Interface shear transfer of lightweight-aggregate concretes cast at different times

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- This study examined the direct shear transfer across an interface of all-lightweight and sand-lightweight concretes cast at different times.
- The investigation included 36 push-off specimens constructed with a cold joint along the shear plane. Test variables included concrete unit weight and compressive strength and surface preparation of the shear interface.
- Results suggest that concrete unit weight did not play a significant role in the shear strength of the specimens in this study.
- Shear strengths computed using the shear friction design provisions in the *Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI 318R-11)* and *PCI Design Handbook: Precast and Prestressed Concrete* were conservative.

The 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 effects on shear transfer strength.[1–7] The shear friction design provisions presented in American Concrete Institute's (ACI'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* (seventh 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 (that is, cold-joint conditions).

Current ACI 318-11 and *PCI Design Handbook* shear friction design provisions present a similar approach in which the nominal shear strength (force) V_n is computed as

Table 1. Coefficient of friction and maximum shear strength for different interface conditions

Case	Crack interface condition	μ	ACI 318-11 maximum V_n*	*PCI Design Handbook* maximum V_u/ϕ*
1	Concrete to concrete, cast monolithically	1.4λ	For normalweight concrete: $0.2f'_cA_c \le (480 + 0.08f'_c)A_c \le 1600A_c$ For all other cases: $0.2\,f'_cA_c \le 800A_c$	$0.30\lambda f'_cA_{cr} \le 1000\lambda A_{cr}$
2	Concrete to hardened concrete with roughened surface	1.0λ		$0.25\lambda f'_cA_{cr} \le 1000\lambda A_{cr}$
3	Concrete placed against hardened concrete not intentionally roughened	0.6λ	$0.2\,f'_cA_c \le 800A_c$	$0.20\lambda f'_cA_{cr} \le 800\lambda A_{cr}$
4	Concrete to steel	0.7λ		$0.20\lambda f'_cA_{cr} \le 800\lambda A_{cr}$

* The equations presented are in units of lb-in.

Note: $A_c = A_{cr}$ = area of concrete shear interface; f'_c = 28-day concrete compressive strength (also at test day); V_n = nominal shear force; V_u = ultimate shear force; λ = modification factor reflecting the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength; μ = coefficient of friction; ϕ = strength reduction factor.

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:

$V_n = \mu A_{vf} f_y$ (11-25)[8] and (5-32a)[9]

In Eq. (11-25) and (5-32a), 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 (**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] Table 1 also summarizes upper limits on the shear strength for the ACI 318-11 and *PCI Design Handbook* shear friction design provisions.

An alternative approach to designing the shear friction reinforcement is presented in the *PCI Design Handbook* in which μ in Eq. (5-32a) 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 Eq. (11-25) and (5-32a) can also be expressed in terms of nominal shear stress v_n (Eq. [1]):

$v_n = \mu\rho f_y$ (1)

ρ = shear friction reinforcement ratio = A_{vf}/A_c

A_c = area of the shear plane

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 the shear friction of lightweight aggregate concretes with a cold-joint condition. This condition can be the result of precasting 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, **Fig. 1** (upper and lower) shows precast concrete column corbels that have been cast in advance of the supporting precast concrete column element and two distinctly different shear interface conditions in terms of surface roughness. Figure 1 (center) shows the corbel in place. The *PCI Design Handbook* also notes that the use of self-consolidating concrete 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 with those from normalweight concrete of the same strength and interface condition.

Experimental program

The experimental program included 36 push-off specimens used to investigate 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 ACI 318-11. **Table 2** shows the test matrix. Target unit weights (densities) of fresh concrete were 145, 120, and 108 lb/ft^3 (2320, 1920, and 1730 kg/m^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. The target compressive strength

Cast corbel at precasting facility

Corbel in place

Corbel casting at precasting facility

Figure 1. Precast concrete column corbels cast in advance of supporting precast concrete column element.

Table 2. Test matrix and series designation

Concrete type and target unit weight	Target concrete compressive strength, psi	Shear interface condition	Series designation
Normalweight, 145 lb/ft^3	5000	Roughened	N-5-R
		Smooth	N-5-S
	8000	Roughened	N-8-R
		Smooth	N-8-S
Sand-lightweight, 120 lb/ft^3	5000	Roughened	S-5-R
		Smooth	S-5-S
	8000	Roughened	S-8-R
		Smooth	S-8-S
All-lightweight, 108 lb/ft^3	5000	Roughened	A-5-R
		Smooth	A-5-S
	8000	Roughened	A-8-R
		Smooth	A-8-S

Note: 1 ft = 0.305 m; 1 lb = 4.448 N; 1 psi = 6.895 kPa.

of concrete was either 5000 or 8000 psi (34 or 55 MPa). Interface condition was either roughened (0.25 in. [6 mm] 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 with previous tests. The shear plane was 11.0 in. (280 mm) long and 4.5 in. (110 mm) wide, with an area of shear plane A_c of 49.5 in.^{2} (32,000 mm^2). Shear reinforcement consisting of three no. 3 (10M) 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 (456 MPa). **Figure 2** shows test specimen dimensions and reinforcement.

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] The coarse aggregate grading used was selected to consist of 100% passing a $^1/_2$ in. (13 mm) sieve and less than 5% passing a no. 8 sieve (2.4 mm). The sand-lightweight concrete comprised a lightweight expanded shale coarse aggregate with an ASTM C330[12] blended grading with 100% passing a $^1/_2$ in. sieve and less than 10% passing a no. 8 sieve. The fine aggregate was the same natural sand used in the normalweight concrete. The all-lightweight concrete consisted of an ASTM C330 structural aggregate gradation containing lightweight expanded shale aggregate with 100% passing a ½ in. sieve with 100% retained on the pan. No normalweight sands were used in the production of the all-

