Composite Shear Stud Strength at Early Concrete Ages

Cem Topkaya[1]; Joseph A. Yura[2]; and Eric B. Williamson[3]

Abstract: Composite action between a reinforced concrete deck and steel girders is usually achieved by making use of welded headed shear studs. The mechanics of shear studs embedded in mature concrete has been investigated extensively in the past. Current literature, however, lacks experimental evidence of steel–concrete interface behavior at early concrete ages. This information is useful in understanding the behavior of bridges during construction. Current testing methods are not suitable for determining the response of shear studs embedded in early-age concrete. In order to avoid this limitation, a new pushout test setup has been developed. A total of 24 pushout tests were performed at concrete ages ranging from 4 h to 28 days. Test results were used to develop load–slip curves and strength expressions. Furthermore, the variation of concrete properties with time and the applicability of the existing code equations for predicting early-age concrete stiffness were examined. Test results revealed that shear transfer is achieved at very early concrete ages and rate of stiffness gain of concrete is greater than that of strength.

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Introduction

Composite members consisting of a reinforced concrete deck supported on steel girders are widely used in building and bridge construction. Composite action between a steel girder and concrete deck is achieved by the horizontal transfer of shear at the steel–concrete interface. This transfer can be attributed to several mechanisms, including adhesion, friction, and bearing (Viest et al. 1997). Because of their lack of reliability, adhesion and friction are typically ignored for design. Therefore, steel elements welded to the girder and embedded in the concrete are assumed to provide a reliable shear connection through bearing. Among the many types of connectors available, welded headed shear studs are the most widely used.

All the research reported to date has focused on the behavior of shear studs embedded in mature concrete. An area that has been overlooked for many years is the behavior of studs during early ages of concrete. This information is particularly useful in investigating the behavior of bridges during construction and the development of composite strength and stiffness prior to the removal of shoring. In a long-span, continuous, composite bridge, the deck is usually cast in a number of stages due to the large volume of concrete and the need to control shrinkage. Each concrete pour takes around 2–4 h to complete depending on the bridge dimensions. The time gap between pouring stages could vary from hours to several days. As a result, portions of bridge girders may become partially composite in sequential stages. Recent field studies on curved trapezoidal steel box girders (Topkaya 2002) revealed that measured cross-sectional stresses and brace member forces during construction are significantly different than the analytical predictions if the girders are assumed to act noncompositely. Analysis for construction loading should take into account the partial composite action developing between the concrete pouring stages. In order to accurately model this phenomenon, a thorough understanding of the behavior of the concrete deck–steel girder interface at early ages is essential.

An investigation of shear stud behavior is carried out by performing pushout tests. A new test setup for performing pushout tests on specimens with early-age concrete is proposed. A total of 24 pushout tests were performed at concrete ages ranging from 4 h to 28 days. In this paper a summary of the previous research on shear studs and early-age concrete is given. The results from the pushout tests on specimens with early-age concrete are used to develop load–slip curves and strength expressions. The variation of concrete material properties with time is examined, and the use of existing code equations for predicting early-age concrete stiffness is evaluated. The effects of changing concrete strength and stiffness on the performance of shear studs preloaded at early ages are presented.

Previous Research

Overview of Mechanical Properties of Mature Concrete

The constitutive properties of mature concrete have been well documented. Parameters considered to be the most significant in defining concrete behavior are compressive strength (f_c'), stiffness (E_c), and stress–strain response. The strength and stiffness vary according to the mix design used. In general, concrete exhibits a nonlinear stress–strain response for loading in compression. The stress–strain curve can be visualized as having a rising portion followed by a descending branch (MacGregor 1997). The

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rising portion resembles a parabola with its vertex at the maximum compressive stress. This stress is reached at a strain value between 0.0015 and 0.003.

The initial tangent modulus increases with an increase in compressive strength. The modulus of elasticity of the concrete E_c is a function of the modulus of elasticity of the cement paste and that of the aggregate. Empirical relations have been developed to express E_c as a function of f_c'. For normal weight concrete with a density of 2,300 kg/m^3 (145 lb/ft^3), American Concrete Institute (ACI) Sec 8.5.1 (ACI 1999) gives the modulus of elasticity as

$$E_c = 4{,}730\sqrt{f_c'} \ \text{MPa}$$
$$(E_c = 57{,}000\sqrt{f_c'} \ \text{psi}) \qquad (1)$$

This equation was derived from short duration tests on concrete and corresponds to the secant modulus of elasticity at approximately $0.45-0.5 f_c'$. Because this equation does not depend upon the type of aggregate used, there is wide scatter in the data. Measured values may range from 80 to 120% of the specified value. (ACI 1999)

Overview of Mechanical Properties of Concrete at Early Ages

Concrete gains stiffness and strength with time. The rate of strength gain is dependent on the type of cement and admixtures used as well as the moisture and temperature conditions during curing. Most of the previous research work has focused on the strength gain of concrete at different times and temperature conditions (MacGregor 1997). Apart from the strength gain, other mechanical properties at early ages have been investigated by several researchers. Below is a summary of the key work in this field.

Lew and Reichard (1978) investigated the rate of gain of the compressive strength, splitting tensile strength, pullout bond strength, and elastic modulus with temperature and time. Standard cylinder compression tests, splitting tensile tests, and pullout bond tests were performed on specimens cured at different temperatures. Tests were carried out at ages varying from 1 to 42 days. Lew and Reichard (1978) determined that the rate of increase in the splitting tensile strength was approximately the same as that of compressive strength. In addition, the rate of increase in the pullout bond strength and the modulus were found to be slightly greater than that of the compressive strength.

Oluokun et al. (1991) investigated the applicability of existing relations to characterize the properties of concrete at early ages. Cylinder compressive strength, elastic modulus, and Poisson's ratio were tested for four different concrete mixes at concrete ages ranging from 6 h to 28 days. A significant finding of these researchers was that the ACI 318 relation for elastic modulus is valid at ages 12 h and greater. Poisson's ratio was found to be insensitive to the age and concrete mix and could be taken as 0.19.

