INTERFACE STRENGTH OF HOLLOW CORE SLABS WITH CAST-IN-PLACE TOPPINGS

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ABSTRACT

The horizontal shear strength of the interface between prestressed concrete hollow core slabs and cast-in-place concrete topping slabs was evaluated through a set of 24 push-off experiments. The push-off test specimens featured segments of dry-mix and wet-mix hollow core slabs with a variety of surface treatments including machine finished, sandblasted, broom roughened, rake roughened and grouted. A cast-in-place slab was poured on top of the hollow core specimens to form a 15 inch by 15 inch interface between the two materials. Results indicate the average horizontal shear strength of the push-off specimens was 227 psi. Higher shear strength and slip capacity was observed in specimens that were broom roughened in the direction transverse to the applied shear force and in grouted dry-mix specimens. Specimens with machine finished surfaces had lower average horizontal shear strength than those with intentionally roughened surfaces, but still exceeded the shear strength of 80 psi specified in the ACI 318-08 code. A method to comparatively quantify the surface roughness of the hollow core slabs with different surface treatments was adapted from an existing ASTM standard for pavements. This standard specifies the procedure to determine mean texture depth that can be correlated to horizontal shear strength of the push-off specimens. Analytical studies were also performed to estimate the maximum horizontal shear stresses that can be expected in composite hollow core slabs under normal construction conditions.

Keywords: Hollow Core Slabs, Composites, Push-off Testing, Horizontal Shear Strength, Roughening, Sand Patch Test

INTRODUCTION

Hollow core slabs are prestressed concrete building elements that have been used in a variety of structural applications since their origination in the 1950s, including residential and commercial buildings, parking structures and short span bridges. The slabs contain voids that run continuously along their length, which helps reduce dead weight and material cost. A photograph of a hollow core slab can be seen in Figure 1.

Figure 1. Photograph of a typical hollow core slab.

Hollow core slabs are economical, have good fire resistance and sound insulation properties, and are capable of spanning long distances with relatively small depths. Common depths of prestressed hollow core slabs range between 6 and 10 in. (150 and 250 mm) for spans of approximately 30 ft. (9 m). More recently, hollow core slabs with depths as large as 16 in. (410 mm) have become available, and are capable of spanning over 50 ft. (15 m).

In practice, a concrete topping layer is often cast-in-place onto the top surface of hollow core slabs to create a continuous level finished surface. The topping layer is typically 2 in. (50 mm) deep. The topping slab may increase the flexural and shear strength, and flexural stiffness of the slab if composite action is developed with the hollow core units. Otherwise the weight of the topping slab must simply be considered as superimposed dead load.

Composite action between the cast-in-place topping and hollow core unit is developed primarily through bond between the two concretes. Steel reinforcement that is often used to promote composite action across concretes cast at different times is not practical for this application because of the automated fabrication process of hollow core units. Interface shear strength may possibly be increased by roughening the precast surface prior to placement of the topping slab concrete.

The ACI 318-08[1] code currently limits the horizontal shear strength of unreinforced, intentionally roughened composite interfaces to a stress of 80 psi (0.55 MPa). According to the ACI 318-08 code, surfaces roughened to an amplitude of approximately 0.25 in. (6.4 mm) qualify as intentionally roughened. However, Section 5.3.5 of the *PCI Design Handbook*[2] indicates that normal finishing methods used for precast concrete surfaces may qualify as intentionally roughening.

The purpose of this research study was to investigate the influence of different surface preparation techniques on interface shear strength of hollow core slabs and cast-in-place toppings. Only those techniques that are practically feasible were included in this study.

EXPERIMENTAL TESTING

The experimental testing program was developed with the primary goal of determining the horizontal shear strength of composite interfaces between precast hollow core slabs and cast-in-place concrete toppings. Twenty-four specimens representative of typical hollow core slab construction were fabricated at two different producer facilities and tested in the laboratory after cast-in-place topping was placed. Pairs of hollow core specimens were prepared using different surface roughening techniques during fabrication to examine the effect of top surface condition on interface shear strength. The two producers that fabricated the hollow core units use distinctly different casting machines and therefore employ different concrete mixes in their process. These two were selected to make the results of this study broader in application.

SPECIMEN DESCRIPTION

The interface shear strength of laboratory specimens was determined using 24 push-off specimens. These specimens consisted of a top block of cast-in-place concrete that was cast directly onto the top surface of a hollow core segment (bottom block), as shown in Figure 2. Hollow core segments were fabricated by cutting a 36-in. length of slab from units being fabricated using standard hollow core manufacturing equipment to ensure realistic fabrication procedures.

The geometry of the push-off test specimen was designed to ensure that load application, reaction and composite interface were located along the same plane to only generate horizontal shear stresses on the interface (Figure 2a, Figure 3). This configuration avoided the creation of normal stresses on the composite interface, which may affect the experimental results. To facilitate loading along this plane, the top block was cast into an L-shape and a hollow structural steel (HSS) assembly was embedded into the bottom hollow core block using eight shear studs and additional cast-in-place concrete that filled the voids of the slab.

The interface area consisted of a 15 in. by 15 in. (381 mm by 381 mm) contact surface between the top and bottom blocks. This contact surface was designed to be smaller than the area of the bottom block covered by the top block (Figure 2b). To ensure that shear stresses developed only in the 15 in. by 15 in. area between blocks, the remaining surface was intentionally separated using smooth tape. Furthermore, the top block geometry and weight avoided creation of significant normal stresses on the interface area. No steel reinforcement passed through the composite interface between top and bottom blocks for any of the test specimens.

The bottom blocks were provided by two different hollow core slab fabricators: one that uses a dry-mix fabrication process and one that uses a wet-mix process. The top surfaces of the bottom blocks were finished as listed in Table 1. Surface preparation techniques included machine finished specimens, roughened specimens using either a rake or broom depending on hollow core manufacturing process, sandblasted specimens, and grouted specimens. All roughening operations were performed at the hollow core fabrication plant except for grout application, which was conducted in the laboratory prior to casting the top block. For the grouted specimens, a non-shrink commercially available sand/cement grout was applied to the cleaned hollow core slab surfaces without any further preparation. The grout was applied in a thin (1/16 in. [1.59 mm]) layer and was allowed to dry between 24 to 48 hours before placing the top block. All dry-mix bottom blocks were cast on a single day. All wet-mix bottom blocks were cast on a single day except for specimen WET-LBX-2, which was cast one week later than the others.