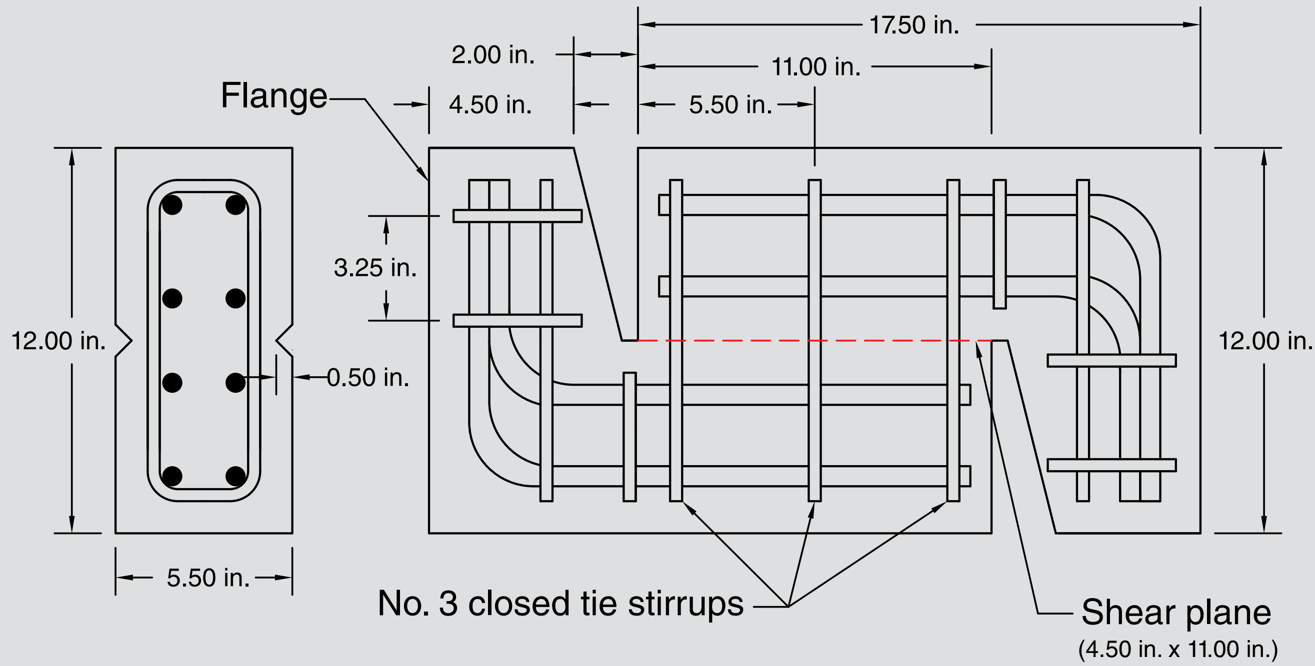

Figure 2. Test specimen. Note: dimensions shown in figure are measured to nearest 0.25 in. No. 3 = 10M; 1 in. = 25.4 mm.

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. Additional information about the lightweight aggregate gradings and properties is summarized by Sneed and Shaw.[13] For each concrete type, Type I/II portland cement was used with water-cement ratios ranging from 0.40 to 0.60. A high-range water-reducing admixture was used in the 8000 psi (55 MPa) concrete mixtures to reduce the water demand. **Table 3** summarizes properties of the concrete mixtures. Values of concrete density reported in Table 3 correspond to the unit weights measured on the fresh concrete. The properties of the hardened concrete presented in Table 3 include the 28-day compressive strength f'_c, splitting tensile strength f_t, and modulus of elasticity E_c.

Specimens were constructed with custom-built formwork to facilitate production of the cold joint along the shear plane. **Figure 3** shows the concrete was placed with the cold joint oriented horizontally. 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. The surface

Table 3. Concrete properties

Concrete mixture	Density of plastic concrete, lb/ft^3	Target f'_c, psi	f'_c,* psi	f'_c at test day,* psi	f_t,† psi	E_c,‡ psi
Normalweight, 5000 psi	145.0	5000	4860	4860	420	3.70×10^6
Normalweight, 8000 psi	144.0	8000	7550	7550	540	3.80×10^6
Sand lightweight, 5000 psi	118.0	5000	4600	4600	320	3.65×10^6
Sand lightweight, 8000 psi	118.0	8000	7200	7200	510	3.75×10^6
All lightweight, 5000 psi	108.0	5000	6080	6080	510	2.90×10^6
All lightweight, 8000 psi	109.0	8000	7840	7840	520	3.30×10^6

*ASTM C1231
†ASTM C496
‡ASTM C469
Note: E_c = modulus of elasticity of concrete; f'_c = 28-day concrete compressive strength (also at test day); f_t = splitting tensile strength. 1 ft = 0.305 m; 1 lb = 0.454 kg; 1 psi = 6.895 kPa.

Figure 3. Test specimen casting.

roughness was measured using a digital caliper at 10 locations on the shear interface. The average value of measured scoring line depth, that is, its measure of roughness, ranged from 0.245 to 0.260 in. (6.2 to 6.6 mm) 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. This amount of time was selected to provide enough time to allow formation of the cold joint but to minimize differences in concrete compressive strengths at test date.

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. (0.38 mm) per minute. An external confinement system was added to the top and bottom flanges of the specimens to prevent 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 gauges were attached to one leg of each stirrup crossing the shear plane. **Figure 4** shows the test setup and instrumentation.

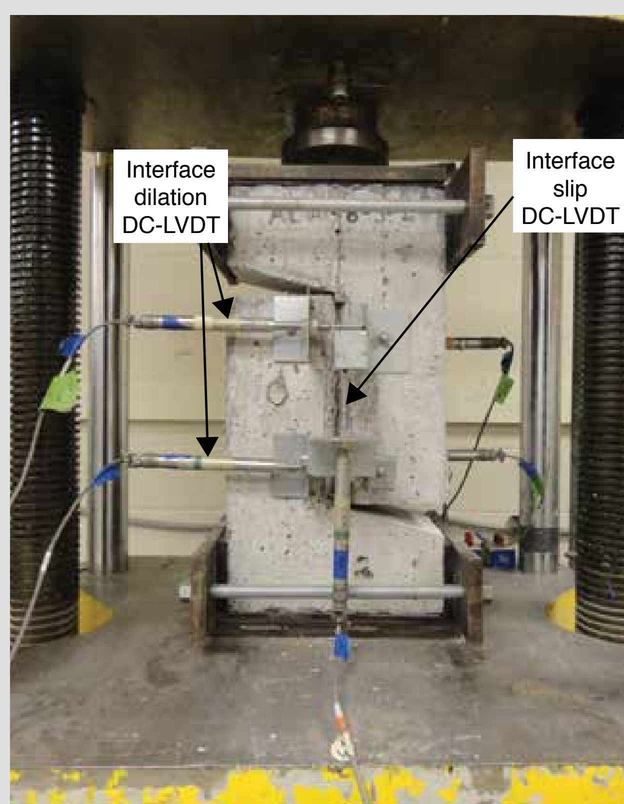

Figure 4. Test setup and instrumentation. Note: DC-LVDT = direct current linear variable displacement transducer.

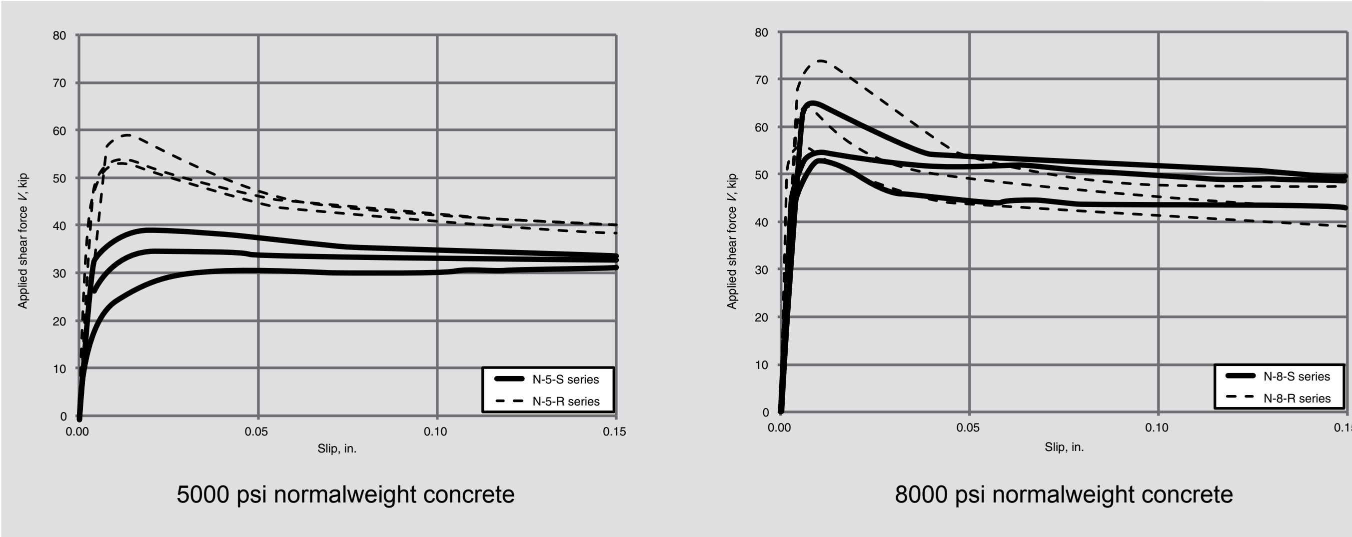

Figure 5. Applied shear force *V*–slip relations for normalweight concrete specimens. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 psi = 6.895 kPa.

