DEVELOPMENT LENGTH OF STANDARD HOOKS IN SPECIFIED DENSITY CONCRETE

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ABSTRACT

Current building codes and design guidelines, such as ACI 318 and the AASHTO LRFD Bridge Design Specifications, require development lengths of reinforcing bars placed in lightweight concrete to be increased by approximately thirty percent as compared to similar bars in regular weight concrete. Specified density concrete, with unit weights between lightweight and normal weight concrete, has gained popularity in the precast concrete industry due to several factors including longer span lengths and reduced transportation costs. Although the hardened properties of these specified density concretes are understood, under current design practices the development length of reinforcing steel must be increased in the same fashion as lightweight concrete.

This paper discusses results from a research study that investigated differences in the failure load required to yield reinforcing bars cast in both normal (145 pcf) and specified density (125 pcf) concretes. The main purpose of the study was to validate the need for an increase in development length when considering standard hooks in tension cast in specified density concretes. The test method consisted of pouring specimens of both concrete types with reinforcing bars with 90 degree bends placed so that a variety of embedment depths could be tested. Results were compared to validate the need for increased development length when considering specified density concrete.

Keywords: Bond Strength, Development Length, Specified Density Concrete

INTRODUCTION

Current building codes and bridge design guidelines require reinforcing steel to be embedded to a specified development length beyond a critical section in order to fully develop the tensile strength of the bar. In many instances, the required development length of a straight bar exceeds the geometric dimensions of the structural member such as a column, beam, or footing. In these instances, the bar may be developed through the use of a standard hook consisting of a 90 or 180 degree bend. These hooks reduce the length of bar needed and generally allow bar development in a smaller structural section.

These same standards require that the development length of reinforcing bars with standard hooks placed in concrete containing lightweight aggregates to be increased by approximately thirty percent as compared to similar bars in normal weight concrete. Concretes with unit weights between lightweight and normal weight concrete, sometimes referred to as specified density concrete, are not specifically addressed when considering development length with standard hooks. This type of concrete has gained popularity due to several factors including increased span lengths of members with similar cross sections, reduced transportation costs, and reduced erection costs. Currently, specified density concrete must be approached in the same manner as lightweight concrete when calculation of development length is considered.

While the basic properties (strength, unit weight, etc) of specified density concrete are well understood, little research has been published in relation to its bond strength and the required development length of reinforcing steel. Investigation of the bond strength characteristics and development length required for reinforcing steel in these types of concretes may lead to a better understanding of these physical properties and either validate current requirements or support a change in the code-required increase when using specified density concrete. The latter option would improve efficiency in both cost and use of materials when constructing reinforced specified density concrete structures or structural elements.

SPECIFIED DENSITY CONCRETE

The primary difference between specified density and normal density concrete is unit weight. This type of concrete can be produced by a basic replacement of a portion of the regular weight aggregate with lightweight aggregate. As the percentage of replacement increases, the unit weight decreases and approaches that of lightweight concrete. This can be accomplished through the augmentation of any normal weight mix design with proper adjustment in mix water to account for different aggregate properties.

LIGHTWEIGHT AGGREGATES

Several different types of lightweight aggregate are available, both natural and manufactured. The three primary types of manufactured aggregate include slates, shales, and clays that are expanded under intense heat. Each of these aggregate types has somewhat different properties dependent on the base material properties and manufacturing process. In particular, the absorption of these aggregates when compared to that of standard aggregates is considerably higher. These aggregates typically have a higher cost than normally available local materials. However, this increase in cost due to a partial replacement of regular weight aggregate may be offset by lower transportation costs of precast members, reduced structure weight leading to saving in seismic regions, and reduced foundation costs.

CURRENT CODE REQUIREMENTS

Three primary codes and specifications are used by engineers, contractors, and fabricators when constructing or repairing buildings and bridges throughout the United States. Two bridge design specifications are published by the American Association of State Highway and Transportation Officials (AASHTO). These include the *"AASHTO LRFD Bridge Design Specifications"* and the *"Standard Specifications for Highway Bridges"*. The building code typically used for design of concrete building structures and components is *"ACI 318 - Building Code Requirements for Structural Concrete and Commentary"*, published by the American Concrete Institute (ACI).

Each of these widely used publications generally defines a standard hook in a similar manner and follows the same methodology when considering the development of reinforcing steel with standard hooks. The basic requirements of a standad hook are provided in Table 1 and are dependent upon the diameter of the bar, d_b, which is used[1]. As shown, requirements differ for longitudinal and horizontal reinforcing bars.

