COMPARISON OF PULLOUT STRENGTH OF HEADED STUDS IN NORMAL AND LIGHTWEIGHT CONCRETES

Marcus L. Knight, Ph.D., P.E., Middle Tennessee State University, Murfreesboro, TN

ABSTRACT

Precast concrete elements are frequently constructed utilizing varying coarse aggregates for a variety of reasons including architectural appearances, local availability, reduced transportation costs and reductions in dead weight to help minimize the size of structural members and reduce seismic forces. Embedded items utilizing headed studs are cast in such elements for various reasons including connection of structural members together and to attach architectural cladding. The research study presented herein investigated the differences in pullout strength of headed studs in concretes made with traditional crushed limestone aggregate (control) and three other frequently used coarse aggregates including river gravel, expanded slate, and expanded clay. Four mixes were tested that differed in water content and aggregate type with similar plastic and hardened properties. Specimens were cast with embedded headed studs and tested in tension until failure following ASTM C900. The test results were examined and significant differences were identified in the tensile force required to fail the headed stud/concrete connection when comparing different aggregates. The results suggested that aggregate specific factors may be needed for accurate and efficient calculation of design capacities and that the tensile strength of the concrete may be appropriate for use in determining design strengths.

Keywords: Headed stud, pullout strength, lightweight concrete

INTRODUCTION

Precast concrete elements are frequently constructed utilizing varying coarse aggregates for a variety of reasons including architectural appearances, local availability, reduced transportation costs and reductions in dead weight to help minimize the size of structural members and reduce seismic forces. Embedded items utilizing headed studs are cast in such elements for various reasons including connection of structural members together and to attach architectural cladding. Connections must be designed in these elements following standard design guidelines that are developed and adjusted to address all situations. The study presented herein examined these relationships through laboratory tensile testing of headed studs cast in different types of concrete.

BACKGROUND

Much work has been done in both laboratory tests and computational work when considering the capacity of headed studs (acting individually or as part of a group) in shear, tension, and combinations of both[1]. Building codes, such as ACI 318 "*Building Code Requirements for Structural Concrete*" and design guidelines such as the "*PCI Design Handbook*" address the design capacities of such connections [2,3]. These guidelines have been updated several times throughout the past decades as understanding of the failure mechanisms has improved [1]. Although these changes have been made, several similarities have been mainstays in the relationship used to determine the design capacities of these anchors. The most obvious of these similarities is the use of concrete compressive strength.

The simplest of these connections is a one stud configuration and the most basic type of loading for such connections is pure tension. The two primary failure mechanisms include failure of the steel stud itself and failure of the surrounding concrete. Failure of the steel stud in pure tension is fairly well understood with applicable design relationships. However, understanding all of the factors that affect the failure of the concrete in this loading situation, as well as providing a relationship for design purposes that efficiently and accurately guides the designer in all situations is more complex and contains several additional considerations.

The sixth edition of the *PCI Design Handbook* identifies three basic failure mechanisms that must be checked to determine the tensile capacity of a stud based on concrete failure. These include breakout, pullout, and side-face blowout, with the design capacity taken as the minimum of the three calculations [3].

The relationship for breakout (N_{cb}) provides a design capacity based on a conical failure of the concrete in the surrounding area of the stud head and is illustrated in Equation 1 below [3]. This relationship is based on the compressive strength of concrete (f'_c), the effective embedment depth (h_{ef}), a concrete density factor (λ), and several additional factors including a cracking factor (C_{crb}), projected surface area for the failure cone (A_N), an edge distance factor (ψ_{ed}), and if needed, an eccentricity factor ($\psi_{ed,N}$).

$$N_{cb} = 3.33\lambda \sqrt{\frac{f'_c}{h_{ef}}} A_N C_{crb} \psi_{ed,N} \qquad \text{Equation 1}$$

The concrete density factor (λ) accounts for the differences in performance based on the density of the concrete and is taken as 1.0 for normal weight concrete, 0.85 for sand lightweight concrete, and 0.75 for all lightweight concrete [3]. The effective embedment length is the embedment between the concrete surface to the nearest face of the stud head plus the thickness of any attached plates and minus any weld burn off during stud attachment. The cracking coefficient is used to reduce the design values when it is assumed that the section of concrete in the vicinity of the stud will be cracked and is taken as 1.0 for uncracked concrete and 0.8 for locations where concrete is likely to become cracked. Finally, the edge distance factor (ψ_{ed}) is calculated following Equation 2 where $d_{e,min}$ is the minimum distance from the center of any stud to the edge of the concrete member [3].