Results and discussion

This section summarizes and discusses the test results. Additional information is included in Sneed and Shaw. [13]

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. In addition to cracking of the shear interface, spalling of the concrete cover was observed adjacent to the shear plane crack for many specimens.

Figures 5, 6, and **7** show applied shear force *V*–slip relations for the normalweight, sand-lightweight, and all-lightweight series specimens, respectively. The figures show 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 ultimate 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. In other words, after the peak shear force was achieved, the shear force decreased more rapidly with increasing slip, though the residual strength

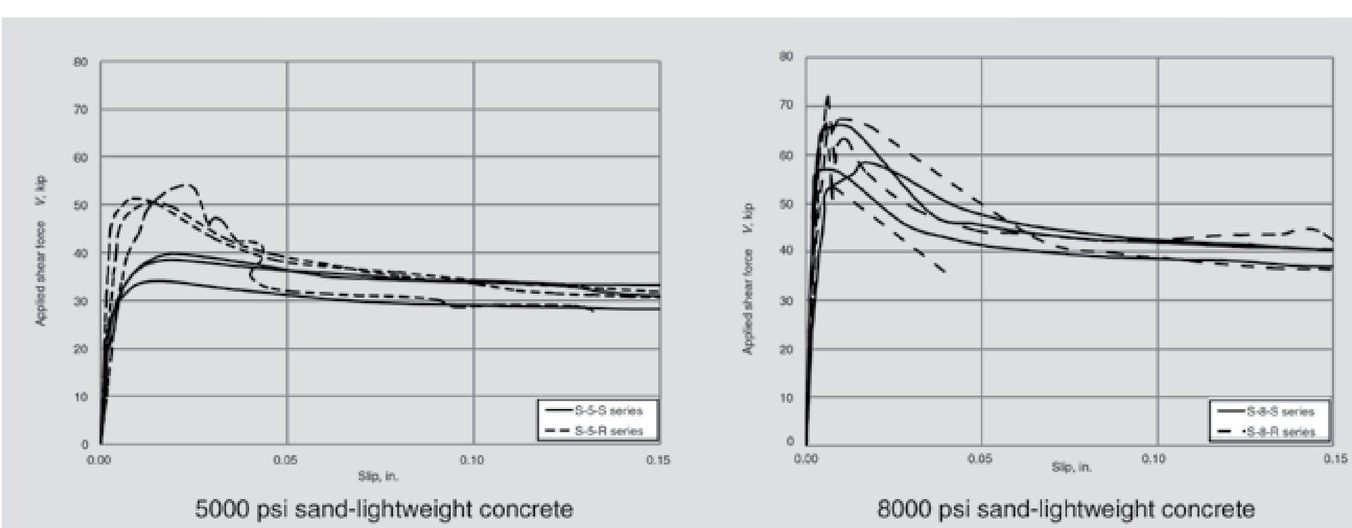

Figure 6. Applied shear force *V*–slip relations for sand-lightweight concrete specimens. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 psi = 6.895 kPa.

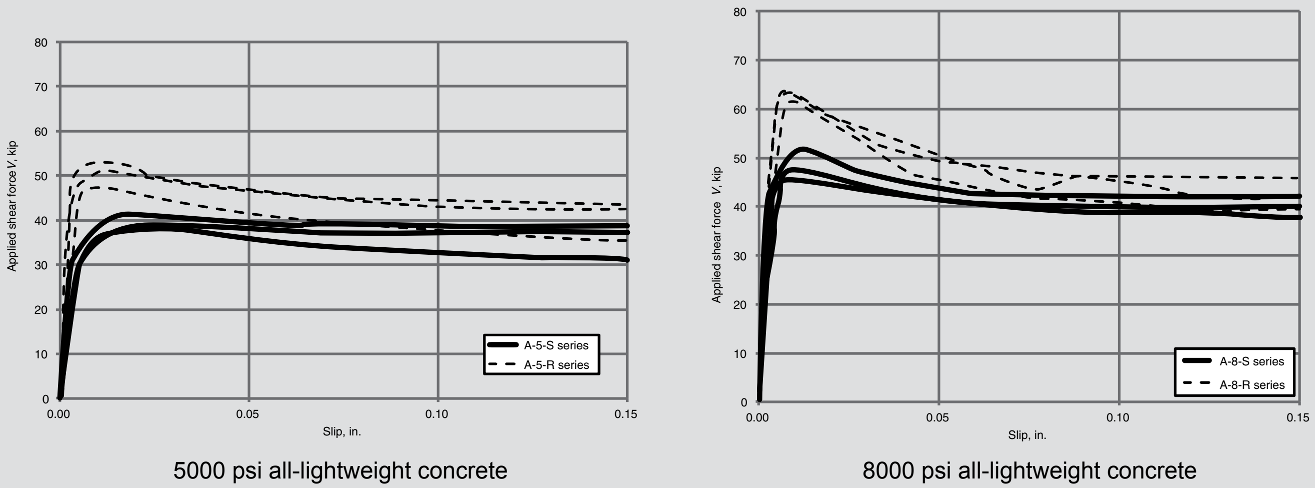

Figure 7. Applied shear force V–slip relations for all-lightweight concrete specimens. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 psi = 6.895 kPa.

was similar to that of the corresponding specimens with a smooth interface.

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., 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 and possibly the relative strengths of paste and aggregate used in the production of the lightweight aggregate concretes in the different studies. This highlights the need to examine lightweight concrete mixtures with different types of aggregates.

Shear strength

Table 4 summarizes results of each test specimen. Specimen designation is given by the following notation: the first value indicates the concrete type (N = normalweight, S = sand-lightweight, and A = all-lightweight), the second value indicates the target compressive strength of concrete in units of ksi, the third value indicates the interface condition (S = smooth and R = roughened), and the fourth value indicates the specimen number in the test series. In the table, V_u is the ultimate (peak) shear force measured during testing; v_u is the ultimate (peak) shear stress measured during testing, which is V_u divided by the area of the shear plane A_c (49.5 in^2 [32,000 mm^2]); V_{ur} is the residual shear force corresponding to a slip of 0.15 in. (0.38 mm); and residual shear strength v_{ur} is the residual shear stress, which is V_{ur} divided by the area of the shear plane A_c. Table 4 also reports values of slip and dilation of the shear plane measured at the peak shear force. Values reported are the average of the DC-LVDT measurements from both sides of the test specimen. Specimens N-5-R-1, 2, and 3 and N-5-S-1, 2, and 3 are not included in the table because premature failure occurred within the flanges of these specimens. (Flanges are indicated in Fig. 2.)