Table 1: Standard Hook Requirements[1]

Longitudinal Reinforcement
180 degree bend, plus a 4.0 d_b extension, but not less than 2.5 in. at the free end of the bar
90 degree bend, plus a 12.0 d_b extension at the free end of the bar
Horizontal Reinforcement
No. 5 bar and smaller – 90 degree bend plus a 6.0 d_b extension at the free end of the bar
No. 6, No. 7, and No. 8 bars – 90 bend plus 12 d_b extension at the free end of the bar
No. 8 bar and smaller - 135 degree bend plus 6 d_b extension at free end of bar

Also, these codes provide specific parameters concerned with the dimensions of bar bends as shown in Figure 1[2]. Figure 1 also illustrates that the required development length is the same if a 90 or 180 degree hook is utilized. Calculation of the development length follows approximately the same procedure in each publication. An equation is provided that allows calculation of a basic development length, with subsequent multiplication by modification factors that increase or decrease the required length based on several material and design parameters. Each of the codes restricts the minimum size of the development length to 6 inches or 8 times the diameter of the bar, whichever is greater[1,2,3].

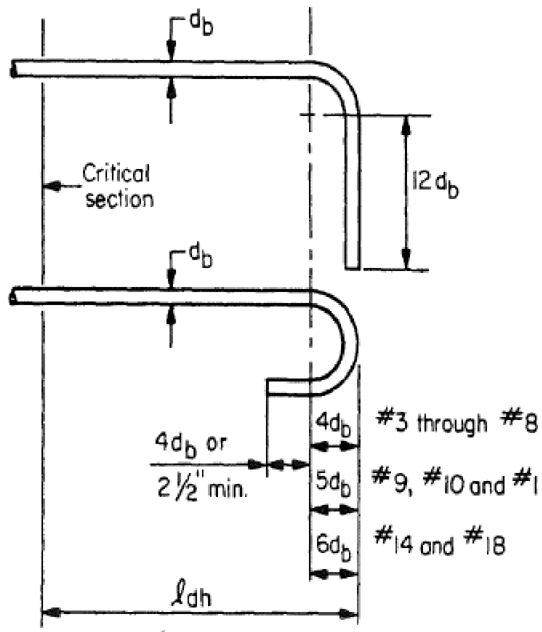

Figure 1: AASHTO Standard Hook Requirements

The AASHTO Standard Specifications discuss the development length of standard hooks in tension in section 8.29[3]. The basic development length of the bar is calculated following Equation 1. This equation is based on the diameter of the bar (d_b) in inches and the specified concrete compressive strength (f'_c) in psi. Modification factors, shown in Table 2, include those for yield strength other than 60 ksi, concrete cover, confinement within ties or stirrups, excess reinforcement, lightweight aggregate, and epoxy-coated reinforcing steel.

$$l_{dh} = \frac{1200 d_b}{\sqrt{f'_c}} \qquad \text{Equation 1}$$

The AASHTO LRFD specification discusses development of standard hooks in tension in section 5.11.2.4[2]. The calculation for basic development length is provided in Equation 2, and is based on the diameter of the bar *(d_b)* in inches and the specified compressive strength *(f'_c)* in ksi. Although the equation for calculation of development length is slightly different than the standard specification, the modification factors are the same.

$$l_{dh} = \frac{38.0 d_b}{\sqrt{f'_c}} \qquad \text{Equation 2}$$

Section 12.5 of ACI 318 addresses the calculation of the required development length of standard hooks in tension [1]. Development length is calculated following Equation 3 shown below. The development length is a function of several material properties including yield strength of the reinforcing steel (f_y) in psi, the diameter of the reinforcing bar (d_b) in inches, and the specified concrete compressive strength (f'_c) in psi. Also, two other factors are involved that address the use of lightweight aggregate and epoxy coating on the reinforcing steel. The modification factors provided in ACI 318 are illustrated in Table 2, and include factors for excessive reinforcement, cover, and enclosure in stirrups.

$$l_{dh} = d_b \frac{0.02\psi_e f_y}{\lambda\sqrt{f'_c}} \qquad \text{Equation 3}$$

$$\psi_e = \textit{taken as } 1.2 \ \textit{ for epoxy coated bars } (1.0 \textit{ otherwise})$$
$$\lambda = 0.75 \textit{ for lightweight concrete } (1.0 \textit{ otherwise})$$

Table 2: Code Modification Factors[1,2,3]