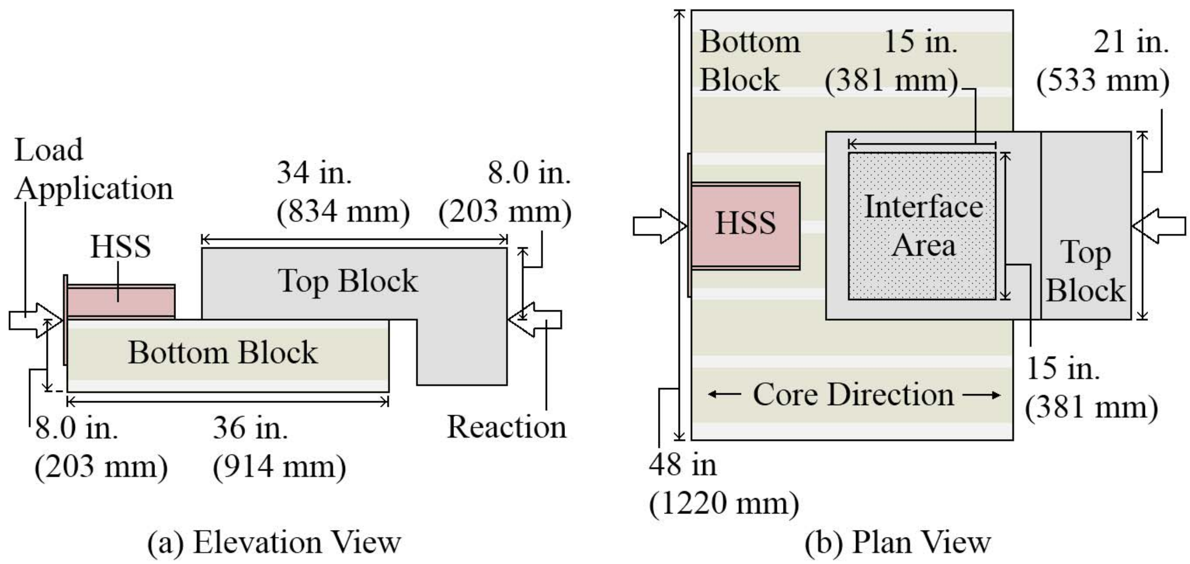


Figure 2. Dimensions of push-off specimen

Figure 3. Photograph of test specimen prior to experimentation

In machine finished specimens (DRY-MFX and WET-MFX) the surface of the hollow core specimens was as produced by the fabrication machine. Machine finished specimens represent roughness typical of hollow core concrete elements dependent on the fabrication method used and properties of the concrete mix.

Table 1. Specimen labels, concrete material strengths and surface roughness measurements.

Specimen label	Bottom block surface preparation	Top block compressive strength, psi (MPa)	Top block tensile strength, psi (MPa)	Bottom block comp. strength, psi (MPa)
DRY-MFX-1	Machine finished	4670 (32.2)	420 (2.9)	6920 (47.7)
DRY-MFX-2		3780 (26.1)	360 (2.5)	7170 (49.4)
DRY-SBX-1	Sandblasted	4510 (31.1)	410 (2.8)	7310 (50.4)
DRY-SBX-2		5000 (34.5)	440 (3.0)	7740 (53.4)
DRY-LRX-1	Longitudinally rake roughened	4630 (31.9)	420 (2.9)	7600 (52.4)
DRY-LRX-2		5020 (34.6)	450 (3.1)	8010 (55.3)
DRY-TBX-1	Transversely broom roughened	4750 (32.7)	450 (3.1)	7450 (51.3)
DRY-TBX-2		5140 (35.4)	480 (3.3)	7880 (54.3)
DRY-MFG-1	Machine finished, grouted	4670 (32.2)	410 (2.8)	8150 (56.2)
DRY-MFG-2		5050 (34.8)	440 (3.0)	8430 (58.1)
DRY-LRG-1	Longitudinally rake roughened and grouted	4820 (33.2)	450 (3.1)	8290 (57.2)
DRY-LRG-2		5110 (35.3)	440 (3.1)	8580 (59.2)
WET-MFX-1	Machine finished	5180 (35.7)	440 (3.0)	9700 (66.9)
WET-MFX-2		5180 (35.7)	450 (3.1)	9730 (67.1)
WET-SBX-1	Sandblasted	4960 (34.2)	430 (3.0)	9750 (67.2)
WET-SBX-2		4530 (31.2)	440 (3.0)	9760 (67.3)
WET-LBX-1	Longitudinally broom roughened	5190 (35.8)	450 (3.1)	9720 (67.0)
WET-LBX-2		4810 (33.2)	410 (2.8)	9780 (67.4)
WET-TBX-1	Transversely broom roughened	4930 (34.0)	410 (2.8)	9810 (67.7)
WET-TBX-2		4140 (28.5)	470 (3.2)	9830 (67.8)
WET-MFG-1	Machine finished, grouted	4310 (29.7)	420 (2.9)	9850 (67.9)
WET-MFG-2		5420 (37.3)	420 (2.9)	9880 (68.1)
WET-LBG-1	Longitudinally broom roughened and grouted	4510 (31.1)	380 (2.6)	9900 (68.2)
WET-LBG-2		4100 (28.3)	370 (2.5)	9920 (68.4)

The surface of the DRY-LRX specimens was roughened using a rake attached to the hollow core fabrication machine that was dragged along the surface prior to concrete setting. All other roughened specimens from either the dry-mix or the wet-mix fabrication process were roughened by hand.

MATERIALS

The cast-in-place top blocks were fabricated using a design compressive strength of 4000 psi (27.6 MPa). The mix used to construct the top blocks utilized small 3/8 in. (10 mm) coarse aggregate to reflect typical overlay concrete mixes. Vibration was used to compact the top block concrete after placement. The top block was covered with wet burlap and plastic wrap for 48 hours after casting. Push-off specimens were typically tested 6 days after casting the top block.

Three 8 in. by 4 in. (200 mm by 100 mm) compression cylinders and two 12 in. by 6 in. (300 mm by 150 mm) split (tension) cylinders were tested for each top block. These cylinders were subjected to the same curing conditions as their companion top block. Each hollow core slab manufacturer provided a total of twelve 8 in. by 4 in. (200 by 100 mm) concrete cylinders. Compression testing of these cylinders was conducted at different times throughout the duration of the entire set of tests from each manufacturer to track concrete strength gain with time and allow estimation of the strength of each hollow core slab at the time of testing. The grout used in specimens DRY-MFG, DRY-LRG, WET-MFG, and WET-LBG was tested using 2 in. (50 mm) cube compression tests.