Khan et al. (1995) focused on the early-age, compressive stress–strain properties of low-, medium-, and high-strength concretes. The specimens were subjected to three different curing conditions, namely, temperature matched, sealed, and air-dry curing. Stress–strain behavior was monitored at ages ranging from 8 h to 91 days. Their study revealed that during the first few hours of hydration, the stress–strain response exhibited extremely low moduli, low compressive strength, and very high strains corresponding to peak compressive stress. After about 24 h, the response for all of the concretes started to resemble the response at 28 days. The elastic modulus was observed to grow very rapidly at early ages. In addition, the writers concluded that the ACI expression for elastic modulus overestimates the stiffness for very early-age concretes.

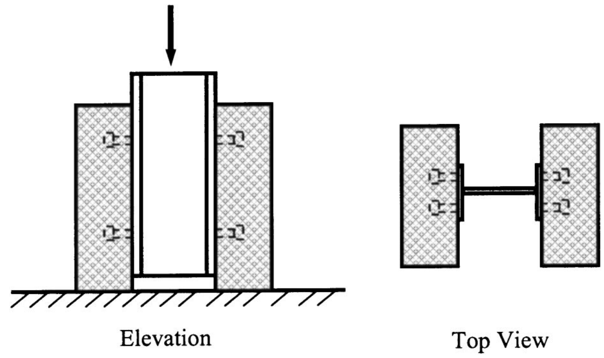

Fig. 1. Conventional pushout test setup

Overview of Behavior of Shear Studs

An experimental investigation of shear stud behavior is usually carried out by performing pushout tests. Although there is not a standardized procedure for fabricating and testing pushout test specimens, most researchers have used similar, though slightly different, procedures (Viest et al. 1997). In a typical pushout test specimen, studs are welded to both flanges of a W shape. Later, a slab is poured on each side of the W shape so that the studs will be embedded in concrete. The specimens are tested by applying an axial force to the W shape. A conventional pushout test specimen is shown in Fig. 1. During the test, vertical slip between the slab and beam are measured. Specimens are generally loaded to failure, with or without unloading and reloading, during the test. A load–slip response for a shear stud such as the one shown in Fig. 2 is obtained as a result of a pushout test. The load–slip behavior is nonlinear. In general, the unloading of specimens does not affect the envelope of the curves. The reloading is linear until the maximum load prior to unloading is reached.

The ultimate strength of a shear stud and the mathematical representation of the load–slip relationship are the two most important results of a pushout test. A large body of knowledge exists for shear stud tests (Viest et al. 1997). The following equation is recommended by the American Institute of Steel Construction (AISC 1994) specification to predict the ultimate strength of a shear stud:

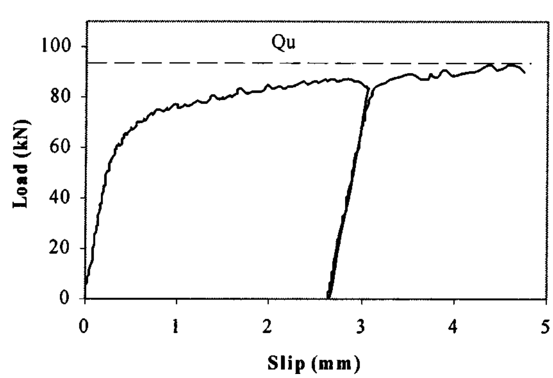

Fig. 2. Typical load–slip response for shear stud

$$Q_u = 0.5 A_{sc} \sqrt{f_c' E_c} \leqslant A_{sc} F_u \tag{2}$$

where Q_u=ultimate strength of a shear stud (N); A_{sc}=cross-sectional area of shear stud (mm^2); F_u=minimum specified tensile strength of stud steel; and f_c' and E_c are in MPa.

The mechanics of shear transfer is not yet fully understood. It requires micromodeling of the shear connector. However, specimens cut into halves after testing give some insight into the deformation pattern (Ollgaard et al. 1971). An interesting observation is that shear studs exhibit ductile behavior. Formation of high local stresses results in the global ductility of the connection. Concrete, however, will experience inelastic, permanent deformations or local crushing around the welded part of the stud. The void that forms due to local crushing permits the stud to deform (Viest et al. 1997). Because of the deformations occurring in the stud, the overall behavior is ductile.

As mentioned earlier, there is no standard procedure for pushout tests. There is wide scatter in the results due to differences in test specimens, the methods of casting, and test procedures. Test setups like the one shown in Fig. 1 are prone to premature separation between the slab and the steel W shape in the direction normal to the slab surface. In addition, results are affected by the frictional forces developing between the base of the test slabs and the reaction floor due to the tendency of the slab to separate.

Another discrepancy arises during the interpretation of the test results. The ultimate strength of the shear connector is defined as the maximum load attained per stud during a test. This ultimate strength value is directly used in the design of shear connectors without considering the interface displacement demand. In the study by Ollgaard et al. (1971), the maximum load was reached at slips varying from 5.84 mm (0.23 in.) to 10.7 mm (0.42 in.). In reality, these magnitudes of interface slip could not be easily tolerated by a structure. Therefore, during the design stage, values lower than the ultimate strength should be used to limit the interface slip demands.

Investigation of Steel–Concrete Interface Behavior at Early Ages

Current literature lacks experimental evidence of steel–concrete interface behavior at early concrete ages. This information is essential in understanding the shear transfer between a concrete deck and girder top flanges during construction of bridges. All pushout tests previously reported were performed on mature concrete. It is necessary to obtain load–slip curves for studs embedded in concrete and subjected to shear forces from 3 to 48 h after concrete has been poured. Obtaining this information entails certain experimental challenges. Standard pushout tests were found not suitable for testing specimens at early ages. There are constraints on the test setup that need to be addressed in testing specimens with early-age concrete.