	ACI	AASHTO
Reinforcement has a yield strength exceeding 60 ksi	---	$\frac{f_y}{60.0}$
For No. 11 bar and smaller hooks with side cover (normal to plane of hook) not less that 2.5 in., and for 90-degree hook with cover on bar extension beyond hook not less than 2 in.	0.7	0.7
For 90-degree hooks of No. 11 and smaller bars that are either enclosed within ties or stirrups perpendicular to the bar being developed, spaced not greater that $3d_b$ along l_{dh}: or enclosed within ties or stirrups parallel to the bar being developed, spaces not greater than $3d_b$ along the length of the tail extension of the hook plus bend	0.8	0.8
For 180 degree hooks of No. 11 and smaller bars that are enclosed within ties or stirrups perpendicular to the bar being developed, spaces not greater that $3d_b$ along l_{dh}	0.8	0.8
Where anchorage or development for F_y is not specifically required, reinforcement in excess of that required by analysis	$\frac{A_s \textit{required}}{A_s \textit{provided}}$	$\frac{A_s \textit{required}}{A_s \textit{provided}}$
Lightweight aggregate is used	---	1.3
Epoxy-coated reinforcement is used	---	1.2

Although the AASHTO and ACI equations appear different, each results in essentially the same development length. The three processes are dependent upon the same characteristics, although the unit of measure may be different (psi vs. ksi). In particular, each of the three processes is dependent on the square root of f'_c in the denominator. When comparing how each process addresses lightweight concrete, the two AASHTO examples require an increase of thirty percent in development length and the ACI process results in an increase of 33 percent. A simple example of development length calculation is provided in Table 3. The example presented illustrates this process on an epoxy-coated number 6 bar in lightweight concrete with a specified compressive strength of 5,000 psi. The calculations result in development lengths of 20.37, 19.89, and 19.86 inches for the ACI, AASHTO Standard, and AASHTO LRFD processes, respectively. Although slightly different, the results provided in Table 3 indicate that a very similar development length is required regardless of code.

Table 3: Development Length Example

	ACI	AASHTO Standard	AASHTO LRFD
Basic Development Length (in)	20.37	12.75	12.73
Lightweight Modification Factor (in)	---	1.3	1.3
Epoxy Modification Factor (in)	---	1.2	1.2
Total Development Length (in)	20.37	19.89	19.86

METHODOLOGY

To investigate the need for the previously described modification factors when using specified density concrete, a methodology was developed to compare the pull out strength of reinforcing steel in specified density concrete as compared to normal density concrete. The methodology developed included casting concrete specimens of same dimension and embedding reinforcing steel with standard hooks at varying depths. After curing, each specimen would be tested until failure and results compared to validate the need for, or magnitude of, the modification factor. The concrete to be used for each of the two different densities was similar in all facets (including strength, spread, and air content) with the exception of unit weight. Reinforcing steel was chosen as number 4 bars with standard 90 degree hooks meeting the requirements shown in Figure 1. The hooks were embedded at depths ranging from 2 inches through 8 inches. Two specimens of each embedment length were cast using each type of concrete.

SPECIMENS

Specimen size was chosen considering several factors including at least 2 inches of clear cover around the bar, suitable size of surface area for the testing apparatus, and minimizing the weight for ease of use during the transport and testing phase. The final dimensions of the samples were chosen as 7 inches wide, 14 inches long, and varying depths equal to the embedment length plus 2 inches. The specimens were cast using wooden forms as detailed in Figure 2.

