at a rate of 0.015 in. per minute. An external confinement system was added to the top and bottom flanges of the specimens to mitigate premature failure in the flanges. Two direct current linear variable displacement transducers (DC-LVDTs) were installed on each face of the specimen to monitor dilation (separation) of the shear plane. One additional DC-LVDT was installed on each face of the specimen to monitor slip of the interface. Uniaxial electrical resistance gages were attached to one leg of each stirrup crossing the shear plane. The test setup and instrumentation are shown in Figure 5.

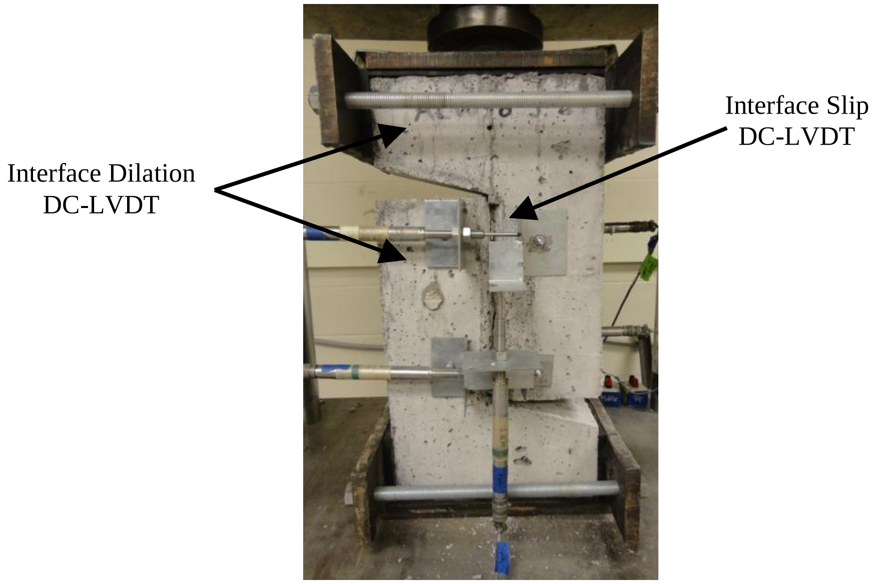

Fig. 5 Test setup and instrumentation

RESULTS AND DISCUSSION

OBSERVED BEHAVIOR

The general behavior of all specimens was similar. No cracks were observed during testing of the specimens in the region adjacent to the shear plane. This is similar to previous research conducted by Mattock et al.[5] on monolithic lightweight aggregate concrete specimens with a precracked interface. For the specimens with a roughened interface, the peak shear force was associated with the appearance of a vertical crack along the shear plane and noticeable separation of the crack interface surfaces. Strain measured in the interface reinforcement indicated that yielding of reinforcement occurred at the peak shear force. The smooth interface specimens exhibited similar cracks along the shear plane, but with lesser observed separation of the crack interface surfaces than the specimens with roughened interfaces. Figure 6 shows examples of cracks observed in the specimens at peak load with the different interface conditions. In addition to cracking of the shear interface, spalling of the concrete cover was observed adjacent to the shear plane crack for many specimens.

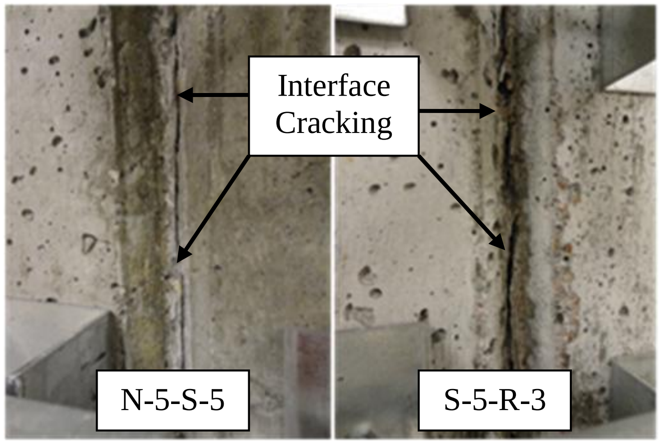

Fig. 6 Typical failure crack along shear plane for specimens with smooth interface (N-5-S-5 shown) (left) and roughened interface (S-5-R-3 shown) (right)

Applied shear force *V*-slip relations for the normalweight, sand-lightweight, and all-lightweight series specimens are shown in Figures 7, 8, and 9, respectively. The figures show that slip occurred immediately upon loading for all specimens, and that the initial stiffness of the smooth and roughened interface specimens was similar. For the specimens with a smooth interface, the slip tended to increase at an increasing rate until the peak shear force V_u was achieved. After the peak shear force was achieved, the applied shear force reduced with increasing slip until a nearly constant value of applied shear force was reached for all specimens in a given series. Specimens with a roughened interface behaved in a more brittle manner than the corresponding smooth interface specimens, i.e., after the peak shear force was achieved, the shear force decreased more rapidly with increasing slip, although the residual strength was similar to that of the corresponding specimens with a smooth interface.