1. The testing should be completed in a very short time period. Otherwise, time elapsed during testing of replicate specimens would cause concrete to change properties. A guideline established for the research reported herein was to have all replicate specimens tested within 15 min.
2. Prior to testing, specimens should not be moved because unnecessary handling may damage the early-age concrete. Transportation of specimens may also expand the time interval between tests. This constraint limits the use of a test machine because specimens have to be cast and tested in place.
3. If possible, specimens should not be anchored to the floor or to another fixture. Application of loads to low strength concrete may cause damage to the specimen around anchorage regions, and local failures in these locations may result in undesirable behavior.

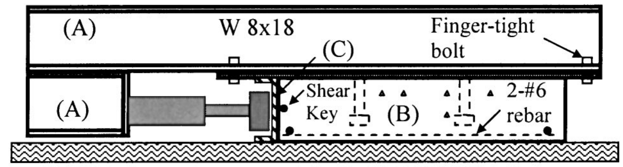

Fig. 3. Schematic of pushout test setup

Pushout Test Setup

A self-contained pushout test setup was developed for testing shear studs embedded in early-age concrete that meets all the above-mentioned constraints. The test setup consisted of a loading fixture (A), a test specimen (B), and a spreader beam (C) (Figs. 3 and 4).

For each specimen, a box-type formwork having dimensions of 915 mm×610 mm×203 mm (36 in.×24 in.×8 in.) was prepared. Plywood was placed on three sides while a 610 mm (24 in.) long C8×11.5 channel section was placed on the remaining side. The channel section served as formwork as well as a spreader beam during the loading process. Two No. 6 reinforcing bars were placed at the bottom in both directions for the ease of handling specimens after testing. Reinforcing bars were located 51 mm (2 in.) from the edges of the formwork. Two shear studs were welded to a 16 mm×254 mm×1219 mm (5/8 in.×10 in.×48 in.) flat plate using standard stud installation equipment. A plastic sheet was wrapped around the flat plate to prevent bonding between the steel plate and the concrete. The flat plate was placed on top of the formwork with the studs oriented downward. After completing all the forms for each test specimen, concrete was cast inside all the forms and vibrated according to standard construction practices.

The specimens were tested by making use of a loading fixture. A loading fixture was constructed by welding a 305 mm (12 in.) long and an 1829 mm (72 in.) long W8×18 steel section together. A 267 kN (60 kip) capacity hydraulic ram was bolted to a plate that was welded to the short section of the loading fixture. The loading fixture was lifted into position and was connected to the flat plate of the test specimen by four 19 mm (3/4 in.) diameter A325 bolts. Two holes with a diameter 17 mm (11/16 in.) were drilled into the flange of the channel section, while, two holes with a diameter 27 mm (17/16 in.) were drilled into the flat plate at coinciding locations. Two 16 mm (5/8 in.) diameter A325 bolts were used to connect the two parts. These bolts were necessary to

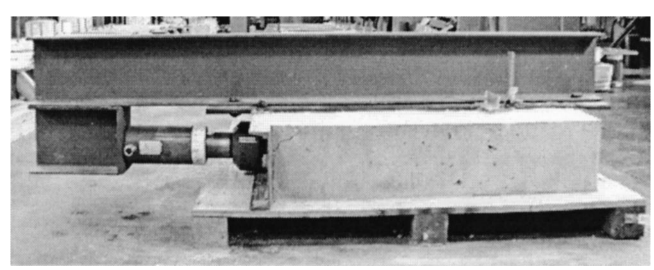

Fig. 4. Side view of pushout test setup

Table 1. Composition and Properties of Concrete Mix

Material	Source	Weight
Cement	TXI type I/II	255 kg/m^3 (430 lb/yd^3)
Fly ash	JTM Industries Class C	89 kg/m^3 (150 lb/yd^3)
Fine aggregate	TXI concrete sand	693 kg/m^3 (1,168 lb/yd^3)
Coarse aggregate	TXI 1″ washed gravel	1,158 kg/m^3 (1,952 lb/yd^3)
Total water	City of Austin	121 kg/m^3 (204 lb/yd^3)
Water reducer/retarder	D-65	0.93 kg/m^3 (25 oz/yd^3)
Water reducer/retarder	D-17	0.33 kg/m^3 (9 oz/yd^3)
Air entrainment	Daravair	0.13 kg/m^3 (3.6 oz/yd^3)

counteract the tendency of the loading frame and the concrete slab to separate due to the eccentricity of the jack loading axis and the shear plane. A hydraulic ram was connected to a hand pump in order to apply the loading.

During a typical test, the load–displacement behavior was documented by collecting data at 1 s intervals with a data acquisition system. The load was monitored by making use of a 222 kN (50 kip) load cell that was attached to the loading ram. Displacements were measured with two linear potentiometers that have an accuracy of 0.0025 mm (0.0001 in.).

One minor detail about the setup is also worth mentioning. Although the spreader beam was not connected to the floor, it did not uplift together with the loading beam when both were tied together. The tendency to uplift was prevented by the formation of frictional resistance between the channel section and concrete block as a result of the applied load. In order to increase the resistance against uplift, a layer of No. 6 reinforcing bars was welded to the web of the channel section to act as a shear key. The shear key together with the frictional resistance ensures that the hydraulic ram remains in a horizontal position and the direction of the load does not change throughout the test.

Test Program

A test program was designed to obtain the load–displacement behavior of shear studs embedded in early-age concrete. Aging times were chosen as 4 h, 8 h, 13 h, 22 h, 3 days, 7 days, 14 days, and 28 days after initial casting. At all of these ages, concrete cylinders were also tested to obtain material properties. For each time period, three pushout tests, three cylinder compression tests, and three split cylinder tests were performed.