INSTRUMENTATION

Specimens were instrumented with as many as eight displacement transducers to record relative movement between the top and bottom blocks during testing (Figure 4). Six transducers were arranged along the two sides (North and South) of the specimen to measure relative horizontal slip between the top and bottom blocks. Two additional gages were installed on either side of the specimen to monitor vertical movement of the top block relative to the bottom block.

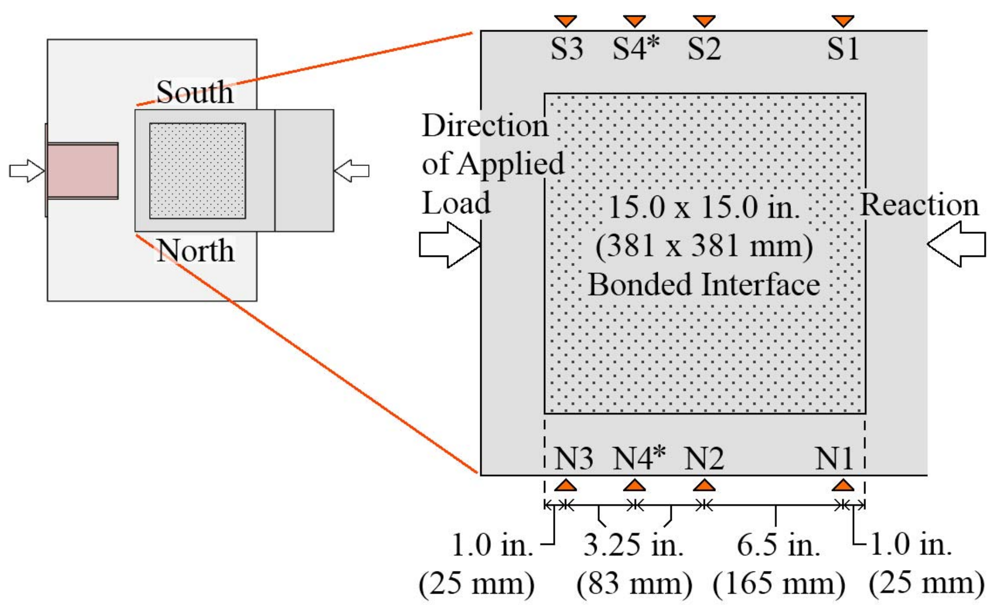


Figure 4. Position of displacement transducers.
*Note: Gages N4 and S4 measure vertical displacement, all others measure horizontal slip.

SURFACE ROUGHNESS QUANTIFICATION

A surface roughness quantification method was established to be able to relate the effect of surface roughness to interface shear strength. In the past, surface roughness has been qualitatively identified by indicating the tool used to produce the roughness condition. The roughness of two surfaces prepared using the same type of tool may vary considerably depending on the condition of the tool, the pressure applied by the individual and the properties of the concrete mix. So a more reliable method was needed to establish surface roughness independent of the tool and applied pressure.

Surface roughness was quantified by adapting a standard test method used for roughness measurement in pavements. The method, referred as the sand patch test, was adapted from ASTM E965[3], "Standard Test for Measuring Pavement Macrotexture Depth Using a Volumetric Technique".

The test involved spreading a known volume of well graded sand onto the roughened surface in a circular pattern using a rubber spreading disc. Spreading continued until the sand patch size no longer increased, at which point the diameter of the sand patch was measured at four different locations. Using Equation 1, the average diameter of the sand patch was related to the macrotexture depth (MTD) of the surface, which is defined as the average depth between the bottom of the surface voids and the top of the surface aggregate particles. The test was repeated four times for each specimen surface, and the mean macrotexture depth (MMTD) was found by averaging the results from the four tests.

$$\mathrm{MTD} = \frac{4V}{\pi D^2} \tag{1}$$

where:

MTD = Macrotexture depth
V = Volume of sand used in the measurement
D = Average measured diameter of the sand patch

The ASTM E965 standard specifies using sand passing a No. 50 sieve and retained on a No. 100 sieve for pavement surfaces. Because concrete surfaces are smoother than typical asphalt pavement, sand passing a No. 100 sieve and retained on a No. 200 sieve was used instead. Additionally, it was found that a volume of 1 in^3 (16 cm^3) of sand was more suitable for use on the precast concrete surfaces used in this study, rather than 2 in^3 (33 cm^3) recommended in the ASTM standard. A hockey puck was used as the rubber spreading disc; the puck had a diameter of 3.0 in. (76 mm) and weighed 0.36 lb (160 g).

The sand patch test could not be used on concrete with very irregular texture, such as rake roughened surfaces, where the rubber spreading tool could not remain horizontal. In these specimens, the MMTD was approximated by taking measurements of the roughened surface using Vernier calipers. The depth probe of the Vernier calipers was used to measure the depth of surface voids (such as the rake grooves) and the height of concrete pieces protruding from the surface. The width of the rake grooves was measured using the inside jaws of the Vernier calipers. For the rake roughened specimens, a rake groove depth measurement and a raised ridge height measurement was taken at 9 different locations throughout the interface (resulting in 18 different measurements) for each raked specimen.

EXPERIMENTAL TESTING RESULTS

Top block compressive and split cylinder strength, and estimated bottom block compressive strength at the time of specimen testing are listed in Table 1.

A summary of results from the push-off specimens are listed in Table 2, including maximum applied shear force, average interfacial shear stress at maximum force, average horizontal slip at failure (as measured by gages N1 and S1), and average vertical displacement of top block at failure (as measured by gages N4 and S4). The average interface shear stress was simply found by dividing the maximum force by the total interface area of the specimen (15 in. by 15 in. [381 mm by 381 mm]). For all specimens, the shear stress at failure exceeded the maximum stress value of 80 psi (0.55 MPa) specified by ACI 318-08. The average interface shear strength of all specimens was 227 psi (1.57 MPa).

Also listed in Table 2 are the mean macrotexture depth (MMTD) measurements for the bottom block surfaces of the specimens. For grouted specimens, an additional set of MMTD measurements was taken on representative grouted surfaces.

Failure of all specimens was sudden and brittle, without visual indications of impending failure. All push-off specimens failed clearly along the interface plane. No cracks were observed on either the top or bottom blocks prior to failure of any specimen.

A typical set of force displacement plots can be seen in Figure 5. In this plot, the displacement measurements taken by each row of instruments have been averaged. The first row of transducers measured higher slip than the second and third rows for all specimens excluding a single dry-mix rake roughened specimen, in which the second row of instruments recorded the highest displacements. The vertical displacements were nearly equivalent in magnitude to the horizontal displacements for all push-off specimens, which is consistent with the findings of past researchers Seible and Latham[4].