$$\psi_{ed,N} = 0.7 + 0.3\left(\frac{d_{e,\min}}{1.5h_{ef}}\right) \leq 1.0 \qquad \text{Equation 2}$$

The pullout strength (N_{pn}) calculation is used to determine the capacity of the stud if failure is attributable to crushing from the bearing of the stud head against the concrete while loaded in tension [3]. This relationship is provided in Equation 3 and is based on the bearing area of the stud in tension (A_{brg}), compressive strength (f'_c), and a cracking coefficient (C_{crp}) to account for differences in sections that remain uncracked ($C_{crp} = 1.0$) and those likely to become cracked ($C_{crp} = 0.70$).

$$N_{pn} = 11.2 A_{brg} f'_c C_{crp} \qquad \text{Equation 3}$$

The third failure mode, side face blowout (N_{sb}), can be calculated using Equation 4 [3]. This is only required when the edge distance (d_e = distance between the center of the stud and edge of concrete) is less than $0.4h_{ef}$. If required, the calculation is based on the distance from a stud to the closest edge (d_{e1}), the area of the head (A_{brg}), and compressive strength (f'_c). There are also multipliers for situations with multiple stud configurations.

$$N_{sb} = 160 d_{e1} \sqrt{A_{brg}} \sqrt{f'_c} \qquad \text{Equation 4}$$

The breakout and pullout loads were calculated for a single stud embedded in concrete of varying compressive strengths. The stud was assumed to have a 0.75 inch shaft diameter, 1.25 inch head diameter, 0.375 inch head thickness, and to be embedded such that no edge conditions or cracking was present. Also, the stud was assumed to be embedded in normal weight, sand lightweight, and all lightweight concretes for comparison. The design breakout loads, following equations 1 and 2, are plotted in Figure 1. As shown, the breakout load for normal weight concrete ranged from approximately 2,700 pounds to 3,700 pounds. The values for sand lightweight and all lightweight concrete are also provided. As shown, these lines are replicas of the normal weight data, only shifted lower due to the influence of the concrete density factor.