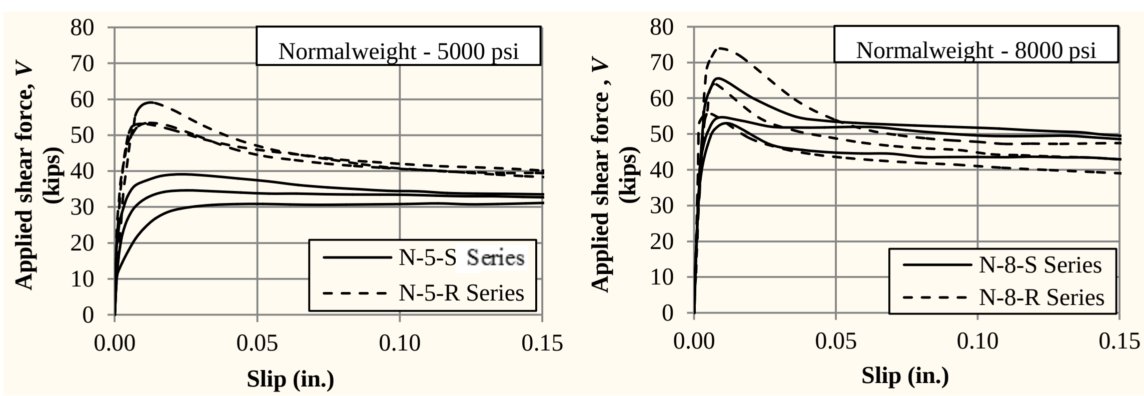

Fig. 7 Applied shear force *V*-slip relations for normalweight concrete specimens with 5000 psi concrete (left) and 8000 psi concrete (right)

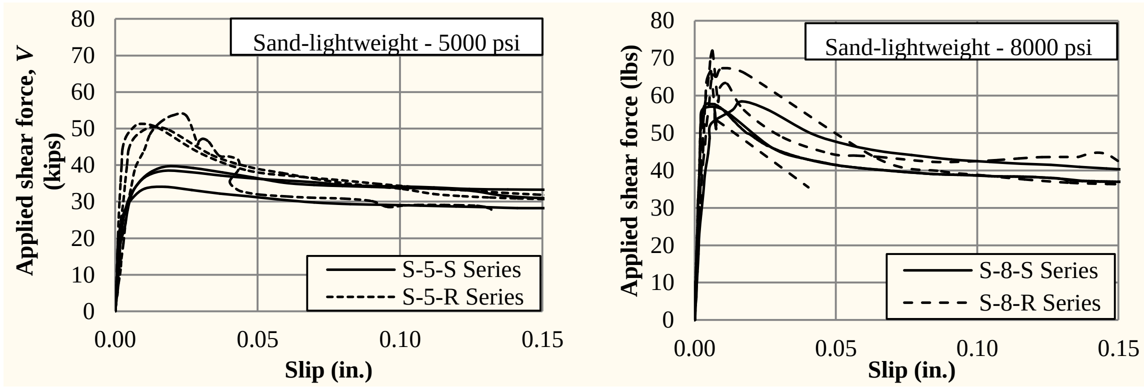

Fig. 8 Applied shear force V -slip relations for sand-lightweight concrete specimens with 5000 psi concrete (left) and 8000 psi concrete (right)

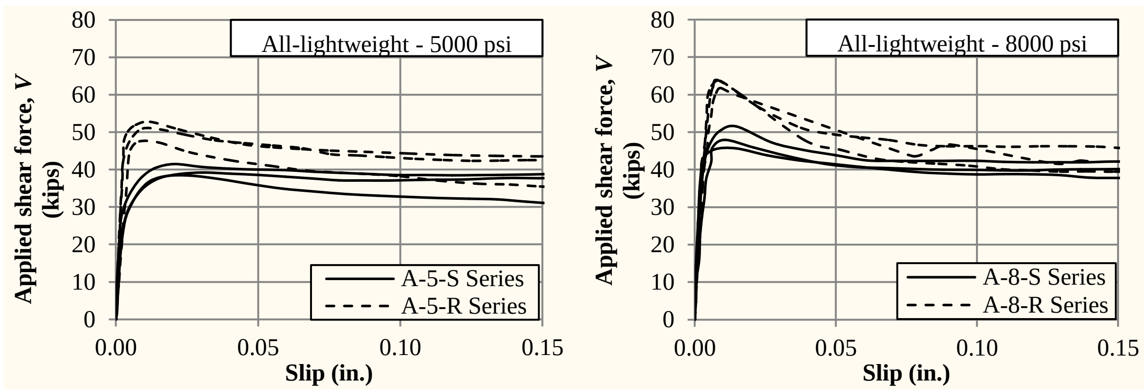

Fig. 9 Applied shear force V -slip relations for all-lightweight concrete specimens with 5000 psi concrete (left) and 8000 psi concrete (right)

Comparison of the applied shear force-slip relations for specimens of the same concrete type and same interface condition indicates that the deformation behavior was more brittle for specimens with higher compressive strengths, that is, after the peak shear force was achieved, the shear force decreased more rapidly with increasing slip. This observation was also made by Mattock et al.[5]. The applied shear force-slip relations also indicate that specimens with normalweight concrete tended to be more brittle than lightweight companion specimens. These findings are different from those by Mattock et al.[5], who observed that lightweight concrete specimens were more brittle than companion normalweight concrete specimens. A possible explanation for this difference may be differences in aggregate used in the production of the lightweight aggregate concretes. This highlights the need to examine lightweight concrete mixtures with different types of aggregates.