Of the four non-grouted machine finished specimens, only specimen DRY-MFX-1 exhibited areas of exposed top block aggregate on the failure surface (Figure 6). This specimen had the highest strength of all non-grouted machine finished specimens.

The dry-mix longitudinally raked specimens had deep grooves that were approximately 0.25 in. (64 mm) deep and spaced at 5 in. (125 mm) on center. The concrete that was displaced during raking formed raised ridges of hardened concrete beside the rake grooves on the bottom blocks. These raised ridges were not well adhered to the bottom block surface and sheared off after failure of these specimens (Figure 7). The cast-in-place concrete that filled the grooves did not shear from the top block during loading perhaps because the grooves were in the same direction as the applied shear force.

Table 2. Experimental results summary.

Specimen label	Max shear force, kip (kN)	Interface shear stress, psi (MPa)	Horizontal slip at failure, in. (mm)	Vertical disp. at failure, in. (mm)	MMTD of bottom block surface, in. (mm)	MMTD of grout surface, in. (mm)
DRY-MFX-1	46.5 (208)	207 (1.42)	0.0006 (0.016)	not recorded	0.0099 (0.2515)	—
DRY-MFX-2	34.2 (153)	152 (1.05)	0.0001 (0.002)	not recorded	0.0094 (0.2388)	—
DRY-SBX-1	36.4 (163)	162 (1.12)	0.0010 (0.025)	not recorded	0.0113 (0.2870)	—
DRY-SBX-2	48.4 (217)	215 (1.48)	0.0017 (0.043)	0.0003 (0.009)	0.0122 (0.3099)	—
DRY-LRX-1	50.2 (225)	223 (1.54)	0.0021 (0.053)	not recorded	0.0221 (0.5613)	—
DRY-LRX-2	46.1 (207)	205 (1.41)	0.0013 (0.033)	0.0012 (0.031)	0.0233 (0.5918)	—
DRY-TBX-1	64.7 (290)	288 (1.98)	0.0018 (0.046)	not recorded	0.0294 (0.7468)	—
DRY-TBX-2	71.8 (322)	319 (2.20)	0.0034 (0.086)	0.0018 (0.046)	0.0326 (0.8280)	—
DRY-MFG-1	62.0 (278)	276 (1.90)	0.0016 (0.041)	0.0011 (0.028)	0.0086 (0.2184)	0.0208 (0.5283)
DRY-MFG-2	84.8 (380)	377 (2.60)	0.0029 (0.074)	0.0017 (0.043)	0.0087 (0.2210)	0.0208 (0.5283)
DRY-LRG-1	62.2 (279)	276 (1.91)	0.0029 (0.074)	0.0013 (0.033)	0.0215 (0.5461)	0.0270 (0.6858)
DRY-LRG-2	59.8 (268)	266 (1.83)	0.0026 (0.066)	0.0012 (0.030)	0.0193 (0.4902)	0.0270 (0.6858)
WET-MFX-1	44.6 (200)	198 (1.37)	0.0014 (0.036)	0.0002 (0.005)	0.0146 (0.3708)	—
WET-MFX-2	28.7 (129)	128 (0.88)	0.0009 (0.023)	0.0002 (0.006)	0.0149 (0.3785)	—
WET-SBX-1	60.2 (270)	268 (1.85)	0.0019 (0.048)	0.0006 (0.016)	0.0173 (0.4394)	—
WET-SBX-2	50.6 (227)	225 (1.55)	0.0024 (0.061)	0.0007 (0.017)	0.0173 (0.4394)	—
WET-LBX-1	49.9 (224)	222 (1.53)	0.0019 (0.048)	0.0006 (0.015)	0.0423 (1.0744)	—
WET-LBX-2	32.4 (145)	144 (0.99)	0.0011 (0.028)	0.0002 (0.005)	0.0366 (0.9296)	—
WET-TBX-1	57.9 (259)	257 (1.77)	0.0025 (0.064)	0.0010 (0.025)	0.0474 (1.2040)	—
WET-TBX-2	55.7 (250)	248 (1.71)	0.0022 (0.056)	0.0005 (0.012)	0.0400 (1.0160)	—
WET-MFG-1	35.4 (159)	157 (1.08)	0.0010 (0.025)	0.0001 (0.001)	0.0130 (0.3302)	0.0208 (0.5283)
WET-MFG-2	37.2 (167)	165 (1.14)	0.0015 (0.038)	0.0004 (0.011)	0.0130 (0.3302)	0.0208 (0.5283)
WET-LBG-1	55.6 (249)	247 (1.70)	0.0021 (0.053)	0.0009 (0.024)	0.0380 (0.9652)	0.0210 (0.5334)
WET-LBG-2	49.1 (220)	218 (1.50)	0.0021 (0.053)	0.0006 (0.016)	0.0359 (0.9119)	0.0210 (0.5334)

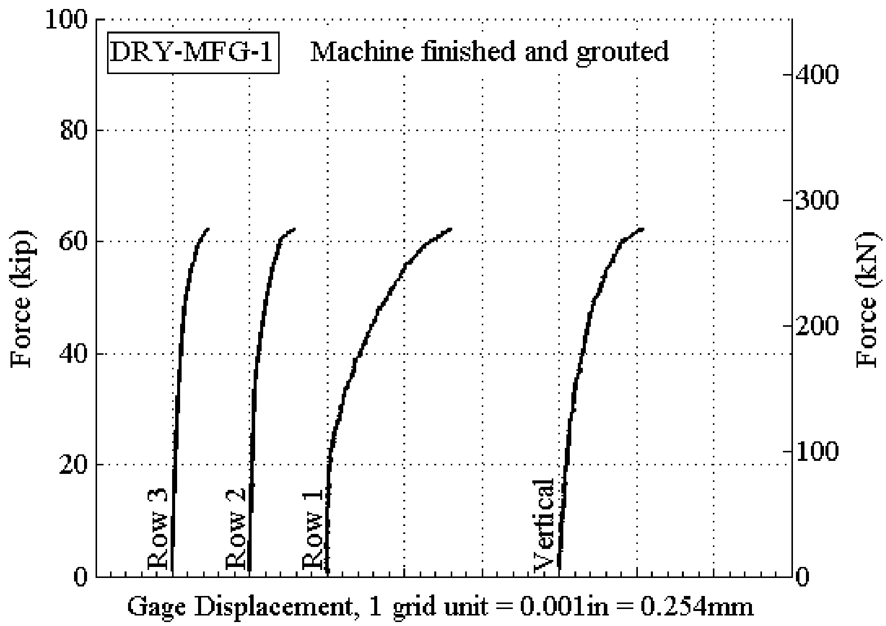


Figure 5. Force-displacement plots for specimen DRY-MFG-1.