In **Fig. 8**, ultimate shear stress 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 by solid markers in the figure. Considering the average values for each series, the data in Fig. 8 show that specimens with the same interface condition and concrete compressive strength had nearly the same ultimate shear stress 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 (1) indicates that the nominal shear stress 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. Because specimens with the same interface condition and concrete compressive strength had approximately the same ultimate shear stress v_u, Eq. (1) suggests that the value of μ was approximately the same, irrespective of concrete type. In addition, for each specimen, the value of μ computed by Eq. (11-25), (5-32a), and (1), 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.

As expected, Fig. 8 also shows that the average values of v_u for specimens with a roughened interface are larger than

Table 4. Summary of test results										
Specimen	f'_c at test day, psi	V_u, lb	v_u, psi	Average v_u, psi	Slip at V_u, in.	Dilation at V_u, in.	V_{ur}, lb	v_{ur}, psi	Average v_{ur}, psi	Average $\frac{v_u}{V_{ur}}$
N-5-R-4	4860	59,060	1190		0.013	0.007	39,470	800		
N-5-R-5	4860	53,420	1080	1115	0.010	0.006	40,140	810	790	1.41
N-5-R-6	4860	53,440	1080		0.012	0.007	38,360	770		
N-5-S-4	4860	32,705	660		0.057	0.015	38,150	770		
N-5-S-5	4860	34,678	700	717	0.030	0.008	31,150	630	682	1.05
N-5-S-6	4860	39,154	790		0.031	0.007	32,000	650		
S-5-R-1	4550	51,431	1040		0.010	0.007	30,500	620		
S-5-R-2	4550	50,396	1020	1049	0.014	0.008	29,600	600	603	1.74
S-5-R-3	4550	53,904	1090		0.022	0.007	29,300	590		
S-5-S-1	4550	38,532	780		0.019	0.006	33,200	670		
S-5-S-2	4550	34,112	690	757	0.016	0.003	27,900	560	610	1.24
S-5-S-3	4550	39,796	800		0.021	0.007	29,500	600		
A-5-R-1	6080	48,439	980		0.010	0.005	35,000	710		
A-5-R-2	6080	52,797	1070	1030	0.011	0.005	43,000	870	800	1.29
A-5-R-3	6080	51,408	1040		0.013	0.004	40,500	820		
A-5-S-1	6080	41,471	840		0.021	0.006	38,500	780		
A-5-S-2	6080	40,079	810	813	0.023	0.005	32,000	650	727	1.13
A-5-S-3	6080	39,247	790		0.032	0.007	37,000	750		
N-8-R-1	7550	74,040	1500		0.010	0.008	47,500	960		
N-8-R-2	7550	56,090	1130	1310	0.008	0.005	39,050	790	873	1.50
N-8-R-3	7550	64,140	1300		0.007	0.005	43,000	870		
N-8-S-1	7550	65,572	1320		0.010	0.006	49,500	1000		
N-8-S-2	7550	53,305	1080	1173	0.010	0.005	42,950	870	937	1.25
N-8-S-3	7550	55,327	1120		0.001	0.006	46,695	940		
S-8-R-1	7210	72,045	1460		0.007	0.006	43,660	880		
S-8-R-2	7210	67,380	1360	1390	0.010	0.006	36,300	730	805	1.76
S-8-R-3	7210	66,725	1350		0.006	0.005	n/a	n/a		
S-8-S-1	7210	67,025	1350		0.007	0.006	40,480	820		
S-8-S-2	7210	57,876	1170	1237	0.005	0.003	36,970	750	793	1.56
S-8-S-3	7210	58,863	1190		0.018	0.007	40,340	810		
A-8-R-1	7845	61,774	1250		0.009	0.003	41,330	830		
A-8-R-2	7845	63,937	1290	1280	0.008	0.007	45,800	930	853	1.51
A-8-R-3	7845	64,126	1300		0.009	0.006	39,450	800		
A-8-S-1	7845	46,090	930		0.011	0.004	37,790	760		
A-8-S-2	7845	48,035	970	983	0.012	0.006	40,185	810	807	1.22
A-8-S-3	7845	51,740	1050		0.012	0.004	42,140	850		

Note: f'_c = 28-day concrete compressive strength (also at test day); n/a = not applicable; v_u = ultimate shear stress; v_{ur} = residual shear stress; V_u = ultimate shear force; V_{ur} = residual shear force. 1 in. = 25.4 mm; 1 lb = 0.454 kg; 1 psi = 6.895 kPa.

those with a smooth interface for the same concrete compressive strength and same unit weight. The applied shear force–slip responses in Fig. 5, 6, and 7 also illustrate that specimens with a roughened interface (the dashed lines in the figures) have a higher ultimate 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.