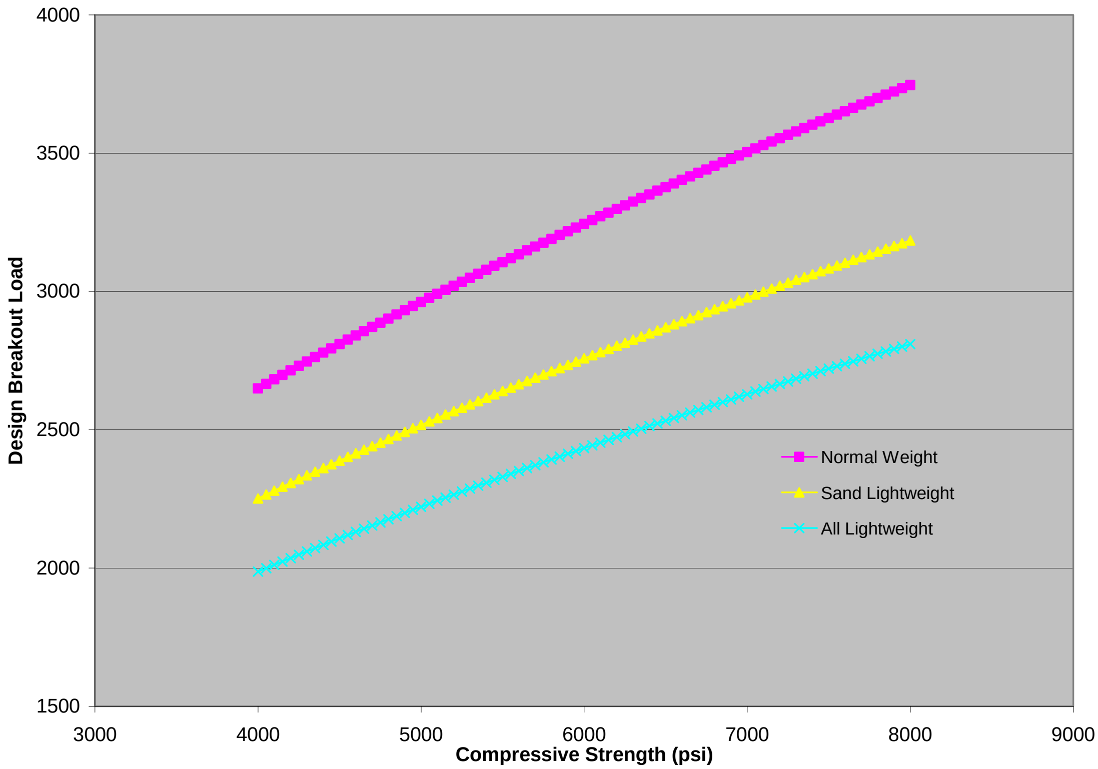

Fig. 1 Design Breakout Load (lbs) for Varying Compressive Strengths

The data for pullout load is provided in Figure 2. As shown, the design pullout load is consistent across all weights of concrete and is linearly proportional to compressive strength. Although pullout is not a reasonable failure mode for the stud configuration chosen, as the graph indicates failure loads greater than the tensile capacity of the stud itself, this failure mechanism may become more prevalent in other possible stud configurations (groups of studs, small edge spacing, etc.). Data was not provided for side-face blowout due to the assumption of no edge conditions.

Relationships similar to those in Equation 1 thru Equation 4 are also available in Appendix D of ACI 318 [2]. Of the three failure types, the most likely to occur is breakout around the embedded stud. Regardless of the design standard that is

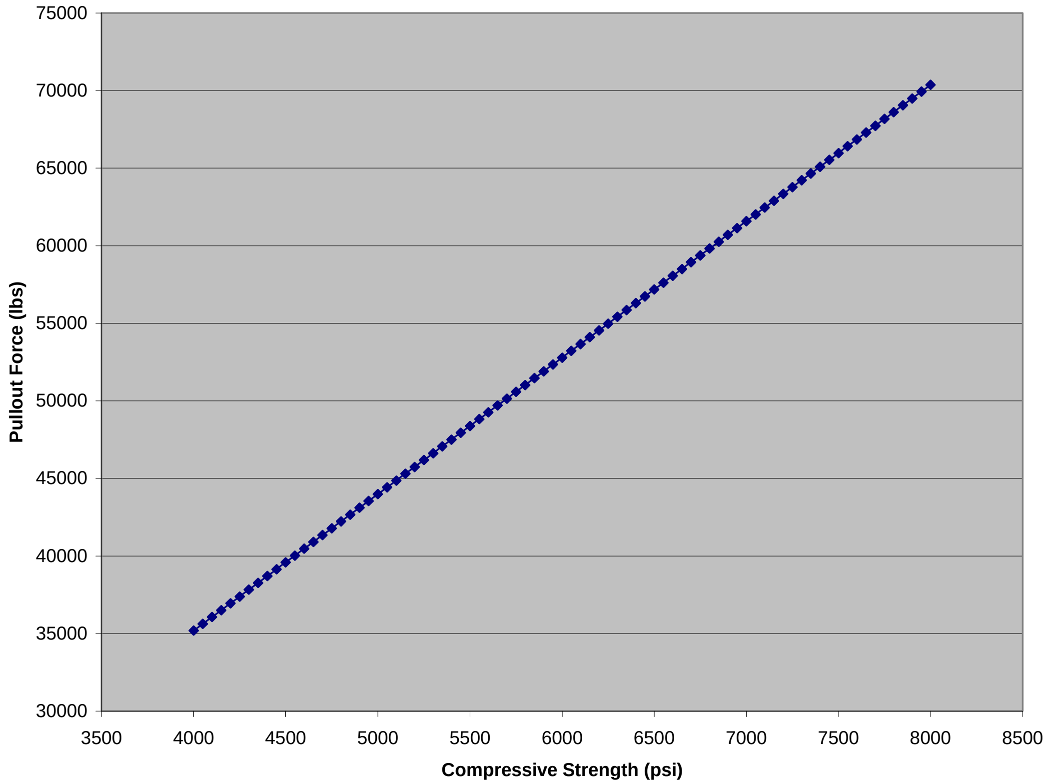

Fig. 2 Design Pullout Load for Varying Compressive Strengths

utilized, the relationship between the expected or design load and material properties for this failure mechanism is the square root of compressive strength.

PURPOSE

The purpose of the research study presented herein was to compare the ultimate tensile pullout capacitates of headed studs embedded in normal and lightweight concretes. As previously noted, current codes and design guidelines require a modification factor to be applied that reduces the design capacity of the stud if the concrete is made with a lightweight coarse aggregate and/or lightweight fine aggregate. The study was aimed at a comparison of the pullout capacities of specimens made with similar concrete strengths and headed studs embedded in similar configurations. Although current codes address these differences, this study focused on confirmation of the design factors accounting for differences in aggregates used when considering pure tensile loading.