SHEAR STRENGTH

Results of each test specimen are summarized in Table 7. Specimen designation is given by the following notation: first value indicates concrete type (N=normalweight, S=sand-lightweight and A=all-lightweight); second value indicates target compressive strength of concrete in units of ksi; third value indicates interface condition (S=smooth and

R=roughened); and fourth value indicates specimen number in test series. In the table, V_u is the peak shear force measured during testing; shear strength v_u is the peak shear force V_u divided by the area of the shear plane A_c (49.5 in^2); V_{ur} is the residual shear force corresponding to a slip of 0.15 in.; and residual shear strength v_{ur} is the residual shear force V_{ur} divided by the area of the shear plane A_c. Values of slip and dilation of the shear plane measured at the peak shear force are also reported in Table 7. Values reported are the average of the DC-LVDT measurements from both sides of the test specimen. It should be noted that Specimens N-5-R-1,2,3 and N-5-S-1,2,3 are not included in the table because premature failure occurred within the flanges of these specimens (flanges are indicated in Figure 2).

In Figure 10, shear strength v_u is plotted versus concrete unit weight for the specimens tested in this study, maintaining the distinction between specimens with different interface conditions and concrete compressive strengths. Average values for each series are shown in Figure 11. The trendlines shown in Figure 11 show that specimens with the same interface condition and concrete compressive strength had nearly the same shear strength v_u irrespective of concrete unit weight (concrete type). These results suggest that concrete type did not play a significant role in the interface shear strength for the cold-joint specimens in this study.

Equation 2 indicates that the nominal shear strength v_n is a function of the coefficient of friction μ and the clamping stress ρf_y. As mentioned previously, all specimens tested in this study had the same interface reinforcement and thus the same value of ρf_y. Since specimens with the same interface condition and concrete compressive strength had approximately the same shear strength v_u, therefore Equation 2 suggests that the value of μ was the approximately the same, irrespective of concrete type. Additionally, it should be noted that for each specimen, the value of μ computed by Equations 1 and 2, including λ taken as 1.0 for normalweight concrete, 0.75 for all-lightweight concrete, and 0.85 for sand-lightweight concrete, exceeded the value corresponding to the appropriate interface condition given in Table 1.

Table 7 Summary of Test Results

Specimen ID	f'_c at test day (psi)	V_u (lbs)	v_u (psi)	$v_{u, avg}$ (psi)	Slip at V_u (in)	Dilation at V_u (in)	V_{ur} (lbs)	v_{ur} (psi)	$v_{ur, avg}$ (psi)	$\left(\frac{v_u}{v_{ur}}\right)_{avg}$
N-5-R-4	4860	59060	1190	1115	0.013	0.007	39470	800	790	1.41
N-5-R-5	4860	53420	1080		0.010	0.006	40140	810		
N-5-R-6	4860	53440	1080		0.012	0.007	38360	770		
N-5-S-4	4860	30850	625	705	0.057	0.015	31150	630	645	1.12
N-5-S-5	4860	34678	700		0.030	0.008	32690	660		
N-5-S-6	4860	39154	790		0.031	0.007	32000	650		
S-5-R-1	4550	51431	1040	1117	0.010	0.007	30500	620	603	1.85
S-5-R-2	4550	50396	1020		0.014	0.008	29600	600		
S-5-R-3	4550	63904	1290		0.022	0.007	29300	590		
S-5-S-1	4550	38532	780	757	0.019	0.006	33200	670	610	1.24
S-5-S-2	4550	34112	690		0.016	0.003	27900	560		
S-5-S-3	4550	39796	800		0.021	0.007	29500	600		
A-5-R-1	6080	48439	980	1030	0.010	0.005	35000	710	800	1.29
A-5-R-2	6080	52797	1070		0.011	0.005	43000	870		
A-5-R-3	6080	51408	1040		0.013	0.004	40500	820		
A-5-S-1	6080	41471	840	813	0.021	0.006	38500	780	727	1.13
A-5-S-2	6080	40079	810		0.023	0.005	32000	650		
A-5-S-3	6080	39247	790		0.032	0.007	37000	750		
N-8-R-1	7550	74040	1500	1310	0.010	0.008	47500	960	873	1.50
N-8-R-2	7550	56090	1130		0.008	0.005	39050	790		
N-8-R-3	7550	64140	1300		0.007	0.005	43000	870		
N-8-S-1	7550	65572	1320	1173	0.010	0.006	49500	1000	937	1.25
N-8-S-2	7550	53305	1080		0.010	0.005	42950	870		
N-8-S-3	7550	55327	1120		0.001	0.006	46695	940		
S-8-R-1	7210	72045	1460	1390	0.007	0.006	43660	880	805	1.76
S-8-R-2	7210	67380	1360		0.010	0.006	36300	730		
S-8-R-3	7210	66725	1350		0.006	0.005	N/A	N/A		
S-8-S-1	7210	67025	1350	1237	0.007	0.006	44480	900	820	1.51
S-8-S-2	7210	57876	1170		0.005	0.003	36970	750		
S-8-S-3	7210	58863	1190		0.018	0.007	40340	810		
A-8-R-1	7845	61774	1250	1280	0.009	0.003	41330	830	853	1.51
A-8-R-2	7845	63937	1290		0.008	0.007	45800	930		
A-8-R-3	7845	64126	1300		0.009	0.006	39450	800		
A-8-S-1	7845	46090	930	983	0.011	0.004	37790	760	807	1.22
A-8-S-2	7845	48035	970		0.012	0.006	40185	810		
A-8-S-3	7845	51740	1050		0.012	0.004	42140	850		