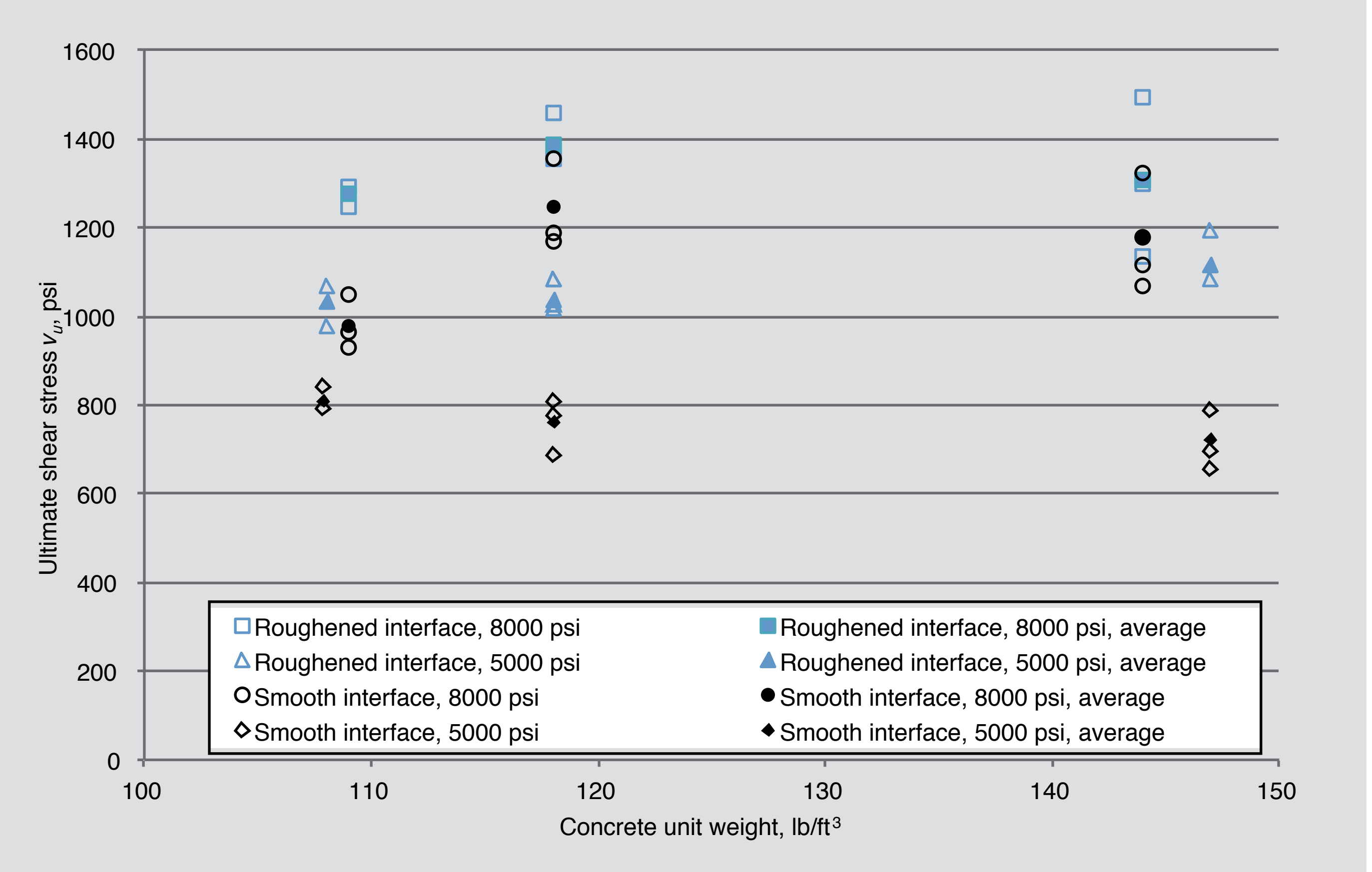

Figure 8. Comparison of ultimate shear stress v_u versus concrete unit weight. Note: 1 ft = 0.305 m; 1 lb = 0.454 kg; 1 psi = 6.895 kPa.

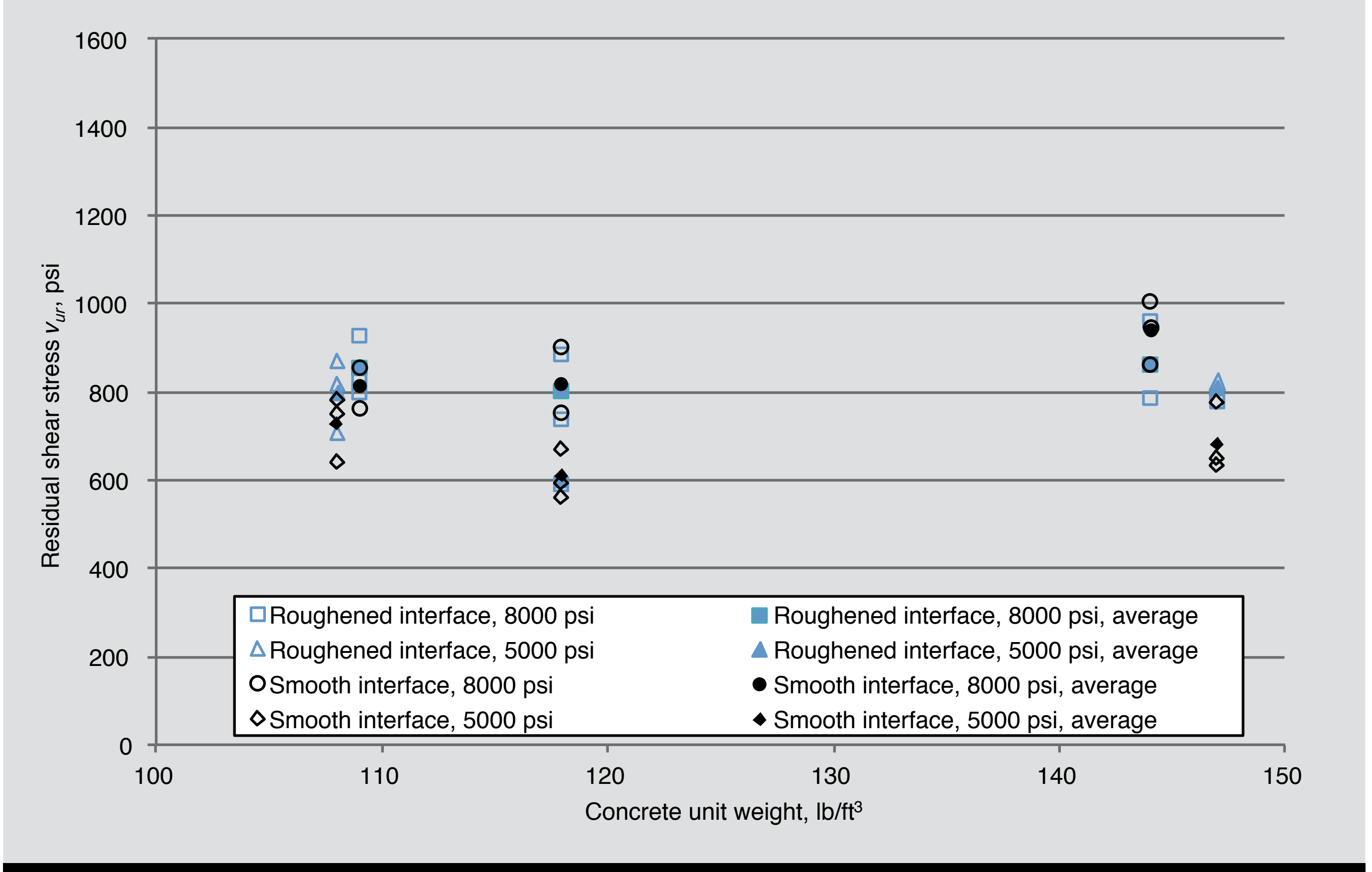

Figure 9. Comparison of residual shear stress v_{ur} versus concrete unit weight. Note: 1 ft = 0.305 m; 1 lb = 0.454 kg; 1 psi = 6.895 kPa.