Class-S type concrete, which is used for bridge slabs in the state of Tex., was selected for use in the test specimens. According to the Tex. Dept. of Transportation construction specifications (TxDOT 1993), Class-S type concrete should meet the following requirements:

- Minimum compressive strength (f'_c) (28 day):28 MPa (4,000 psi);
- Minimum flexural strength (7 day):3.9 MPa (570 psi) [3.6 MPa (525 psi) when Type II or Type I//II cement is used];
- Maximum water/cement ratio: 0.47; and
- Desired slump: 76 mm (3 in.) [102 mm (4 in.) maximum].

Concrete was ordered from a local ready-mix concrete supplier. Weights for the ingredients of the delivered concrete are given in Table 1. The measured slump of the concrete was 89 mm (3.5 in.), and the calculated water/cementitious ratio (including fly ash) of the above mix was 0.35.

A shear stud diameter of 19 mm (3/4 in.) was chosen for all specimens because this size is the most widely used in practice. All studs were 127 mm (5 in.) tall. The pushout specimens were prepared in two rows, each consisting of 12 specimens (Fig. 5). The loading beam was hoisted from one specimen to another for testing.

Test Procedure

The same test procedure was followed for all pushout tests. The specimens were first loaded until a substantial reduction in stiffness was observed in the load–displacement curve. Next, the specimens were unloaded to zero load and reloaded until the load–displacement curve indicated a maximum load had been reached or the shear displacement was excessive (approximately,

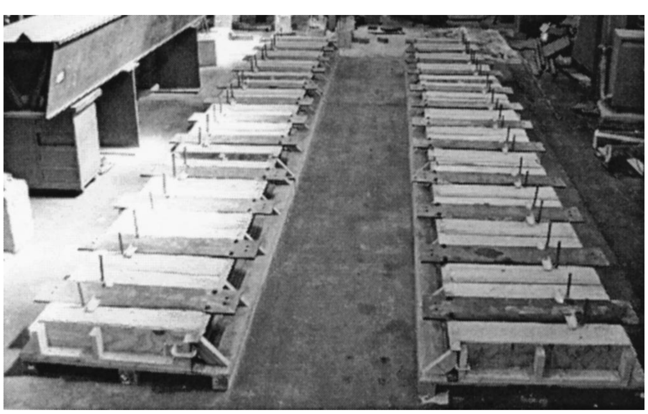

Fig. 5. View of all pushout test specimens

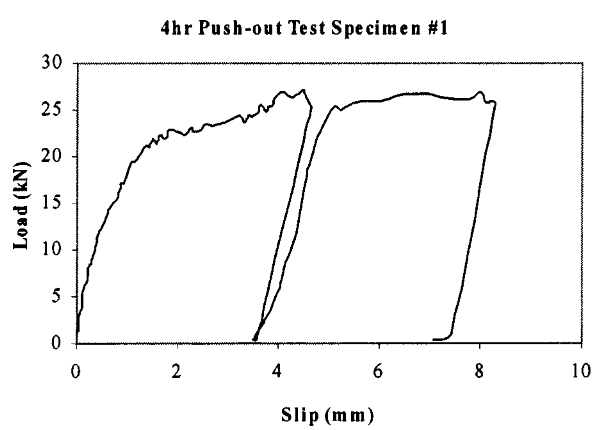

Fig. 6. Typical pushout test result

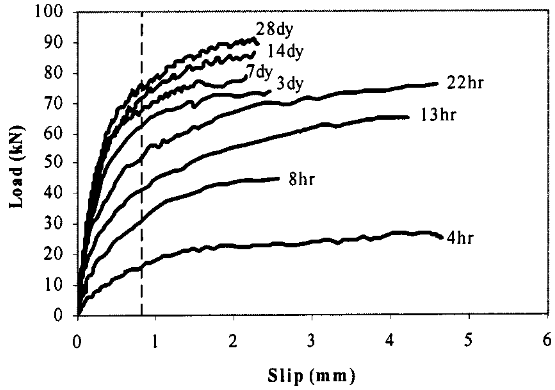

Fig. 7. Load–slip relationship from pushout tests

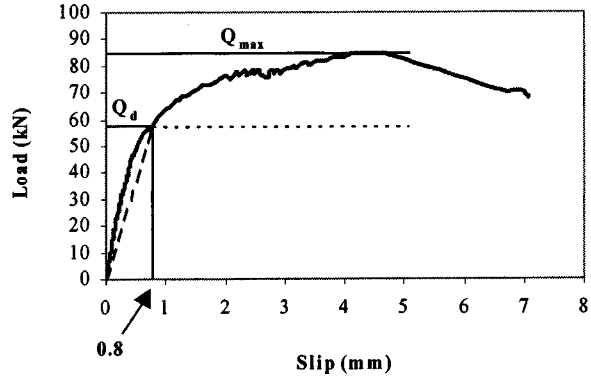

Fig. 8. Definition of design and maximum strength

one half of the stud diameter). Finally, the specimens were unloaded, and the loading beam was removed.

Concrete cylinders were tested under compression (ASTM C 39/C 39M-99) to determine the load–displacement curve. The loading procedure defined in ASTM C 469-94 (ASTM 1994) was used. Specimens were tested using a 2,700 kN (600 kip) compression test machine. A compressometer with a linear potentiometer was placed around the concrete cylinders to monitor the displacement. Because the test machine was load controlled, only the ascending branch of the load–displacement curve was obtained. In addition to compression tests, split cylinder tests were also performed in accordance with ASTM C 496-96 (ASTM 1996) procedures.

The approximate elapsed times for testing of the three pushout specimens, three compression specimens, and three split cylinder specimens were 30, 30, and 20 min, respectively. Therefore, each testing cycle took approximately 80 min to complete. The specimens were cast and air cured inside the laboratory where the ambient temperature was between 30 and 35°C (85–95°F) during the 28 day period.