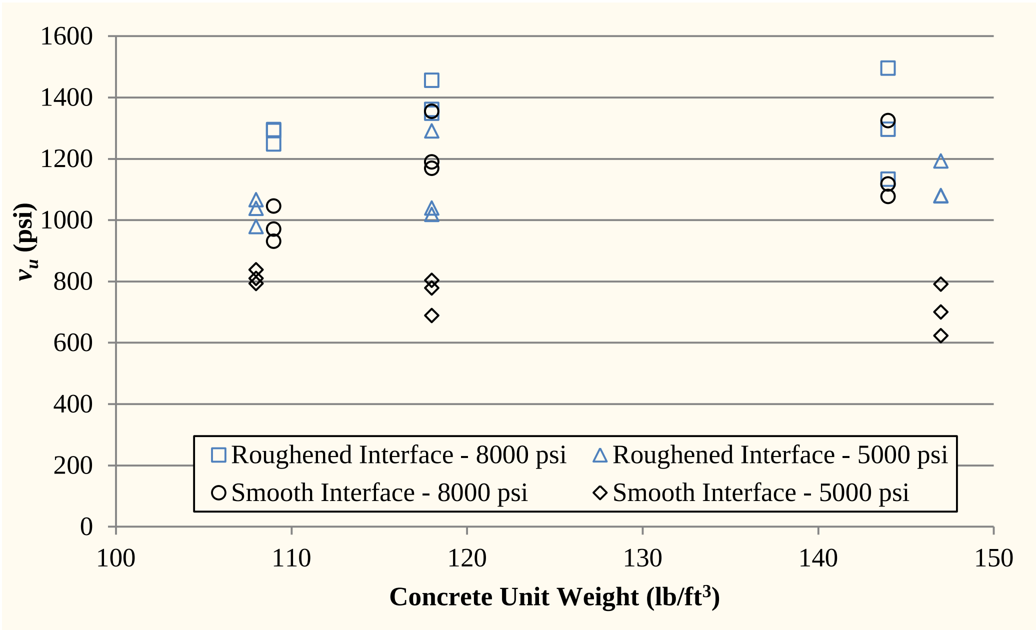

Fig. 10 Comparison of shear strength v_u versus concrete unit weight

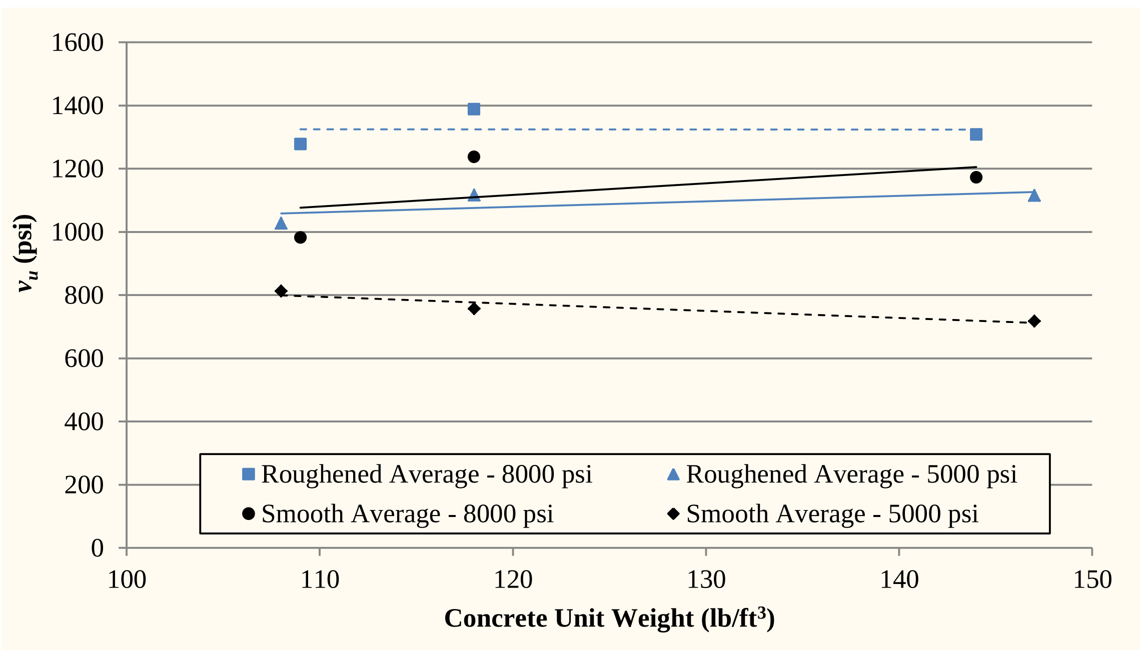

Fig. 11 Comparison of average shear strength v_u versus concrete unit weight

As expected, Figure 11 also shows that the average values of v_u for specimens with a roughened interface are larger than those with a smooth interface for the same concrete compressive strength and same unit weight. The applied shear force-slip responses in Figures 7, 8, and 9 also illustrate that specimens with a roughened interface (the dashed lines in the figures) have a higher peak shear force V_u than those with a smooth interface (the solid lines in the figures) for each concrete type and strength. The increase in shear strength for specimens with a roughened interface is attributed to increased surface interaction and the separation (dilation) that must be achieved to overcome the interlock of the shear interface.

Figure 11 also shows that the average values of v_u for specimens with 8000 psi concrete are larger than those with 5000 psi concrete for the same interface condition and same unit weight. The influence of concrete compressive strength was studied by Kahn and Mitchell[7] for normalweight concrete specimens with uncracked, precracked, and cold-joint conditions, and results are consistent with their findings.

The residual shear strength v_{ur} can be used to compare the post-yield capacity of the specimens. The residual shear strength v_{ur} is plotted versus concrete unit weight for the specimens tested in this study in Figure 12, maintaining the distinction between specimens different interface conditions and concrete compressive strengths. Average values for each series are shown in Figure 13. The trendlines shown in Figure 13 show that the residual shear strength v_{ur} was approximately the same for all specimens irrespective of concrete unit weight (concrete type), compressive strength, and interface condition. These results are similar to those by Mattock et al.[5], who observed that the residual shear strength of monolithic all-lightweight concrete specimens with an uncracked interface was approximately the same as that of specimens with precracked interfaces. Similarly, Kahn and Mitchell[7] observed that the residual shear strength of normalweight high-strength concrete specimens was approximately the same for specimens with uncracked, precracked, and cold-joint conditions.