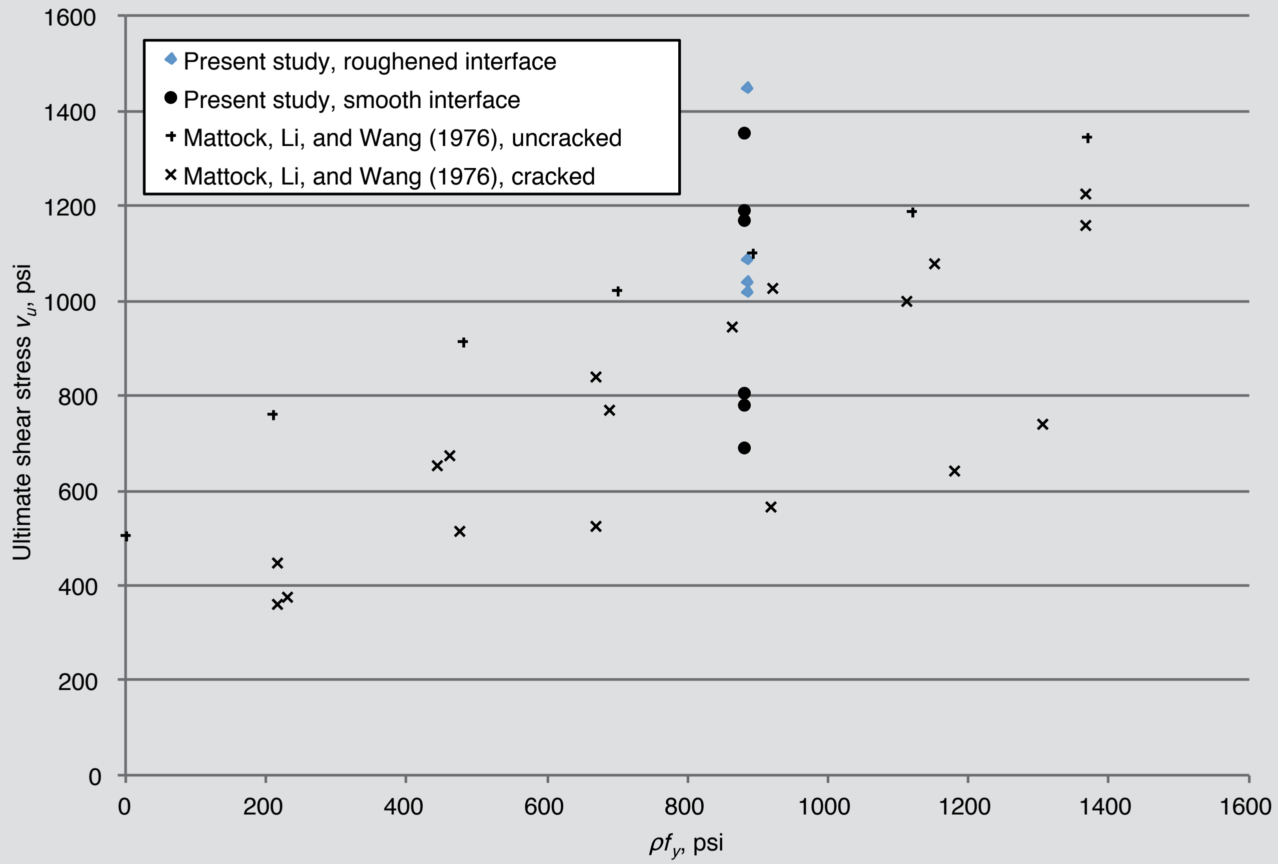

Figure 10. Comparison of ultimate shear stress v_u for specimens with different interface conditions for sand-lightweight concrete. Note: f_y = yield stress of reinforcement; ρ = shear friction reinforcement ratio. 1 psi = 6.895 kPa.

Figure 8 also shows that the average values of v_u for specimens with 8000 psi (55 MPa) concrete are larger than those with 5000 psi (34 MPa) 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. The results of this study are consistent with their findings.

The residual shear stress v_{ur} can be used to compare the post-yield capacity of the specimens. **Figure 9** shows the residual shear stress v_{ur} plotted versus concrete unit weight for the specimens tested in this study, maintaining the distinction between the specimens with different interface conditions and concrete compressive strengths. Average values for each series are shown by solid markers in the figure. Considering the average values for each series, the data in Fig. 9 show that the residual shear strength v_{ur} was approximately the same for all specimens irrespective of concrete unit weight (concrete type) and interface condition. These results are similar to those of 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.

Table 4 shows that the ratio of the ultimate shear stress to the residual shear stress v_u/v_{ur} ranged from 1.29 to 1.76 for all specimens with a roughened interface. No clear trend was observed with respect to concrete type or compressive strength. For specimens with a smooth interface, v_u/v_{ur} ranged from 1.05 to 1.24 for the 5000 psi (34 MPa) specimens and from 1.22 to 1.56 for the 8000 psi (55 MPa) specimens. The slightly larger v_u/v_{ur} ratios for the 8000 psi smooth interface specimens compared with the 5000 psi smooth interface specimens indicate the more brittle behavior of the higher-strength specimens noted previously, which may be due to differences in cohesion among the different concrete mixtures.

Figures 10 and **11** compare the ultimate shear stress v_u for the specimens in this study with previous data from the literature on sand-lightweight and all-lightweight concrete (Mattock et al.[5]), respectively. The specimens tested by Mattock at al. were cast monolithically, and some specimens were precracked prior to testing (indicated in the figure). Also, the specimens by Mattock et al. had a measured compressive strength of concrete from 2000 to