METHODOLOGY

To determine the magnitude of difference that exists between pullout strength of headed studs in concretes made with different types of coarse aggregates, specimens were created from four different batches of concrete that differed only in coarse aggregates type. Headed studs were embedded at consistent depths in each of the specimens. Subsequent to curing, each of the studs was loaded in tension until failure. Where applicable, the study followed the guidance in ASTM C900 – *"Standard Test Method for Pullout Strength of Hardened Concrete"* [4].

MATERIALS

COARSE AGGREGATES

Four coarse aggregates were chosen for the study including two locally available normal weight aggregates and two commonly used lightweight aggregates. The normal weight aggregates consisted of crushed limestone and river gravel and the lightweight aggregates consisted of expanded slate and expanded clay. Laboratory tests were completed to identify the gradations, absorptions, and unit weight of each aggregate.

Crushed Limestone

Crushed limestone was obtained from the nearest local supplier. The aggregate was fairly angular with slight to moderate dust. The engineering properties of this aggregate are shown in Table 1. Laboratory results indicated that the crushed limestone met the #67 gradation with maximum and nominal maximum sizes of 0.75 inches and 0.375 inches, respectively. The aggregate was found to have a relatively low absorption of 0.7%.

Table 1 Coarse Aggregate Properties

Aggregate Type	Unit Weight (lb/ft^3)	Absorption (%)
Crushed Limestone	158.8	0.7
River Gravel	155.7	0.9
Expanded Slate	46.5 (dry loose)	6.1
Expanded Clay	41.3 (dry loose)	19.8

River Gravel

River gravel was also obtained from a local supplier. This aggregate was very smooth, rounded, and considerably cleaner (less dust) that the crushed limestone. This aggregate was found to meet the #7 gradation with a 0.75 inch maximum size and a 0.5 inch nominal maximum size. The river gravel's engineering properties are provided in Table 1.

Expanded Slate

Expanded slate coarse aggregate was obtained from an out-of-area supplier. The engineering properties of the aggregate were determined. The aggregate met the #67 gradation with maximum and nominal maximum sizes of 1.0 inch and 0.75 inches, respectively. The remaining engineering properties of the aggregate are provided in Table 1.

Expanded Clay

Coarse aggregate consisting of expanded clay was obtained for another out-of-area supplier. The expanded clay aggregate consisted of a #8 gradation with maximum and nominal maximum sizes of 0.50 and 0.375 inches respectively. The absorption and unit weight of this aggregate were calculated and are listed in Table 1.

FINE AGGREGATE

The fine aggregate chosen for the project consisted of a natural sand meeting the gradation requirements of ASTM C33. The other materials properties of this aggregate were also determined including unit weight, fineness modulus, and absorption. These properties are provided in Table 2. This natural sand was used in each of the four different mix designs to maintain consistency throughout the results.

Table 2 Natural Sand Properties

Property	Result
Unit Weight (lb/ft^3)	156.4
Absorption (%)	1.1
Fineness Modulus	2.72

CEMENT AND WATER

Type III Portland Cement was used for each of the mix designs. Although Type III was not required to meet strength requirements, it was used to more accurately follow site conditions at a typical precast concrete plant where speed of operation is of great importance. All cement for the research study was from the same batch and supplier to prevent any apparent differences due to differences in cement producer, age, etc. Tap water was used for each mix design and for conditioning of aggregates.

STEEL STUDS

Standard steel studs for the research study were obtained from a local supplier. The studs were 4.1875 inches long with shaft diameter of 0.75 inch. The head thickness was 0.375 inch with a diameter of 1.250 inches. To facilitate accurate embedment of the studs in concrete specimens, and attachment of the loading device for testing, the first two inches of each stud shaft were machined with threads (16/inch). Changes in the results of the study were not anticipated due to this threading process because stud failure was not within the scope of the study and the combination of embedment length and thread length used ensured that no threads would be embedded in concrete. Information from the stud supplier indicated that the studs met or exceeded the standard criteria including yield strength (51,000 psi @ 0.2% offset), tensile strength (65,000 psi minimum), elongations (min 20%in 2 in.), and reduction of area (50% minimum).