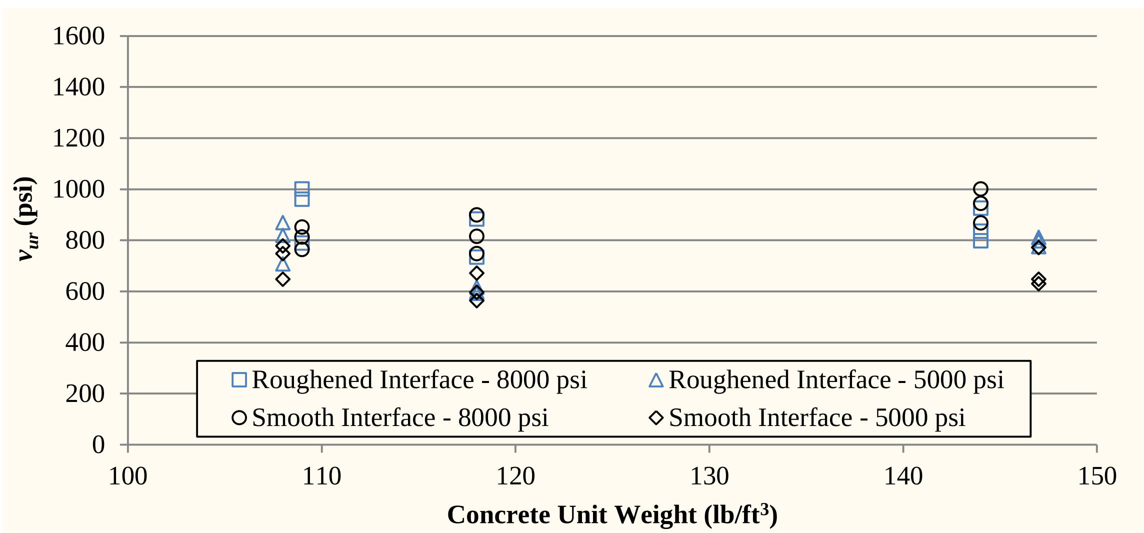

Fig. 12 Comparison of residual shear strength v_{ur} versus concrete unit weight

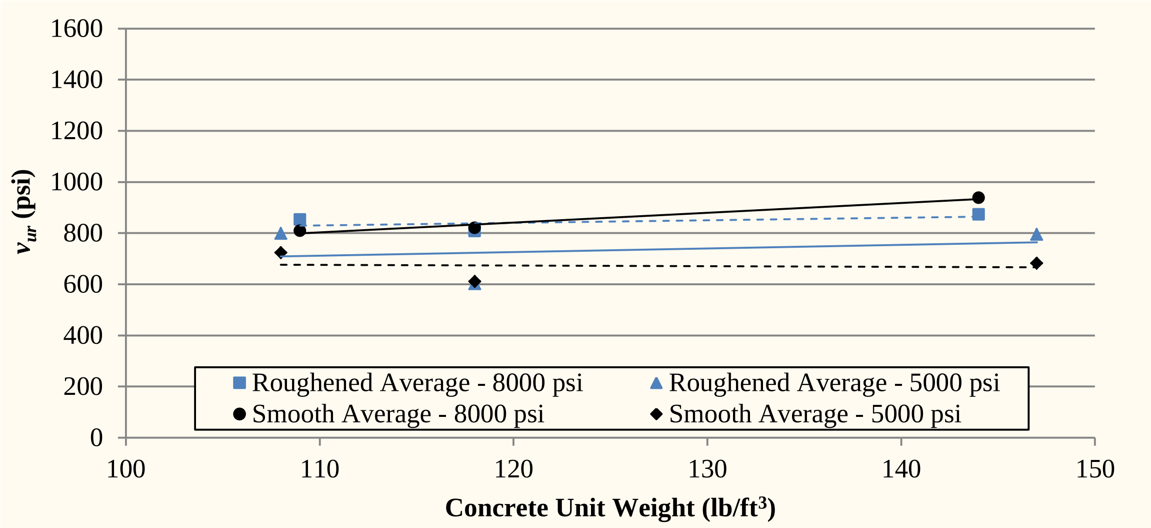

Fig. 13 Comparison of average residual shear strength v_{ur} versus concrete unit weight

Table 7 shows that the ratio of the shear strength to the residual shear strength v_u/v_{ur} ranges from 1.29 to 1.85 for all specimens with a roughened interface. No clear trend is observed with respect to concrete type or compressive strength. For specimens with a smooth interface, v_u/v_{ur} ranges from 1.12 to 1.24 for the 5000 psi specimens and from 1.22 to 1.51 for the 8000 psi specimens. The slightly larger v_u/v_{ur} ratios for the 8000 psi smooth interface specimens compared to the 5000 psi smooth interface specimens indicate more brittle behavior of the higher strength specimens noted previously, which may be due to differences in cohesion among the different concrete mixtures.

The shear strength v_u for the specimens in this study are compared with previous data from the literature on sand-lightweight and all-lightweight concrete (Mattock et al.[5]) in Figures 14 and 15, respectively. It should be noted that the specimens tested by Mattock at al. [5] were cast monolithically, and some specimens were precracked prior to testing (indicated in the figure). Also, the specimens by Mattock et al.