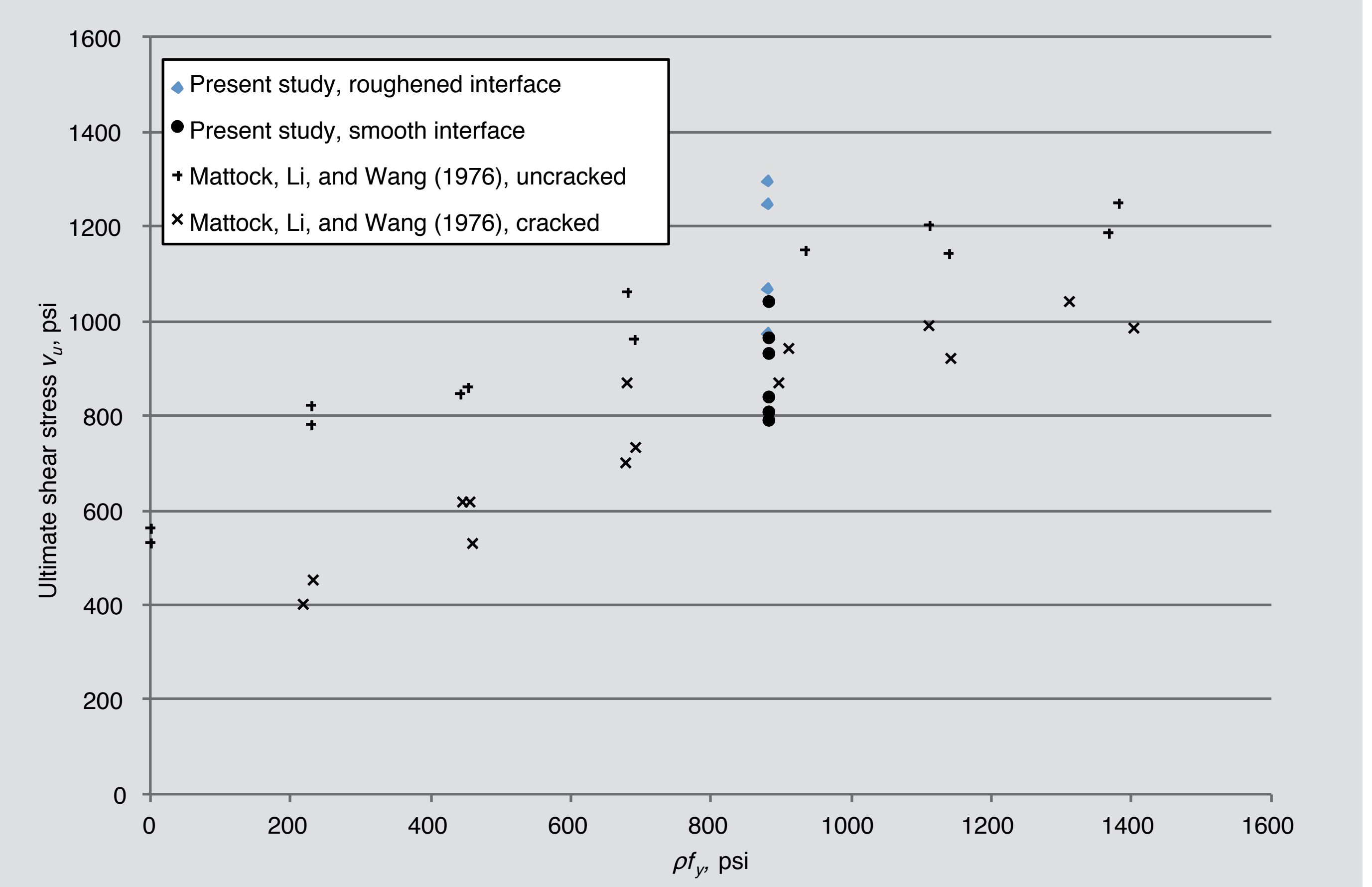

Figure 11. Comparison of ultimate shear stress v_u for specimens with different interface conditions for all-lightweight concrete. Note: f_y = yield stress of reinforcement; ρ = shear friction reinforcement ratio. 1 psi = 6.895 kPa.

6000 psi (14 to 41 MPa), which is similar to those tested in this study (approximately 4600 to 8000 psi [32 to 55 MPa]). In Fig. 10, the sand-lightweight concrete specimens in the Mattock et al. precracked series with relatively low ultimate shear stress v_u correspond to specimens with lower concrete compressive strength (2000 to 2330 psi, series C in Mattock et al.).[5] Unit weights reported by Mattock et al. were dry unit weights (equilibrium); however, calculation based on batch quantities indicates that the wet (fresh) unit weights were approximately 120 and 110 lb/ft^3 (1900 and 1800 kg/m^3) for the sand-lightweight and all-lightweight concretes produced. Results show that the shear strengths of the sand-lightweight and all-lightweight specimens in this study are consistent with specimens by Mattock et al. Interestingly, the cold-joint specimens in this study with a smooth interface had an ultimate shear stress v_u similar to specimens that were monolithic and precracked. Similarly, the cold-joint specimens with a roughened interface had an ultimate shear stress v_u similar to specimens that were monolithic and uncracked.

Figure 12 compares the ultimate shear stress v_u of the sand-lightweight and all-lightweight concrete specimens with a roughened interface with Eq. (1). In comparison with Eq. (1) and design provisions in ACI 318-11 and the *PCI Design Handbook*, the strength reduction factor ϕ was taken as 1.0 because the applied loads and material properties were known. The solid line in the figure represents the results of Eq. (1) computed for a roughened interface condition (0.25 in. [6 mm] amplitude) corresponding to case 2 in Table 1. For case 2, Eq. (1) is limited to 800 psi (6 MPa) in ACI 318-11, and to 1000λ psi (7λ MPa) in the *PCI Design Handbook* (Fig. 12 and Table 1). Values of λ were taken as 0.85 and 0.75 for sand-lightweight and all-lightweight concrete, respectively. Results in Fig. 12 show that the measured shear strength of the sand-lightweight and all-lightweight specimens with a roughened interface was significantly greater than the value computed by Eq. (1) using both ACI 318-11 and the *PCI Design Handbook*. 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.

Figure 13 compares the ultimate shear stress v_u of the sand-lightweight and all-lightweight concrete specimens with a smooth interface condition with Eq. (1). The solid line in the figure represents the results of Eq. (1) computed for an interface that is not intentionally roughened corresponding to case 3 in Table 1. For case 3, Eq. (1) is limited to 800 psi (6 MPa) in ACI 318-11 and to 800λ psi (6λ MPa) in the *PCI Design Handbook* (Fig. 13 and Table 1). Results in Fig. 13 show that the measured shear strength of the

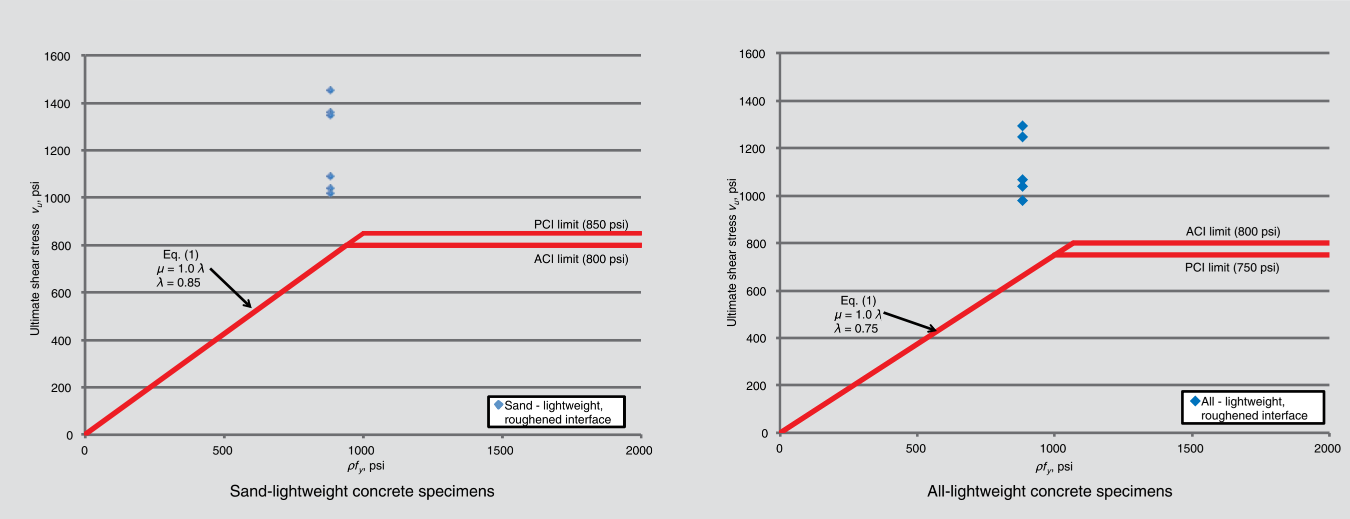

Figure 12. Comparison of ultimate shear stress v_u with Eq. (1) for specimens with a roughened interface. Note: f_y = yield stress of reinforcement; λ = modification factor reflecting the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength; μ= coefficient of friction; ρ = shear friction reinforcement ratio. 1 psi = 6.895 kPa.

sand-lightweight and all-lightweight specimens with a smooth interface was significantly greater than the value predicted by Eq. (1) using both ACI 318-11 and the *PCI Design Handbook*. 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.

As mentioned previously, the interface shear strength for the cold-joint specimens in this study was not significantly influenced by concrete type. In fact, if the value of λ in Eq. (1) was taken as 1.0 (indicating no reduction in shear transfer strength of the sand-lightweight and all-lightweight concretes relative to normalweight concrete), the measured shear strengths of the sand-lightweight and all-lightweight specimens in this study were still greater than the value predicted by Eq. (1).

Conclusion

Test results of 36 push-off 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:

- Specimens with the same interface condition, percentage of reinforcement, and concrete compressive strength had nearly the same shear strength 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.