MIX DESIGNS

A control mix design was developed for use with each of the four different coarse aggregates. The control mix design was based on using crushed limestone as the coarse aggregate, with the remaining mix designs varying only coarse aggregate type/weight and water content to maintain similar consistency and account for actual aggregate moisture conditions. A target compressive strength of 6,000 psi was chosen for the control mix, understanding that the strengths of the remaining three mixes would vary with coarse aggregate type used. Each of the aggregates was moisture conditioned to approximate saturated surface dry condition prior to mixing to minimize adjustments in mix water and to maintain consistency. Each of the mix designs used for the study are illustrated in Table 3.

Table 3 Mix Proportions

Aggregate Type	Water (lbs)	Cement (lbs)	Coarse Aggregate (lbs)	Fine Aggregate (lbs)
Crushed Limestone	19.8	47.1	1842.8	1228.5
River Gravel	19.8	47.1	1818.5	1228.5
Expanded Slate	19.8	47.1	1146.2	1228.5
Expanded Clay	19.8	47.1	967.95	1228.5

SAMPLE PREPARATION/CONFIGURATION

Samples consisted of small rectangular beams with dimensions of 8 inches by 8 inches with studs embedded at a spacing of 8 inches on center. An embedment length of 1.25 inches was selected following ASTM C900 suggested practice. Beams were fabricated long enough to accommodate 5 embedded studs.

Each of the four designs was batched, mixed, plastic tests were performed, and cylinders cast prior to sample fabrication. Beams were completed by filling in two layers of equal volume. Consolidation included internal vibration and mallet taps along the outside of the forms prior to placement of the next layer. Finishing of the beams consisted of basic strike off with a steel rod and floating with a standard trowel.

Beams and cylinders were allowed to match cure in similar conditions (approximately 70 degrees Fahrenheit and 60% humidity) until testing. Cylinders and beams were removed from forms/molds at the same age (2 days).

TEST APPARATUS/PROCEDURES

The test apparatus consisted of a bearing plate, center pull jack for load application, load cell to measure the applied tensile force, a data acquisition system to report and record the data, and a steel rod to connect the load apparatus to the embedded stud. The bearing plate was steel, with a thickness of 1/2 inch with a 2 ¾ inch diameter center hole, both of which met the requirements of ASTM C900. The jack was rated at 60 kips and the load cell was rated at 50 kips. The steel connecting rod was threaded on one end to match a threaded insert on the load cell and drilled and tapped on the other end with threads to match those on the projection of the headed studs.

The set-up for performing a tensile test began by placing/centering the bearing plate around the embedded stud. The threaded rod was then tightened onto the headed stud. The jack was then placed over the steel rod and allowed to rest on the bearing plate with the threaded end of the connecting rod protruding from the top of the jack. Finally, the load cell was connected/tightened to the threaded end of the connecting rod and the data acquisition system was installed.

After setup was complete, each stud was tested in tension until failure. Loading was applied through the use of a manual pump attached to the center pull jack. Load was applied at the approximate rate as specified in ASTM C900 and care was taken to not impact load the specimens. All tests were completed in the same manner and at the same age.

RESULTS

PLASTIC CONCRETE PROPERTIES

The plastic properties for each of the mix designs are provided in Table 4. Results for Temperature and slump were fairly consistent. Results for unit weight varied considerably as expected.

Table 4 Plastic Properties

Aggregate Type	Unit Weight (lb/ft^3)	Slump (in.)	Temperature (deg F)
Crushed Limestone	147.2	1.75	71
River Gravel	146.3	2.25	72
Expanded Slate	121.4	2.0	71
Expanded Clay	114.8	0.75	70

HARDENED CONCRETE PROPERTIES

One set of cylinders from each mix design were tested on the day of pullout testing. The results from these tests are provided in Table 5. As shown, compressive strength ranges from a high of 6,640 psi with the expanded slate aggregate to a low of 5,400 psi for the expanded clay aggregate with the two normal weight aggregate designs in between.

Table 5 Compressive Strength Results

Aggregate Type	Compressive Strength (psi)
Crushed Limestone	6,090
River Gravel	5,950
Expanded Slate	6,640
Expanded Clay	5,400

PULLOUT LOADS

Results of the pullout tests for each of the different mix designs are provided in Table 6. As shown, the failure loads of the different mix designs varied considerably. Failures were as expected and involved a pullout cone (diameter equal to the hole in the bearing plate) and subsequent cracking of the concrete in the vicinity of the embedded stud. One test was deemed invalid due to improper placement of the headed stud (River Gravel No. 5) and was omitted from the results data.