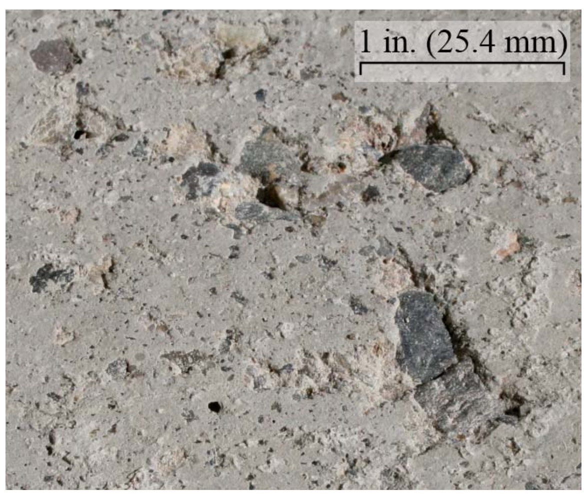
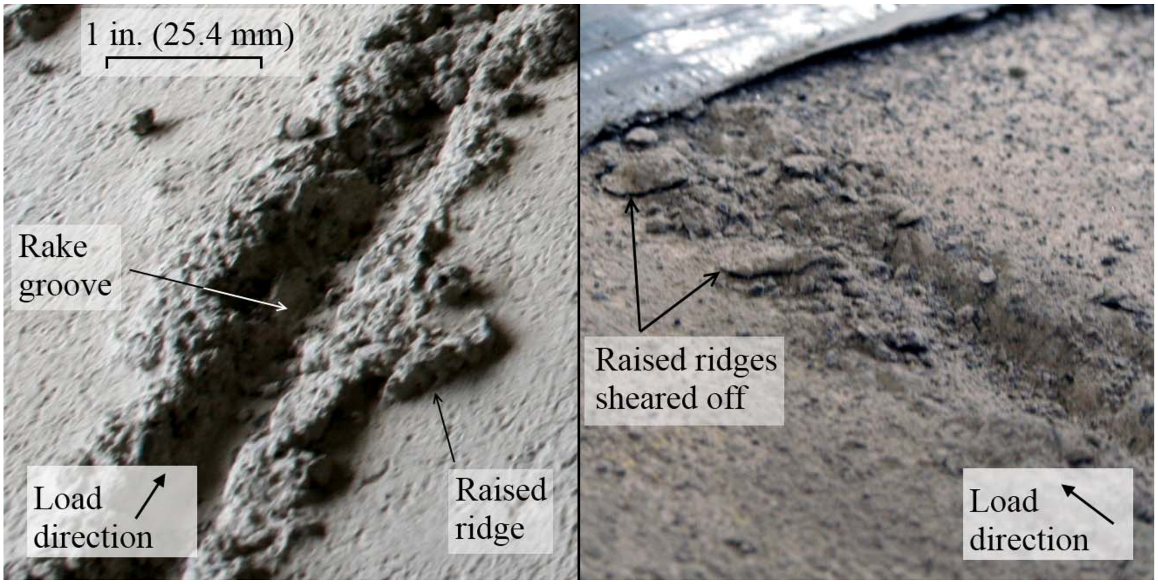


Figure 6. Photograph of exposed aggregate on the top block interface surface after failure of specimen DRY-MFX-1.

The broom roughened surface had the highest MMTD of all surface preparation techniques. The average MMTD of the dry-mix and wet-mix broom roughened specimens was 0.0310 in. (0.787 mm) and 0.0416 in. (1.06 mm), respectively. As expected, the variations in brooming techniques and concrete mix properties resulted in significantly different average MMTD between the dry-mix and wet-mix specimens, despite being roughened by the same type of tool.



(a) (b)

Figure 7. (a) Photograph of a rake groove on a dry-mix bottom block surface before testing. (b) Photograph of a rake groove on a dry-mix bottom block surface after testing.

Specimens that were broom roughened in the transverse direction had the highest interfacial shear strength and horizontal slip capacity among all non-grouted dry and wet-mix specimens. The broom ridges on these specimens were in a direction perpendicular to the applied shear force, this promoted interlocking between the top and bottom blocks.

In sandblasted specimens, roughening was performed after the hollow core slab segments had hardened. As reflected by MMTD measurements, sandblasting only increased the surface roughness of the bottom blocks by a small amount. The average MMTD of the dry-mix and wet-mix sandblasted surfaces was 22% and 17% higher than the corresponding machine finished surfaces. The sandblasting process effectively removed a thin layer of material from the top of the bottom block surfaces. This is the layer that would contain laitance and other debris that detract from the quality of interfacial bond. Compared to the dry-mix machine finished specimens, the dry-mix sandblasted specimens had higher horizontal slip capacity and nearly equal interfacial shear strength. The wet-mix sandblasted specimens had, on average, 51% higher interfacial shear strength and 86% higher horizontal slip capacity compared with corresponding wet-mix machine finished specimens.

The grouted dry-mix specimens had higher interfacial shear strength and horizontal slip capacity than their un-grouted counterparts. On average, dry-mix grouted specimens had higher roughness compared with the dry-mix machine finished and dry-mix longitudinally raked specimens (140% and 32%, respectively). Furthermore, DRY-MFG and DRY-LRG specimens had an average interfacial shear strength approximately 82% and 27% higher, respectively, than corresponding ungrouted specimens. The failure surfaces of the dry-mix grouted specimens showed regions where grout remained bonded to the bottom block, regions where the grout remained bonded to the top block, and regions where a thin layer of the top block concrete (along with the grout) remained bonded to the bottom block. This indicated that the bond between the grout and both bottom and top blocks were of approximately equal strength.

The grouted wet-mix machine finished specimens did not exhibit a marked increase in interfacial shear strength or horizontal slip capacity compared with non-grouted companion specimens, despite an average increase in MMTD of 60% generated by the grout. The grouted wet-mix longitudinally broomed specimens had a 43% lower MMTD after the application of the grout, yet had 27% higher average interfacial shear strength than the non-grouted companion specimens. In the wet-mix grouted machine finished specimens, the entire layer of grout remained bonded to the top block surface except for a small 3 in. by 4 in. (76 mm by 100 mm) area, in which the grout remained bonded to the bottom block. This indicated that the bond between the bottom block and the grout was weaker than the bond between grout and top block. This may be a result of the concrete characteristics used during the fabrication process of the hollow core specimen as will be discussed below.