[5] had a measured compressive strength of concrete between 2000 to 6000 psi, which is similar to those tested in this study (approximately 4600 to 8000 psi). In Figure 14, the sand-lightweight concrete specimens in the Mattock et al.[5] precracked series with relatively lower shear strength v_u correspond to specimens with lower concrete compressive strength (2000 to 2330 psi, Series C in the reference). Specimens by Mattock et al.[5] were cast of concretes with similar unit weights to those in this study. Unit weights reported by Mattock et al.[5] were dry unit weights (equilibrium); however calculation based on batch quantities indicates that the wet (fresh) unit weights were approximately 120 and 110 pcf for the sand-lightweight and all-lightweight concretes produced. Results show that the shear strength of the sand-lightweight and all-lightweight specimens in this study is consistent with specimens by Mattock et al.[5]. Interestingly, the cold-joint specimens in this study with a smooth interface had a shear strength v_u similar to specimens that were monolithic and precracked. Similarly, the cold-joint specimens with a roughened interface had a shear strength v_u similar to specimens that were monolithic and uncracked.

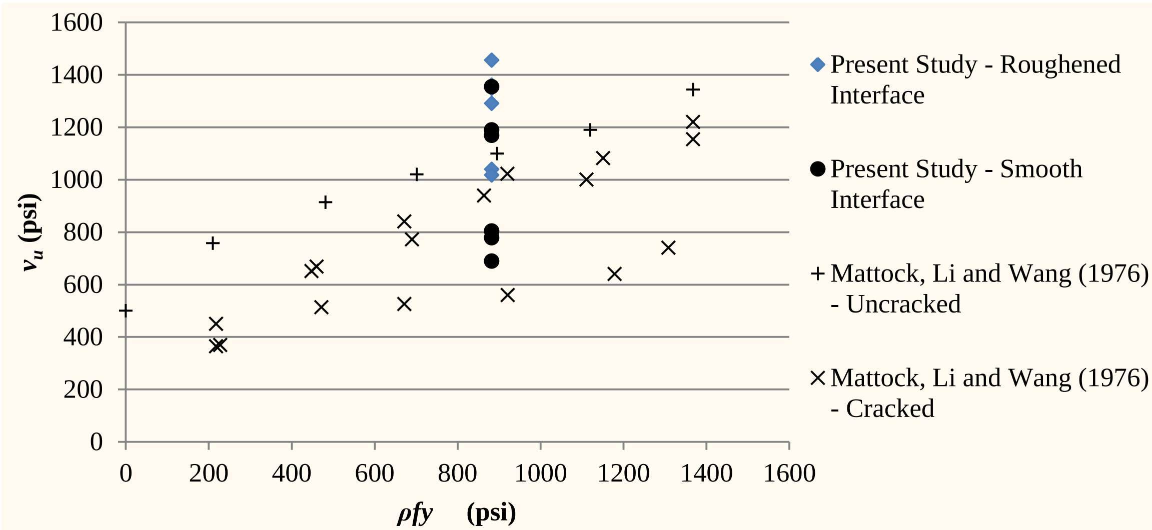

Fig. 14 Comparison of shear strength v_u for specimens with different interface conditions for sand-lightweight concrete