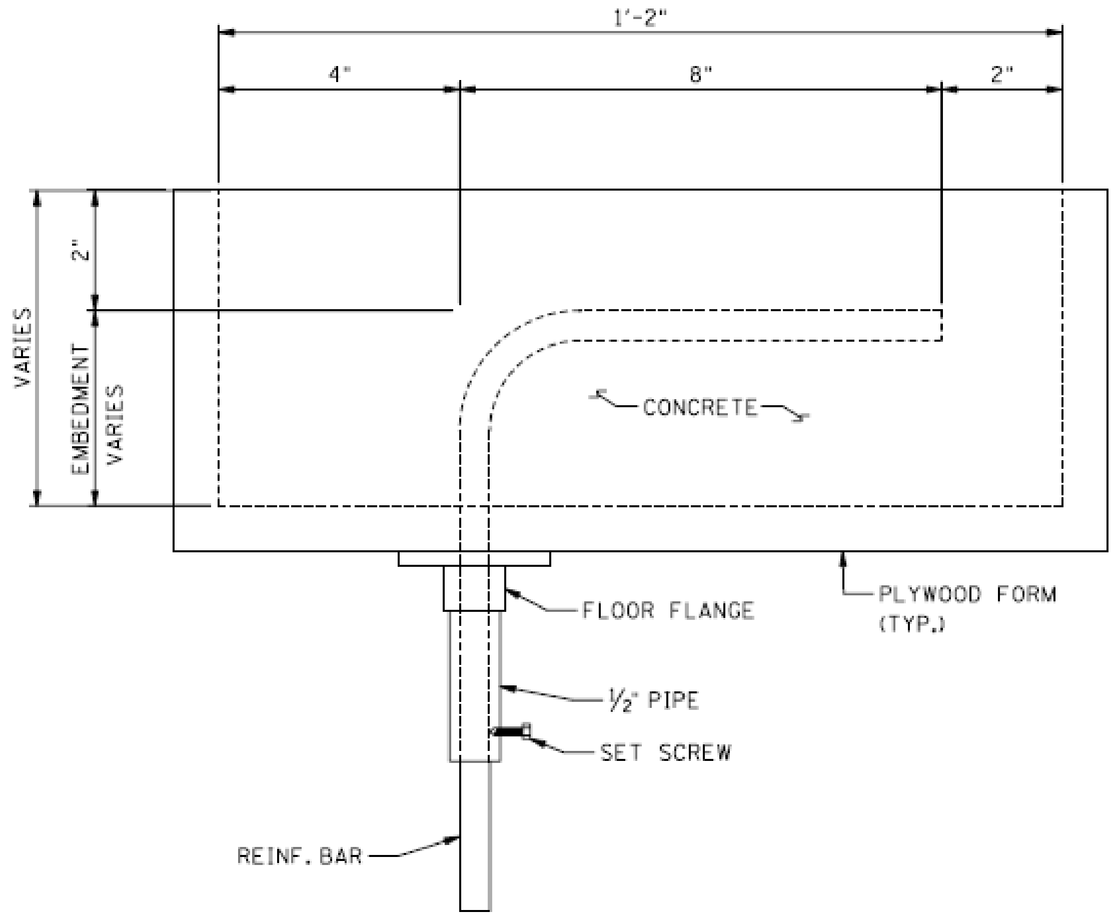

Figure 2: Schematic of Form

The forms included a floor flange and short section of ½ inch pipe that allowed the reinforcing bar to pass through. A set screw in the pipe was used to adjust and maintain the embedment length of the reinforcing bar during concrete placement. Using this type of form required the specimen to be cast upside down and on an elevated support, but did allow consistent and precise embedment lengths and ensured that the bar extended perpendicular to the surface of the specimen. This particular setup also provided a smooth surface for the test equipment to bear against, reducing any point loading and subsequent stress concentrations. Forms were set and rebar embedment depths were checked immediately prior to concrete placement. An example of a form and installed rebar prior to concrete placement is shown in Figure 3 and a specimen immediately after concrete placement is shown in Figure 4.

Figure 3: Example of Form

Figure 4: Completed Specimen

MIX DESIGNS

A local precast manufacturer was consulted in the development of two mix designs that would provide the adequate plastic and hardened properties including unit weight and comparable compressive strengths. The mixes selected were two that the manufacturer commonly produced. In particular, each mix was self consolidating with a water to cement ratio of 0.39 and utilized Type III Portland Cement. The mix design characteristics for the normal density concrete are provided in Table 4.

Table 4: Normal Density Mix Characteristics

Component	Quantity
Portland Cement (Type III)	700 lbs
ASTM C33 Fine Aggregate	1,300 lbs
#67 Limestone Aggregate	1,610 lbs
Water	275 lbs
Superplasticizer	10.5 oz/100wt
Air Entrainer	10.0 oz/100 wt
Accelerator	3.5 oz/100 wt
w/c ratio	0.39

The primary difference between the specified density and normal density mix designs was the substitution of ½ inch lightweight expanded slate aggregate for a portion of the #67 limestone aggregate along with an increased cement content. The mix design characteristics for the specified density mix are provided in Table 5. A visual example of the differences in these mix designs is shown in Figure 5. The sample on the left of Figure 5 represents the specified density with the darker lightweight aggregate.