INFLUENCE OF ROUGHNESS ON INTERFACIAL SHEAR STRENGTH

The relationship between interfacial shear strength and MMTD can be seen in Figure 8 for dry-mix specimens and Figure 9 for wet-mix specimens. For grouted specimens, the MMTD shown in these figures represents the texture measured on top of the grouted surface.

A strong relationship can be observed between MMTD and interface shear strength of dry-mix specimens. The correlation coefficient between these two properties was found to be 0.69 and the r-squared value was found to be 0.47.

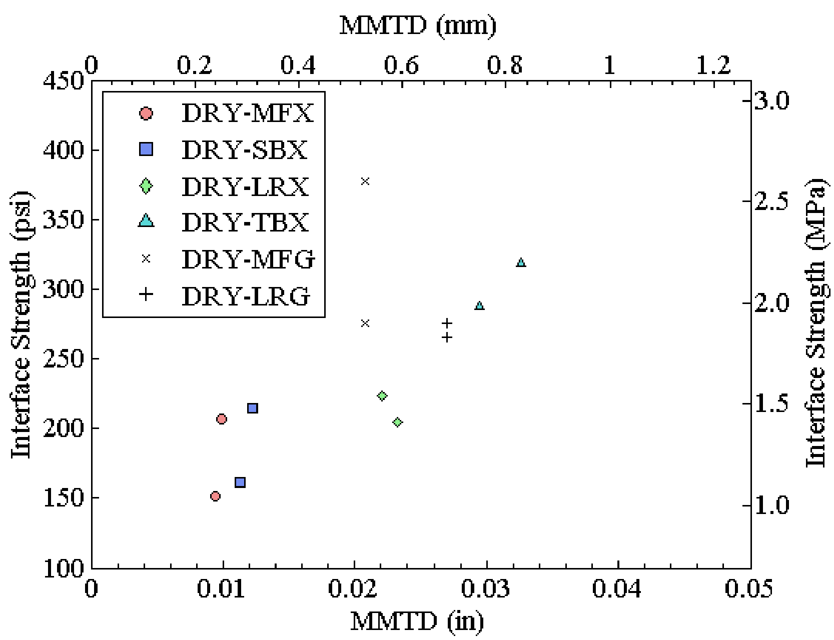


Figure 8. Relationship between mean macrotexture depth (MMTD) and interfacial shear strength for dry-mix specimens without grout.

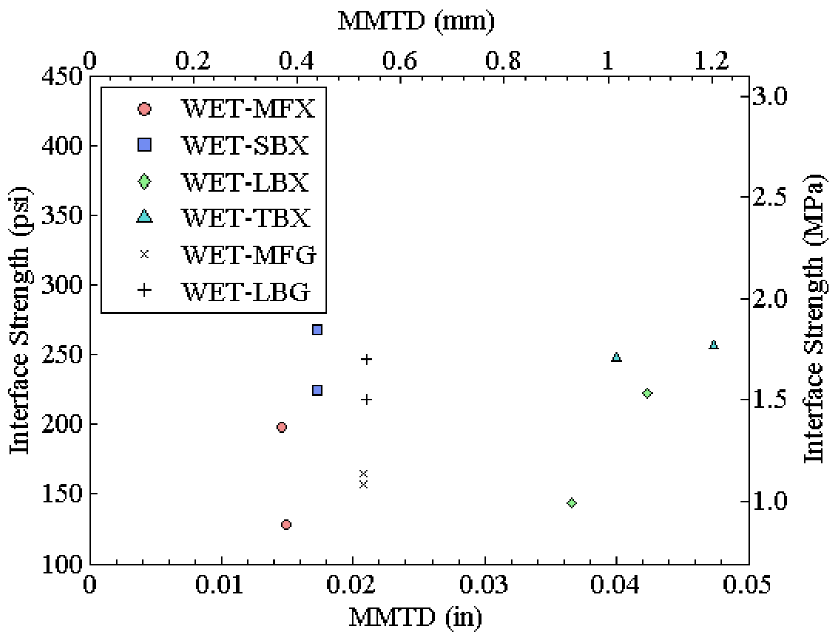


Figure 9. Relationship between mean macrotexture depth (MMTD) and interface shear strength for wet-mix specimens without grout.

In contrast, a weak positive relationship between interface shear strength and MMTD was observed for the wet-mix specimens, with a correlation coefficient of 0.28 and an r-squared value of 0.079.

The surfaces of the wet-mix bottom blocks generally contained more surface laitance than the dry-mix surfaces. A visual comparison between dry-mix and wet-mix broom roughened surfaces can be seen in Figure 10. When present on the surface, laitance accumulated within valleys of the roughness undulations of wet-mix specimens. Proper removal of all laitance from the surface, as specified by Section 17.5.3.2 of ACI 318-08, couldn't be practically achieved simply by brushing and blasting with compressed air. The wet-mix sandblasted specimens, where surface laitance was removed during sandblasting, had significantly higher interfacial shear strength than the machine finished specimens. This indicates that the presence of laitance on the hollow core surface prior to placement of topping slab concrete reduces the quality of bond between the precast and topping slabs.

It was observed that the bottom block surface of specimen WET-LBX-2 had an exceedingly large accumulation of laitance dust (Figure 11). This specimen, which was cast by the fabricator on a different day than all other wet-mix specimens, had lower MMTD, interfacial shear strength, and horizontal slip capacity than other broom roughened specimens. If specimen WET-LBX-2 is omitted from the set of wet-mix data, the correlation coefficient between interface shear strength and MMTD would increase to 0.45 and the r-square value would increase to 0.21.

Figure 10. Visual appearance of dry-mix (left) and wet-mix broom roughened (right) surfaces.

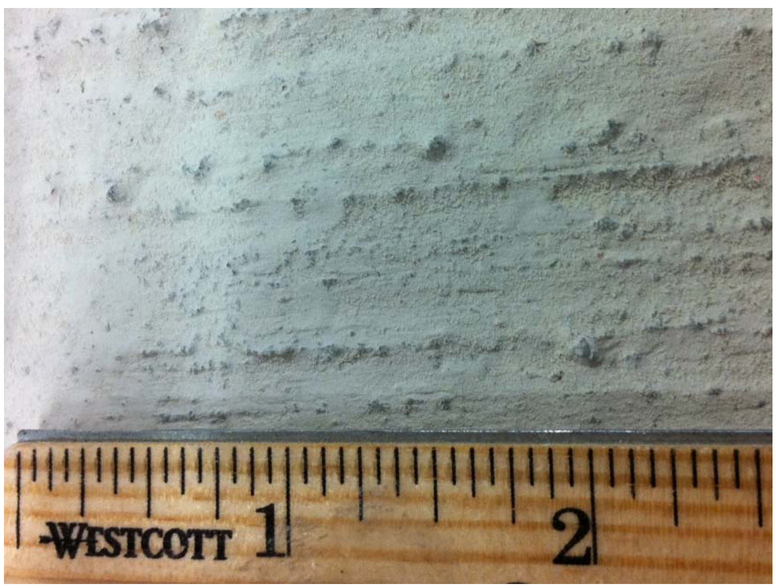


Figure 11. Photograph of bottom block of specimen WET-LBX-2 before placement of top block concrete. This photograph was taken after brushing the surface and blasting the surface with compressed air.