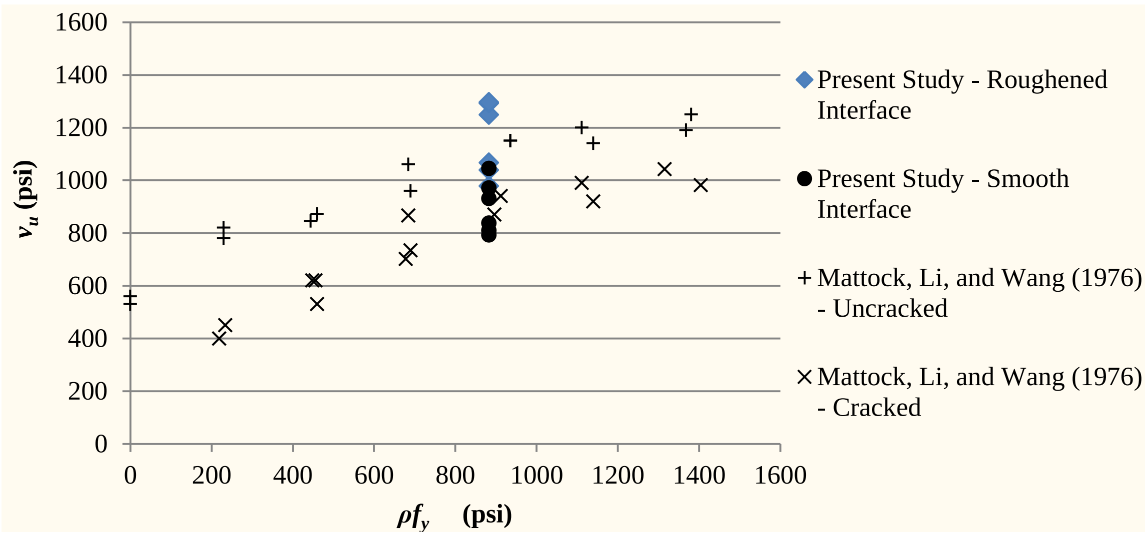

Fig. 15 Comparison of shear strength v_u for specimens with different interface conditions for all-lightweight concrete

Figure 16 compares the shear strength v_u of the sand-lightweight and all-lightweight concrete specimens with a roughened interface condition with Equation 2. It should be noted that in comparisons with Equation 2 and design provisions in the ACI 318[8] code and the PCI Design Handbook[9], the strength reduction factor ϕ was taken as 1.0 since the loads and material properties were known. The solid line in the figure represents the results of Equation 2 computed for a roughened interface condition (0.25 in. amplitude) corresponding to Case 2 in Table 1. For Case 2, Equation 2 is limited to 800 psi in the ACI 318[8] code, and to 1000λ psi in the PCI Design Handbook[9] as shown in the figures. Values of λ were taken as 0.85 and 0.75 for sand-lightweight and all-lightweight concrete, respectively. Results in Figure 16 show that the measured shear strength was significantly larger than the value computed by

Equation 2 for the sand-lightweight and all-lightweight specimens with a roughened interface computed by both the ACI 318[8] code and the PCI Design Handbook[9]. Therefore the shear friction design provisions for Case 2 interface condition in Table 1 are conservative for the sand-lightweight and all-lightweight specimens in this study.

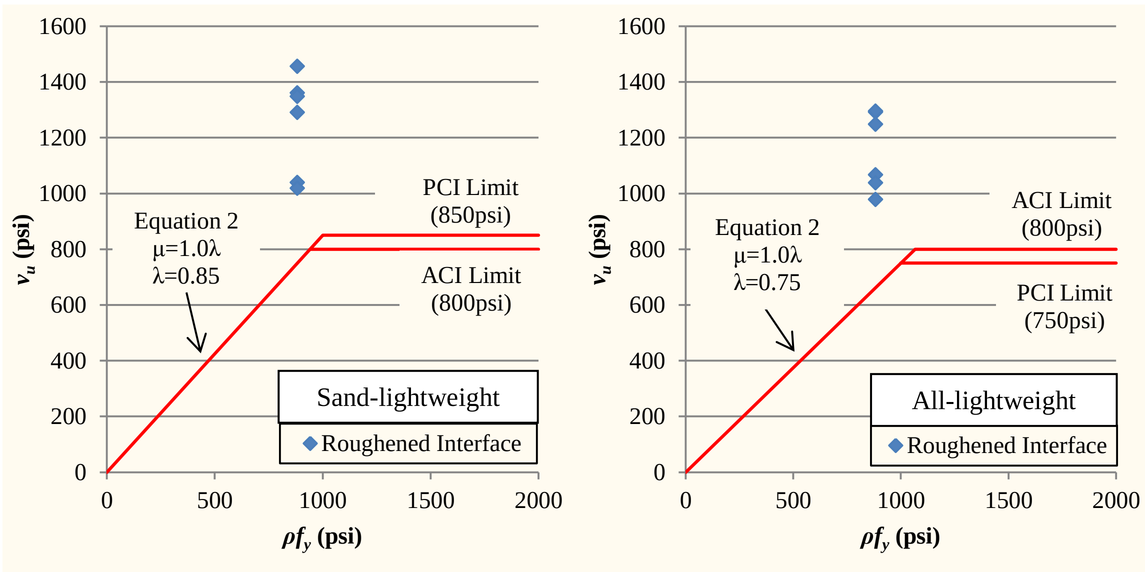

Fig. 16 Comparison of shear strength v_u with Equation 2 for sand-lightweight concrete specimens (left) and all-lightweight concrete specimens (right) with a roughened interface