Test Results

Pushout Tests

As mentioned earlier, three pushout tests were performed for each of the eight time periods. A typical load–displacement response obtained from a pushout test is given in Fig. 6. In addition, the first loading cycle of a representative test for all test times is presented in Fig. 7.

It is evident from the results that even at very early ages, studs exhibit considerable stiffness and strength. In order to quantify the results, certain definitions are required. As explained before, the failure load obtained from a pushout test was considered as the ultimate capacity of the shear stud. However, ultimate strength should not be used directly in design calculations because it imposes very high interface slip demands which a composite structure may not be able to tolerate. In a study by Wang (1998), the design resistance is taken as 80% of the ultimate resistance, and the stiffness is conservatively estimated as the secant stiffness at the design strength with an equivalent slip of 0.8 mm (0.03 in.). A similar yet different procedure is used in this study. The concept of design strength Q_d, which is based on a maximum allowable interface slip, is proposed. The design strength Q_d for studs with early-age or mature concrete is defined as the value of the load attained at a displacement value of 0.8 mm [0.03 in. (diameter/25)] (Fig. 8). This limit ensures that during the lifetime of the structure, the studs do not experience deformations in excess of 0.8 mm (diameter/25). The sensitivity in the definition of design strength was investigated by considering a range of slip limits in the vicinity of 0.8 mm (0.03 in.) of slip. Test results showed that defining the design strength based on slip values of 0.6 mm (0.025 in.) and 0.9 mm (0.035 in.) gives on average 6.7% lower and 5.7% higher design strength values, respectively. As can be seen from these values, design strength is not very sensitive to the slip level in the vicinity of 0.8 mm (0.03 in.).

Table 2. Pushout Test Results

	Stud design strength, Q_d kN (kips)				Stud maximum strength, Q_{max} kN (kips)			
	Specimen number				Specimen number			
Time	1	2	3	Average	1	2	3	Average
4 h	15.8 (3.6)	19.5 (4.4)	16.3 (3.7)	**17.2 (3.9)**	26.7 (6.0)	27.6 (6.2)	27.1 (6.1)	**27.1 (6.1)**
8 h	36.1 (8.1)	27.9 (6.3)	30.6 (6.9)	**31.5 (7.1)**	45.4 (10.2)	39.4 (8.9)	44.5 (10.0)	**43.1 (9.6)**
13 h	45.1 (10.1)	34.2 (7.7)	40.0 (9.0)	**39.8 (8.9)**	60.0 (13.5)	44.9 (10.1)	65.4 (14.7)	**56.8 (12.7)**
22 h	53.1 (11.9)	57.9 (13.0)	51.1 (11.5)	**54.0 (12.1)**	77.8 (17.5)	78.3 (17.6)	77.8 (17.5)	**78.0 (17.5)**
3 day	61.5 (13.8)	64.3 (14.5)	57.6 (13.0)	**61.1 (13.7)**	77.8 (17.5)	86.3 (19.4)	85.0 (19.1)	**83.0 (18.7)**
7 day	66.1 (14.9)	66.9 (15.0)	66.1 (14.9)	**66.3 (14.9)**	81.8 (18.4)	89.8 (20.2)	88.1 (19.8)	**86.6 (19.4)**
14 day	68.1 (15.3)	70.9 (16.0)	N.A.[a]	**69.5 (15.6)**	85.4 (19.2)	89.4 (20.1)	94.3 (21.2)	**89.7 (20.2)**
28 day	81.2 (18.3)	72.8 (16.4)	75.2 (17.0)	**76.4 (17.2)**	93.4 (21.0)	93.4 (21.0)	93.4 (21.0)	**93.4 (21.0)**

[a]Not available

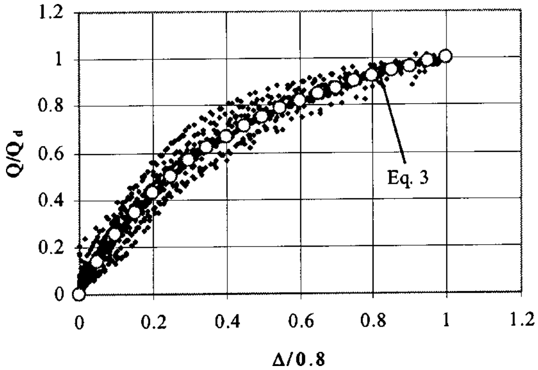

Fig. 9. Load–slip relation for shear studs

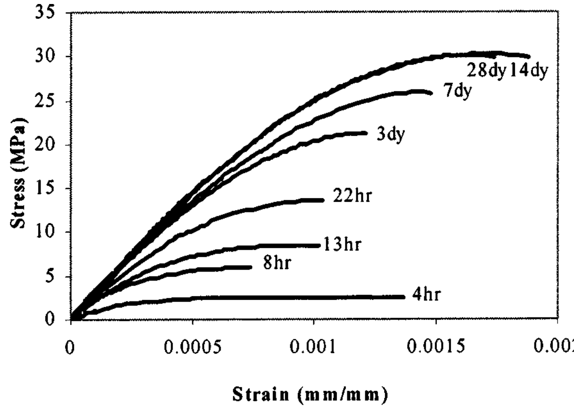

Fig. 10. Compressive stress–strain response

Maximum strength (Q_{max}) is defined as the maximum load attained during the test independent of the value of slip (Fig. 8). Because the specimens were not loaded to failure, the maximum strength at 28 days is expected to be lower than the ultimate value predicted by current design equations. The ultimate strength calculated using the AISC equation with measured concrete properties is 133 kN (30 kips). Table 2 summarizes the design and maximum strength values obtained from the pushout tests.