A strong positive correlation between interfacial shear strength and horizontal slip at failure was observed (Figure 12). The correlation coefficient between these two properties was found to be 0.80 and the r-squared value was found to be 0.65.

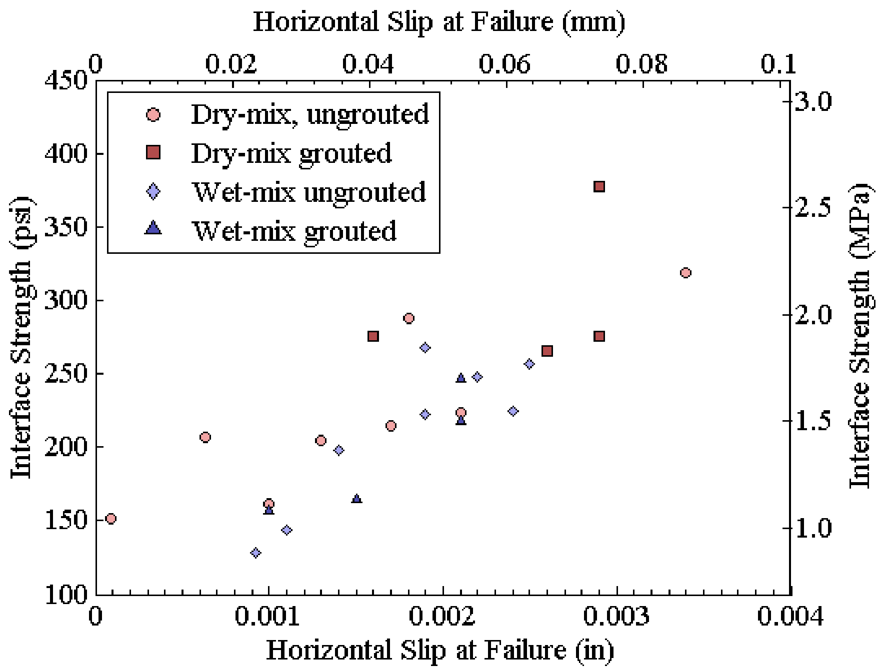


Figure 12. Relationship between interface shear strength and horizontal slip at failure.

HORIZONTAL SHEAR IN HOLLOW CORE SLABS

Section 17.5.3.1 of the ACI 318-08 code specifies Equation 2 as the horizontal shear strength of unreinforced, intentionally roughened composite interfaces. According to ACI 318-08, composite action is achieved if the horizontal shear strength obtained from this equation exceeds the applied vertical shear on a composite beam.

$$\Phi V_{nh} = \Phi(80) b_v d \quad \text{(psi)}$$
$$\Phi V_{nh} = \Phi(0.55) b_v d \quad \text{(MPa)} \qquad (2)$$

where:

Φ = Strength reduction factor for shear (equal to 0.75)
V_{nh} = Horizontal shear strength of interface
b_v = Composite interface contact width
d = Depth of composite section

An alternative method of calculating the strength of horizontal shear connections is shown in ACI 318-08 Section 17.5.4. This alternative method is also represented in Section 5.3.5 of the *PCI Design Handbook*, as shown in Equation 3. According to this method, for a simply supported beam to behave compositely the interface shear strength, ΦV_{nh}, must exceed the change in compressive force in the topping layer calculated between the section of zero moment and the maximum moment section.

$$\Phi V_{nh} = \Phi(80) b_v l_{vh} \quad \text{(psi)}$$
$$\Phi V_{nh} = \Phi(0.55) b_v l_{vh} \quad \text{(MPa)} \tag{3}$$

where:

Φ = Strength reduction factor for shear (equal to 0.75)
V_{nh} = Horizontal shear strength of interface
l_{vh} = Horizontal shear length (half of total span length for simply supported beams with distributed loading)
b_v = Composite interface contact width

The calculation method for horizontal shear presented in the *PCI Design Handbook* (Equation 3) results in an average horizontal shear value along the entire span length. Section 17.5.4 of the ACI 318-08 code states that the change in compressive force in *any* segment shall not exceed ΦV_{nh} as shown in Equation 3. The use of an average horizontal shear value along the entire span length assumes that longitudinal redistribution of horizontal shear will occur, which is unlikely due to the low slip capacity of unreinforced concrete-to-concrete composite connections. To resolve this issue, the average horizontal shear value found using the method presented in the *PCI Design Handbook* can be redistributed to reflect the shape of the shear diagram. This allows the horizontal shear stress to be limited to 80 psi (0.55 MPa) at the ends of the span where shear is most critical. Additional clarity in the *PCI Design Handbook* regarding this issue would be helpful to designers of unreinforced composite flexural elements.

The maximum superimposed distributed live load required to reach flexural, vertical shear and horizontal shear capacity was calculated for generic hollow core slab cross sections with a range of simply supported span lengths. For each span length, the vertical shear capacity was considered to be the smaller of web-shear and flexural-shear capacities as calculated using Section 11.3 of ACI 318-08. Flexural capacity was calculated at the ultimate limit state using Section 5.2.1 of the *PCI Design Handbook*. Horizontal shear strength was calculated using Section 5.3.5 of the *PCI Design Handbook* (Equation 3). During horizontal shear calculations, the average horizontal shear force was redistributed to accurately reflect the shape of the shear diagram and to limit the horizontal shear to a value of 80 psi (0.55 MPa) at the ends of the span.

Horizontal shear of hollow core slabs with composite topping layers tends to be critical in members with low span to depth ratios. The live load capacity of hollow core slabs that have larger web thicknesses to increase web-shear strength may be governed by horizontal shear, as shown in Figure 13 and Figure 14.