Figure 17 compares shear strength v_u of the sand-lightweight and all-lightweight concrete specimens with a smooth interface condition with Equation 2. The solid line in the figure represents the results of Equation 2 computed for an interface that is not intentionally roughened corresponding to Case 3 in Table 1. For Case 3, Equation 2 is limited to 800 psi in the ACI 318[8] code and to 800λ psi in the PCI Design Handbook[9] as shown in the figures. Results in Figure 17 show that the measured shear strength was significantly larger than the value computed by Equation 2 for the sand-lightweight and all-lightweight specimens with a smooth interface computed by both the ACI 318[8] code and the PCI Design Handbook[9]. Therefore the shear friction design provisions for Case 3 interface condition in Table 1 are conservative for the sand-lightweight and all-lightweight specimens with a smooth interface in this study.

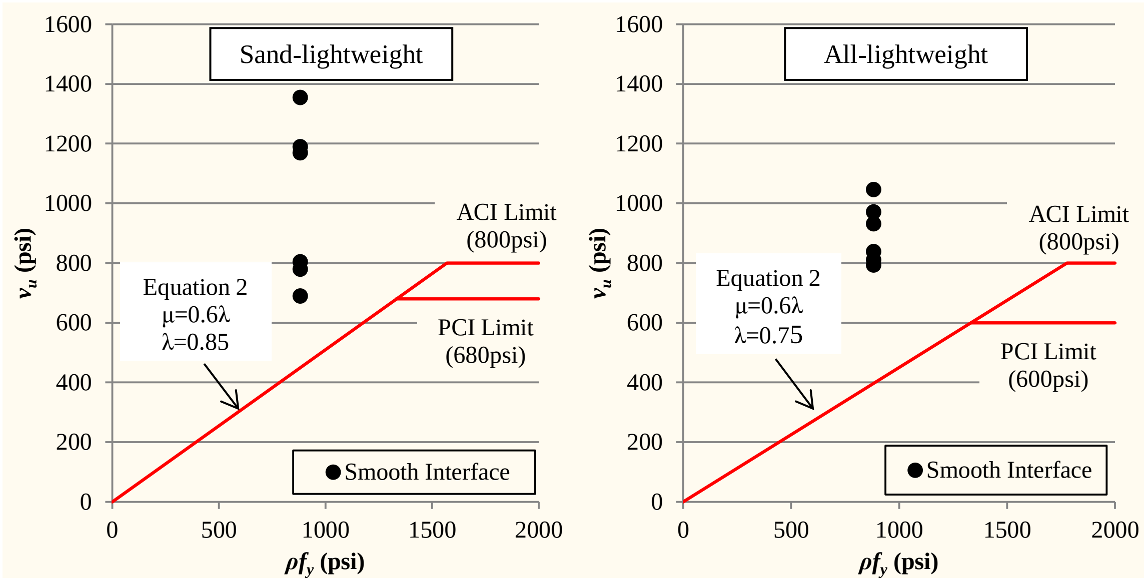

Fig. 17 Comparison of shear strength v_u with Equation 2 for sand-lightweight concrete specimens (left) and all-lightweight concrete specimens (right) with a smooth interface

CONCLUSIONS

Test results of 36 pushoff specimens were described in this paper to investigate the applicability of the shear friction concept for lightweight aggregate concretes with a cold-joint condition at the shear interface. Based on the results of this study, the following conclusions can be made:

1. Specimens with the same interface condition, same percentage of reinforcement, and concrete compressive strength had nearly the same shear strength v_u irrespective of concrete unit weight (concrete type). These results suggest that concrete type did not play a significant role in the interface shear strength for the cold-joint specimens in this study.
2. The shear strength of specimens with a smooth interface was found to be dependent upon concrete compressive strength. The shear strength of specimens with a roughened interface appeared to be independent of concrete compressive strength.
3. The shear strength increased with increasing concrete compressive strength.
4. The residual shear strength was found to be insensitive to concrete type, concrete compressive strength, and interface condition.
5. Shear strengths computed by the ACI 318[8] code and the PCI Design Handbook[9] were conservative for the sand-lightweight and all-lightweight specimens cold-joint specimens in this study.

RECOMMENDATIONS FOR FUTURE WORK

For the specimens tested in this study, a single reinforcement ratio was considered. Further investigation is needed for all-lightweight concrete and sand-lightweight concrete cold-joint specimens with different reinforcement ratios. Additional study is also recommended to determine whether type of lightweight aggregate plays a role in the shear transfer strength for different interface conditions.

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