Table 6 Failure Loads

Aggregate Type	Failure Load (lbs)					
	No. 1	No. 2	No. 3	No. 4	No. 5	Average
Crushed Limestone	6,386	6,915	6,366	6,068	5,761	6,299
River Gravel	4,230	4,785	6,188	5,818	---	5,255
Expanded Slate	5,704	4,988	4,300	4,745	6,000	5,147
Expanded Clay	3,439	3,601	4,572	4,254	3,769	3,927

ANALYSIS OF RESULTS

Prior to further analysis, the results for the laboratory testing were reviewed to verify that all sets of tests met the single operator precision criteria set forth in ATM C900. The results of these calculations are provided in Table 7 and indicate that all tests were acceptably within the +/- 31% of their respective average with a maximum of 17.7% above (River Gravel No. 3) the average and a minimum of 19.5% below (River Gravel No. 1) the average.

Table 7 Precision Check

Aggregate Type	Individual Test Percentage of Average				
	No. 1	No. 2	No. 3	No. 4	No. 5
Crushed Limestone	101.4	109.8	101.1	96.3	91.5
River Gravel	80.5	91.1	117.7	110.7	---
Expanded Slate	110.8	96.9	83.5	92.2	116.6
Expanded Clay	87.6	91.7	116.4	108.3	96.0

The results from the pullout tests were also used to calculate the failure stresses assuming the conical failure as provided in ASTM C900. The results of these calculations are provided in Table 8.

Table 8 Failure Stresses

Aggregate Type	Failure Stress (psi)					
	No. 1	No. 2	No. 3	No. 4	No. 5	Average
Crushed Limestone	359.5	389.3	358.4	341.6	324.3	354.6
River Gravel	238.1	269.4	348.4	327.5	---	295.9
Expanded Slate	321.1	280.8	242.1	267.1	337.8	289.8
Expanded Clay	193.6	202.7	257.4	239.5	212.2	221.1

Although considerable information is available form these results, a method for comparison between the different mixes with different compressive strengths was needed. Due to the failure mechanism noted, the use of Equation 1 to serve as a starting point was deemed appropriate. The crushed limestone mix was used as the control and adjusted to provide an expected result for each of the three additional mixes. Assuming that the design equations were representative of the actual laboratory data, the relationship between the limestone and river gravel mixes would simply be the ratio of the square root of their respective compressive strengths multiplied through the original laboratory data. This same conversion was also true when considering the two lightweight mixes with the addition of the concrete density factor. Results for this conversion for each of these mix designs are provided in Tables 9 and 10.

Table 9 Calculation of Expected Failure Load

Aggregate Type	Compressive Strength (psi)	Control Ratio	λ
Crushed Limestone	6,090	1.000	1.00
River Gravel	5,950	0.988	1.00
Expanded Slate	6,640	1.044	0.85
Expanded Clay	5,400	0.942	0.85

Table 10 Calculation of Expected Failure Load (cont)

Aggregate Type	Average Failure Load (lbs)	Adjusted Control Load (lbs)	Percent of Average (%)
Crushed Limestone	6,299	6,299	100.00
River Gravel	5,255	6,223	118.42
Expanded Slate	5,147	5,590	108.61
Expanded Clay	3,927	5,044	128.44

The results presented in Tables 9 and 10 indicate that the prediction of load based on the control was higher that the actual load in each of the lightweight cases and ranged from approximately 8 percent to 28 percent above the actual results. Also of note, a considerable difference existed between the results of the limestone and river gravel mixes, both considered normal weight. In contrast to the laboratory results, current design procedures would result in similar design capacities of each of these normal weight mixes.

CONCLUSIONS

A study was completed that investigated the pullout strength of headed studs in concretes of similar strengths made with different coarse aggregates. The limited results from the study suggest that the relationships currently used for design of embedded stud connections may be suitable in specific situations. However, in the cases of river gravel and expanded clay aggregates, the study presented herein suggests that the relationship may need further adjustments. The results from the study also indicate that the density factor may not be appropriate for all lightweight aggregates as the design assumption may have over estimated the relationship between normal weight and lightweight concrete. Although the results suggest an over estimation of strength, a more reasonable conclusion is that the design criteria are conservative in nature and have been developed to cover a wide range of aggregate types. Finally, the spread in data resulting from this study suggest that a correction factor may need to be developed on an aggregate specific basis or that the relationships used for design capacities need to be based on the specified tensile strength of the concrete in question. A good first step in this process may be to expand the study presented herein to generate more data across a wider variety of aggregate types, compressive strengths, and stud configurations in order to validate the need for development of such aggregate specific factors or relationships based on tensile strength of concrete.

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