For example, the live load capacity of the 8 in. (203 mm) deep hollow core slab used to construct the curves in Figure 13 is only limited by horizontal shear at very short span lengths below 8 ft. (2.4 m). In comparison, the live load capacity of a 12 in. (305 mm) hollow core slab with thicker web (Figure 14) is controlled by horizontal shear at spans below 21 ft. (6.4 m)

If the lowest average interfacial shear strength measured during the push-off testing program of 128 psi (0.88 MPa) were used in place of the 80 psi (0.55 MPa) horizontal shear stress limit in ACI 318-08, then situations where horizontal shear governs the strength of hollow core slabs become less frequent.

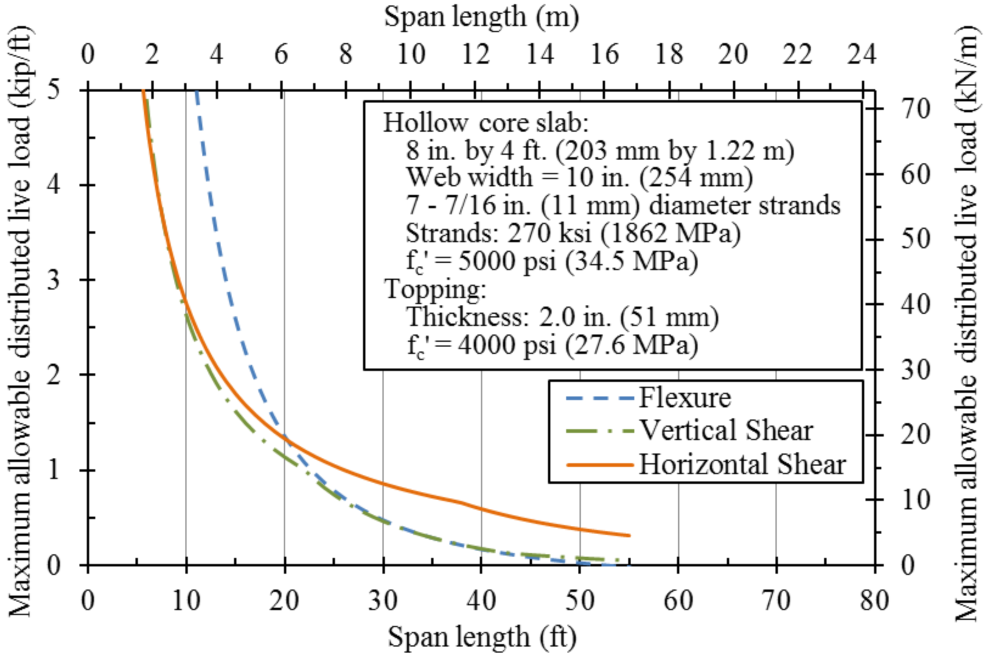


Figure 13. Maximum allowable distributed live load for an 8 in. (203 mm) deep hollow core slab.

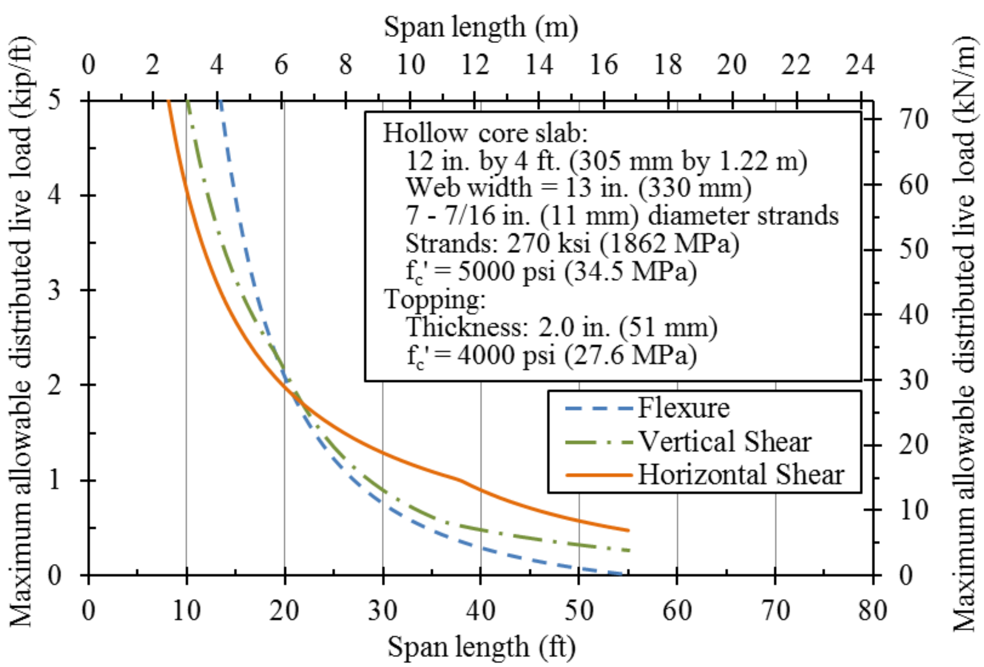


Figure 14. Maximum allowable distributed live load for a 12 in. (305 mm) deep hollow core slab.

CONCLUSIONS

This research investigated the effect of surface roughening on the strength of the composite interface between precast hollow core slabs and cast-in-place topping layers. This was accomplished through a series of 24 push-off test specimens with varying surface roughness properties. Both dry-mix and wet-mix hollow core slabs were tested in this experimental program. Reinforcement was not placed across the composite interface of the push-off specimens. The following conclusions can be made from the results of this study:

1. For dry-mix hollow core slabs, a strong positive correlation was observed between surface roughness and interfacial shear strength and horizontal slip capacity. Based on observations, the interfacial shear strength of wet-mix hollow core slabs was related to both surface roughness and the presence of laitance. Sandblasting removed the laitance layer from the wet-mix hollow core slabs and improved interfacial shear strength by providing a higher quality cohesive bond and, to a lesser extent, increasing the surface roughness.

2. Roughened interfaces exhibited higher strength and horizontal slip capacity than machine finished interfaces. Roughening was found to be most effective when the grooves were oriented in a direction perpendicular to the applied shear force. Grouted dry-mix hollow core slab surfaces had higher interfacial shear strength and horizontal slip capacity than un-grouted companion specimens.

3. The horizontal shear capacity of 80 psi (0.55 MPa) specified by the ACI 318-08 code was found to be conservative for all surface roughness types, including machine finished. The push-off testing program has shown that higher shear strengths of unreinforced composite interfaces can be obtained by roughening the hardened concrete surface.

4. An analysis of simply supported hollow core slabs under distributed loading has shown that the live load capacity of hollow core slabs with low span to depth ratios and thick webs may be governed by horizontal shear.

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