A mathematical representation of the load–slip behavior for shear studs is required for proper modeling of their response in structural analysis. For this purpose, a simple load–slip curve was developed. All load–displacement curves obtained from pushout tests were normalized with respect to design strength and 0.8 mm (0.03 in.) of displacement. All data are plotted on the same figure (Fig. 9). A fifth-degree polynomial with an R^2 value equal to 0.97 was fit to all the data. Subsequently, a simplified equation was developed that represents the fifth-degree curve. The proposed load–slip relationship is given by Eq. (3). This equation gives an initial tangent stiffness of $3.75\,Q_d$ and a secant stiffness at the design load of $1.25\,Q_d$.

$$\frac{Q}{Q_d}=\frac{3\left(\frac{\Delta}{0.8}\right)}{1+2\left(\frac{\Delta}{0.8}\right)} \tag{3}$$

where Δ is specified in millimeters and Q, Q_d are given in a consistent set of force units.

Tests for Determining Concrete Properties

Three compressive and three split cylinder tests were performed on concrete specimens for each time period. During the compressive tests, the displacement was monitored to obtain the stress–strain response. Table 3 summarizes the ultimate compressive strength, secant stiffness at 40% of ultimate strength and split cylinder test results for the concrete specimens. In addition, the stress–strain curves for compression are presented in Fig. 10.

Specimens reached almost 90% of the 28 day stiffness after a 22 h cure. At very early ages, the stress–strain response mimics elasto-plastic behavior. Specimens tested after 1 day exhibit a stress–strain response that is similar to the 28 day response. Fig. 11 presents the time dependence of concrete properties together with the pushout test results. For concrete, the rate of stiffness gain is much higher than the rate of strength gain. The stud maximum and design strength increases faster than concrete strength and slower than concrete stiffness.

Based on the concrete cylinder tests, the applicability of the existing ACI relation [Eq. (1)] in predicting the stiffness of early-age concrete was investigated. Fig. 12 shows a comparison of the

Table 3. Concrete Properties at Different Times

	Specimen number	Time							
		4 h	8 h	13 h	22 h	3 day	7 day	14 day	28 day
Compressive strength MPa (psi)	1	1.97 (286)	4.93 (715)	8.48(1230)	13.59(1970)	24.34(3530)	25.79(3740)	31.24(4530)	30.14(4370)
	2	2.10 (304)	5.74 (832)	8.48(1230)	12.62(1830)	21.24(3080)	30.48(4420)	30.69(4450)	30.14(4370)
	3	2.51 (364)	5.92 (859)	8.62(1250)	12.55(1820)	21.10(3060)	27.86(4040)	30.21(4380)	31.10(4510)
	Average	**2.19 (318)**	**5.53 (802)**	**8.53(1237)**	**12.92(1873)**	**22.23(3223)**	**28.05(4067)**	**30.71(4453)**	**30.46(4417)**
Compressive stiffness GPa (ksi)	1	8.41 (1220)	17.78(2578)	20.00(2900)	23.68(3433)	30.40(4408)	28.05(4067)	29.77(4316)	N.A.[a]
	2	N.A.[a]	19.32(2802)	22.86(3315)	26.68(3868)	27.85(4038)	31.39(4552)	30.81(4468)	28.61(4148)
	3	8.83 (1280)	21.60(3132)	22.10(3204)	25.15(3647)	27.06(3923)	33.03(4789)	29.94(4341)	29.22(4237)
	Average	**8.62 (1250)**	**19.57(2837)**	**21.65(3140)**	**25.17(3649)**	**28.43(4123)**	**30.82(4469)**	**30.17(4375)**	**28.91(4193)**
Tensile Strength MPa (psi)	1	0.26 (38)	0.73 (105)	0.82 (119)	1.92 (278)	2.26 (328)	2.58 (374)	2.35 (340)	2.59 (375)
	2	0.18 (25)	0.65 (93)	1.10 (159)	1.65 (238)	1.95 (282)	2.18 (315)	2.99 (433)	3.11 (450)
	3	0.22 (32)	0.68 (99)	0.98 (141)	1.73 (250)	2.02 (293)	2.20 (318)	3.11 (450)	3.05 (442)
	Average	**0.22 (32)**	**0.68 (99)**	**0.97 (139)**	**1.76 (255)**	**2.08 (301)**	**2.32 (335)**	**2.82 (408)**	**2.92 (422)**

[a]Not available

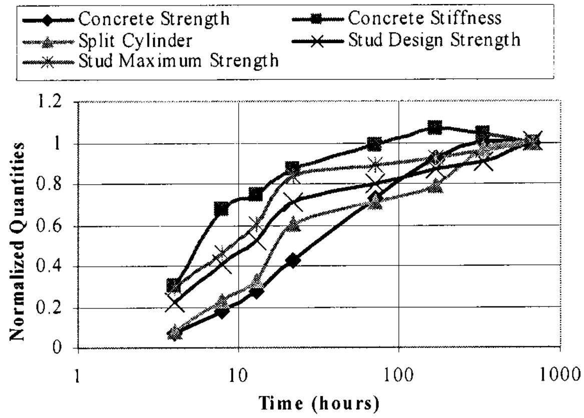

Fig. 11. Time dependence of properties

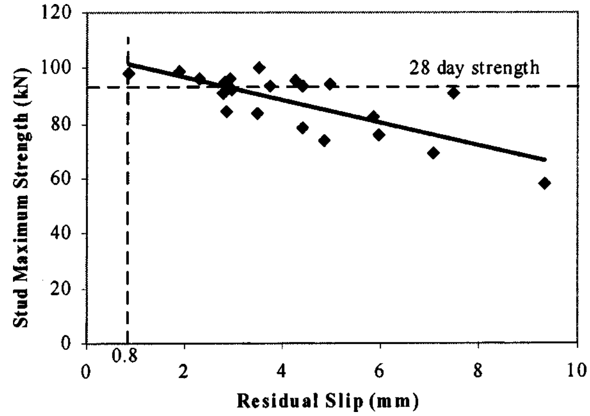

Fig. 13. Residual slip versus maximum strength for retested specimens

test results from four different researchers and the ACI relation. Examination of the data reveals that each set of data is consistent in itself. Data from the current study shows stiffer response, while data from Mo et al. (1998) exhibit more flexible behavior in comparison to ACI's relation. This result could be attributable to different mix designs used for concrete specimens. Also, differences in the stiffness of the aggregates used by the different researchers could cause scatter among test results (Mehta 1986). In general, the ACI relation is satisfactory and applicable in predicting the stiffness of concrete at early ages given its strength.