- The shear strength was found to be dependent on

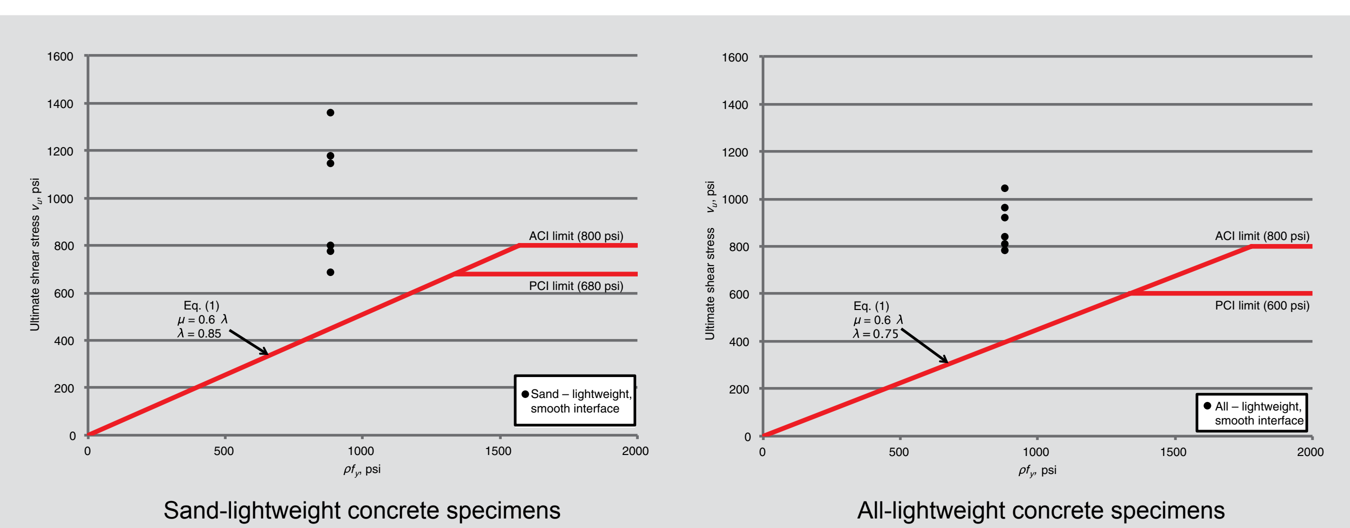

Figure 13. Comparison of ultimate shear stress v_u with Eq. (1) for specimens with a smooth interface. Note: f_y = yield stress of reinforcement; λ = modification factor reflecting the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength; μ = coefficient of friction; ρ = shear friction reinforcement ratio. 1 psi = 6.895 kPa.

concrete compressive strength. The shear strength increased with increasing concrete compressive strength.

- The residual shear strength was found to be insensitive to concrete type and interface condition.

- Shear strengths computed by ACI 318-11 and the *PCI Design Handbook* were conservative for the sand-lightweight and all-lightweight cold-joint specimens in this study, even if the value of the lightweight modification factor λ is taken as 1.0 (indicating no reduction in shear transfer strength of the sand-lightweight and all-lightweight concretes relative to normalweight concrete).

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 the type of lightweight aggregate plays a role in the shear transfer strength for different interface conditions.

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References

1. Anderson, A. R. 1960. "Composite Designs in Precast and Cast-in-Place Concrete." *Progressive Architecture* 41 (9): 172–179.

2. Hofbeck, J. A., I. O. Ibrahim, and A. H. Mattock. 1969. "Shear Transfer in Reinforced Concrete." *Journal of the American Concrete Institute* 66 (2): 119–128.

3. Mattock, A. H., and N. M. Hawkins. 1972. "Shear Transfer in Reinforced Concrete—Recent Research." *PCI Journal* 17 (2): 55–75.

4. Mattock, A. H. 1976. "Shear Transfer Under Monotonic Loading Across and Interface Between Concretes Cast at Different Times." Report SM 76-3. Seattle, WA: University of Washington Department of Civil Engineering.

5. Mattock, A. H., W. K. Li, and T. C. Wang. 1976. "Shear Transfer in Lightweight Reinforced Concrete." *PCI Journal* 21 (1): 20–39.

6. Walraven, J., and J. Stroband. 1994. "Shear Friction in High-Strength Concrete." American Concrete Institute (ACI) Special Publication, SP-42, pp. 311-330. Farmington Hills, MI: ACI.

7. Kahn, L. F., and A. D. Mitchell. 2002. "Shear Friction Tests with High-Strength Concrete." *ACI Structural Journal* 99 (1): 98–103.

8. ACI Committee 318. 2011. *Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI 318R-11)*. Farmington Hills, MI: ACI.

9. PCI Industry Handbook Committee. 2010. *PCI Design Handbook: Precast and Prestressed Concrete*. 7th ed. Chicago, IL: PCI.

10. ASTM A615. 2012. *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. West Conshohocken, PA: ASTM International.

11. ASTM C33. 2013. *Standard Specification for Concrete Aggregates*. West Conshohocken, PA: ASTM International.

12. ASTM C330. 2009. *Standard Specification for Lightweight Aggregates for Structural Concrete*. West Conshohocken, PA: ASTM International.

13. Sneed, L. H., and D. M. Shaw. 2013. "Lightweight Concrete Modification Factor for Shear Friction." Report NUTC R276/R317. Rolla, MO: Center for Transportation Infrastructure and Safety/NUTC Program, Missouri University of Science and Technology.

14. ASTM C1231. 2012. *Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Concrete Cylinders*. West Conshohocken, PA: ASTM International.

15. ASTM C469. 2010. *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. West Conshohocken, PA: ASTM International.

16. ASTM C496. 2011. *Standard Test Method for Split-*

ting Tensile Strength of Cylindrical Concrete Specimens. Conshohocken, PA: ASTM International.

Notation

A_c = area of concrete shear interface

A_{cr} = area of concrete shear interface

A_{vf} = area of shear reinforcement across shear plane

E_c = modulus of elasticity of concrete

f'_c = 28-day concrete compressive strength (also at test day)

f_t = splitting tensile strength

f_y = yield strength of reinforcement

v_n = nominal shear stress

v_u = ultimate shear stress

v_{ur} = residual shear stress

V = shear force

V_n = nominal shear force

V_u = ultimate shear force

V_{ur} = residual shear force

λ = modification factor reflecting the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength

μ = coefficient of friction

μ_e = effective coefficient of friction

ρ = shear friction reinforcement ratio = A_{vf}/A_c

ϕ = strength reduction factor

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Abstract

This study examined the direct shear transfer across an interface of lightweight aggregate concretes cast at different times. 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 included 36 push-off specimens constructed with a cold joint along the shear plane. Test variables included concrete type (unit weight), compressive strength of concrete, and surface preparation of the shear interface. A constant amount of reinforcing steel (1.33%) was provided across the shear plane. Applied shear force–slip relations were presented and discussed. Peak and residual shear strengths were also compared. Results suggest that concrete type did not play a significant role in the shear strength of the specimens in this study. Shear strengths computed using the shear friction design provisions in the *Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI 318R-11)* and *PCI Design Handbook: Precast and Prestressed Concrete* were conservative for the sand-lightweight and all-lightweight specimens.

Keywords

All-lightweight concrete, coefficient of friction, connections, sand-lightweight concrete, shear friction.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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