Retesting Specimens at 28 Days

The effect of loading studs in early-age concrete on the long-term performance was investigated. For this purpose, all specimens were retested after 28 days using the same testing procedure outlined previously. During the original tests, specimens were loaded to different displacement limits. The residual slip level attained in earlier tests is an indication of damage to the early-age concrete. Fig. 13 shows the effect of the level of damage on the long-term ultimate performance of shear studs. For each test specimen, the residual slip value from initial tests was plotted versus the maximum load reached during retesting at 28 days. According to the trend line fitted to the data, the maximum capacity of the stud decreases as the level of damage increases. In addition, the plot reveals that studs loaded to the recommended design displacement value of 0.8 mm (0.03 in.) at early concrete ages are capable of developing their full strength after 28 days.

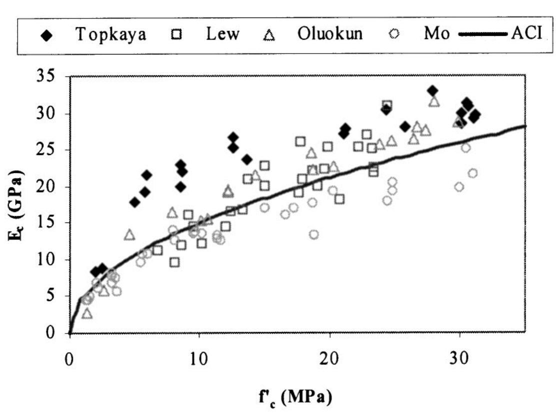

Fig. 12. Concrete stiffness test results

Another observation on the load–slip behavior of retested studs is worth mentioning. Although pretested studs may develop their full capacity at 28 days, there might be a change in their initial stiffness. Fig. 14 qualitatively represents this phenomenon. Load–displacement curves for two specimens are presented. The first specimen was tested at 13 h while the second one was tested at 14 days. Both specimens were retested at 28 days, and they both developed their full capacity. However, for the 13 h specimen, the retesting curve has a very low initial stiffness compared to the 14 day specimen. This observation shows that for specimens tested at very early ages, localized concrete damage around the stud weld location causes a void that results in further stiffness reduction of the overall system.

Effect of Surface Bond

The test setup was designed to obtain the load–slip relation for shear studs by minimizing the effects of bond occurring at the concrete–flat plate interface. This minimization was achieved by wrapping plastic sheets around the steel flat plates. In order to investigate the necessity of these sheets for a standardized test, the plate of one specimen was left unwrapped. This specimen belonged to the group of specimens that were tested at 14 days. Fig. 15 presents the load–slip relationship for this set of specimens. It is clear from the curves that bond between the steel and the concrete influences the initial stiffness of the studs. The secant stiffness at 0.1 mm (0.004 in.) slip was 441 kN/mm (2,500 kip/in.) and 213 kN/mm (1,200 kip/in.) for the unwrapped and wrapped specimens, respectively. For a standardized test, bond should be minimized to obtain conservative initial stiffness values. The use of plastic sheets is one way to eliminate the bond.

Recommendations for Stud Maximum and Design Strength

Based on the experimental data gathered, equations for estimating the design and maximum strength of shear studs were developed. These expressions are applicable to both mature and early-age concretes. The resulting expressions were developed in such a way that they have a form similar to the ones used in the current design specifications. Load on the stud was normalized by the cross-sectional area of the shear connector. Regression analyses were performed to determine the dependence of concrete parameters on the design and maximum connector strength. The coefficients obtained from regression analyses were rounded off to sim-

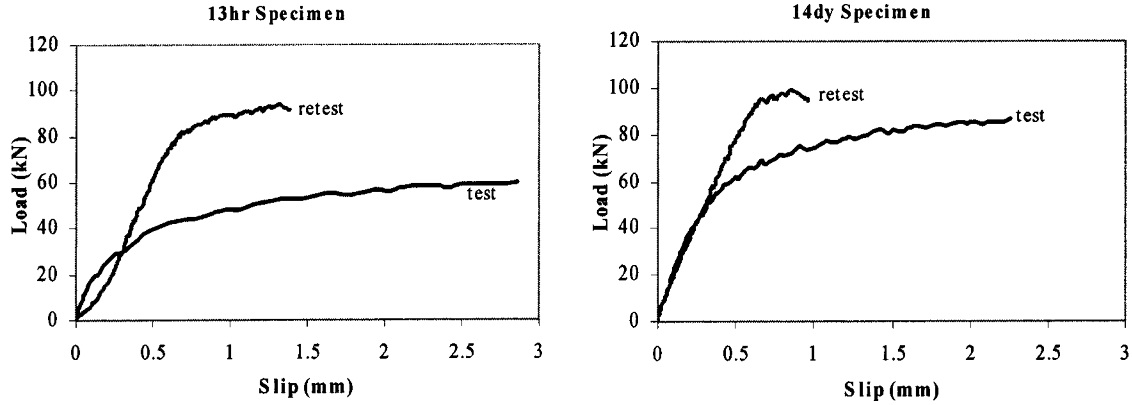

Fig. 14. Load–slip behavior of retested specimens

plify the equations for estimating the design and maximum strength of shear connectors based on early-age concrete properties [Eqs. (4) and (5)]. Fig. 16 compares the experimental data with the values obtained using Eqs. (4) and (5)

$$\frac{Q_{\max}}{A_{\mathrm{sc}}}=5.4(f_c'E_c)^{0.3}\ \ (\mathrm{SI})$$
$$\frac{Q_{\max}}{A_{\mathrm{sc}}}=2.5(f_c'E_c)^{0.3}\ \ (\text{English Units}) \tag{4}$$

$$\frac{Q_d}{A_{\mathrm{sc}}}=3.8(f_c'E_c)^{0.3}\ \ (\mathrm{SI})$$
$$\frac{Q_d}{A_{\mathrm{sc}}}=1.75(f_c'E_c)^{0.3}(\text{English Units}) \tag{5}$$

The units to be used in the above equations are MPa (ksi) for f_c' and E_c, mm^2(in.^{2}) for A_{sc}, and N (kips) for $Q_{\max}$ and Q_d. For the group of specimens that were analyzed, Eq. (4) provides test/estimate ratios with a mean of 0.97 and a coefficient of variation of 0.08. The corresponding mean and coefficient of variation values for Eq. (5) are 1.01 and 0.11, respectively.

The information presented can be used to investigate the behavior of bridges during construction. The concrete properties required in the developed equations can be obtained by testing concrete cylinders for the particular mix that is used if it is different from that reported herein. Furthermore, if a database on the mechanical properties of a certain concrete mix as a function of time and environmental conditions is available, then it could also be used in predicting the required quantities. In a study by Topkaya (2002), the stud and concrete stiffness recommendations developed in this paper were used in the structural analysis of an existing bridge that was monitored during construction. The analytical predictions showed good correlation with the field observations.

Future Research Needs

Several factors need further investigation to provide a better understanding of the behavior of shear studs surrounded by early-age concrete. These factors can be summarized as follows:

1. Only one type of concrete mix design was used in the push-out tests reported in this study. The variation of stud design strength and stiffness with time is influenced by the type of concrete and curing conditions. This study aimed to quantify the strength and stiffness values as a function of the mechanical properties of concrete. Time and curing conditions were excluded in all the developed equations. Future research should concentrate on the development of strength and stiffness equations for shear studs embedded in concretes with different mix designs and subjected to different

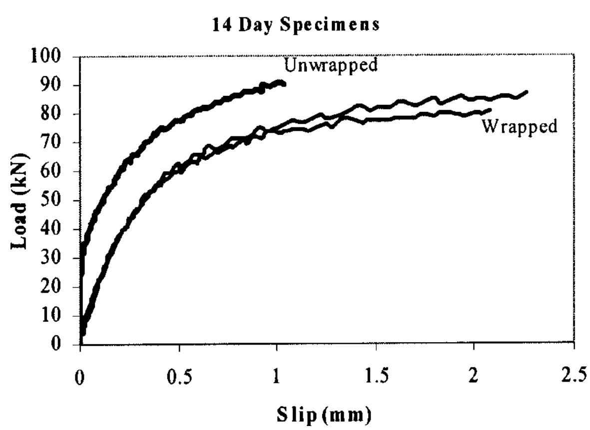

Fig. 15. Effect of steel surface treatment on stud behavior

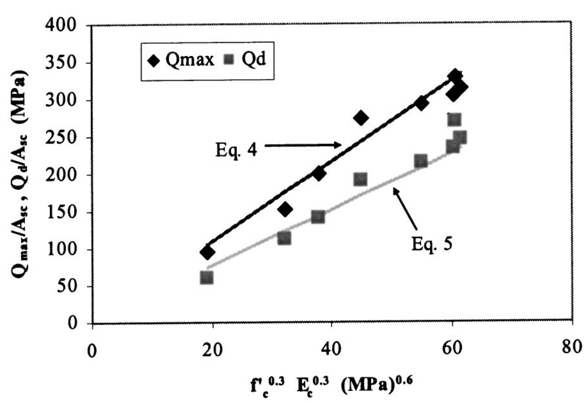

Fig. 16. Stud strength results and recommendations

curing conditions. The possibility of using maturity index for predicting stud properties should be examined.
2. The slab geometry was not considered to be an experimental variable in this study. However, most slabs in practice have haunches and ribbed metal decks. The behavior of shear studs in early-age concrete with different slab conditions needs further investigation.
3. All shear studs used in this study were of the same type and configuration. Future research should focus on the behavior of studs with different spacing and configuration as well as different area and height.

Conclusions

Behavior of shear studs embedded in early-age concrete was presented. Current test methods used for shear stud investigations are not suitable for specimens with early-age concrete. A new pushout test setup was proposed for testing studs surrounded by early-age concrete. Pushout tests were performed at times ranging from 4 h to 28 days after concrete casting. Results obtained in this study support the following conclusions:

1. The proposed pushout test provides an easy and quick method for investigating shear studs embedded in early-age concrete. The setup does not enable the premature separation of the steel–concrete interface and is not influenced by frictional forces developing at the base. This setup could potentially replace existing ones.
2. The concept of design strength was proposed for shear studs. The design strength is based on an interface slip limit and is defined as the load attained at a slip of 0.8 mm (0.03 in. =diameter/25).
3. For the specific type of concrete under the curing conditions mentioned in this study, shear transfer is achieved as early as 4 h. Studs develop considerable strength and stiffness even at very early ages.
4. Equations for predicting the design strength and stiffness of shear studs embedded in early age concrete were developed. These equations are based on the mechanical properties of early-age concrete.
5. The use of existing relations for predicting the stiffness of early-age concrete was investigated. The current ACI equation was found satisfactory for this purpose.
6. The effects of loading early-age concrete were examined. Test results showed that the maximum capacity decreases when the residual slip increases. Studs deformed up to the interface slip limit at early ages were able to develop their full strength at 28 days. Excessive deformations at early ages might also cause a decrease in initial stiffness of the studs.

Acknowledgments

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