Table 5: Specified Density Mix Characteristics

Component	Quantity
Portland Cement (Type III)	750 lbs
ASTM C33 Fine Aggregate	1,255 lbs
1/2" lightweight aggregate	650 lbs
#67 Limestone Aggregate	375 lbs
Water	295 lbs
Superplasticizer	10 oz/100 wt.
Air Entrainer	3 oz/100 wt.
w/c ratio	0.39

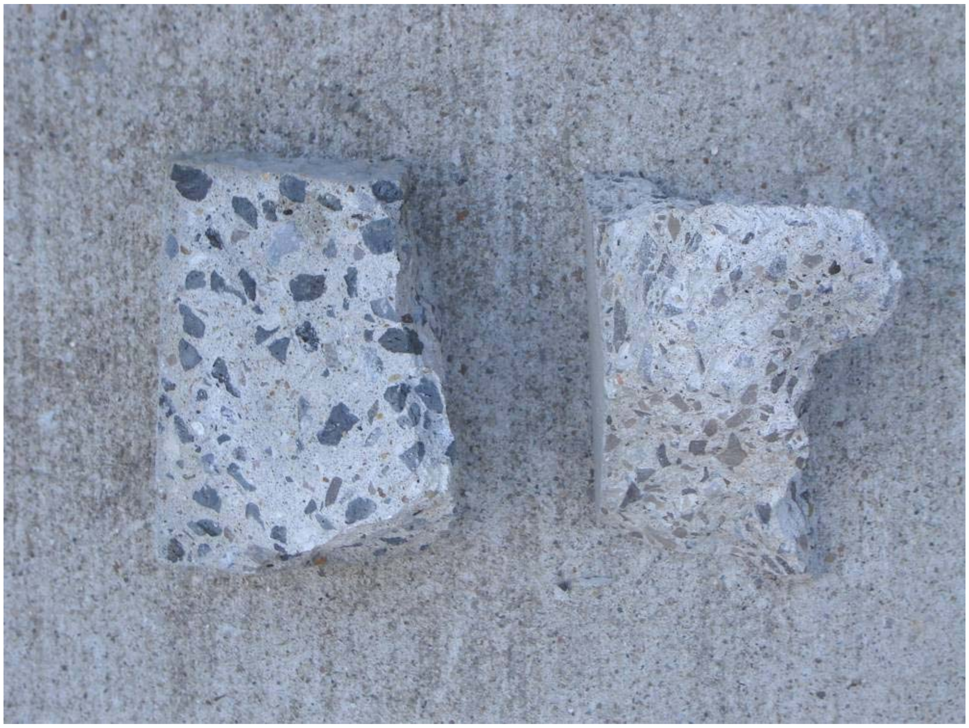

Figure 5: Comparison of Different Mixes

TEST APPARATUS

The apparatus for applying load to the specimens consisted of a 30 ton hydraulic cylinder and pump, load cell, and electronic instrumentation that recorded maximum load. Along with these components, a bearing plate was fabricated that provided a base for the hydraulic cylinder, allowed the load to be applied uniformly, and was recessed to allow the concrete in the immediate area of the bar to fail without any compressive load affecting the results. The bearing plate consisted of two steel plates connected together. The top plate consisted of a 6 inch diameter by 1 inch thick circular plate with a 1 inch diameter hole through the center. The lower plate, or ring, was 3/8 inch thick with an outside diameter of 6 3/8 inches and an inside diameter of 5 3/8 inches. The testing components were placed on the specimen as shown in Figure 6. Two 3/8 inch thick steel washers and a reinforcing steel coupler were also used to prevent movement of the test assembly during load application.

Figure 6: Testing Apparatus

REUSLTS

The plastic properties of the two concrete mixes are provided in Table 6. With the exception of unit weight, the plastic properties were consistent across each respective mix. The unit weights were found to be 124.8 lb/ft^3 and 145.4 lb/ft^3 for the specified and normal density mixes, respectively.

Table 6: Plastic Properties

Property	Specified Density	Normal Density
Entrained Air (%)	5.0	5.6
Concrete Temperature (deg F)	70.0	71.0
Ambient Temperature (deg F)	68.0	75.0
Unit Weight (lb/ft^3)	124.8	145.4
Spread (inches)	21.0	22.5

Compressive strength tests were completed in conjunction with specimen testing and indicated compressive strengths of 5,310 psi and 6,330 psi for the normal and specified density concretes, respectively. Finally, each of the reinforcing bars embedded in the specimens were loaded in tension until failure occurred. Two primary failure mechanisms were evident throughout testing. The most frequent failure mechanism was a failure of the concrete/bond with the reinforcing bar. This mechanism typically resulted in a crack along the back side of the hook extending toward the bottom of the sample. Also, on specimens with deeper embedment, this crack extended parallel to and below the hook extension. This failure mechanism also resulted in concrete cracking and spalling in the area immediately adjacent to the steel as it entered the specimen. The second failure mechanism was yielding and ultimate failure of the reinforcing steel above the specimen. Noticeable deformation of the reinforcing bar was evident prior to ultimate failure. Each of these failure mechanisms are shown in Figures 7 thru 9.

Figure 7: Concrete/Bond Failure

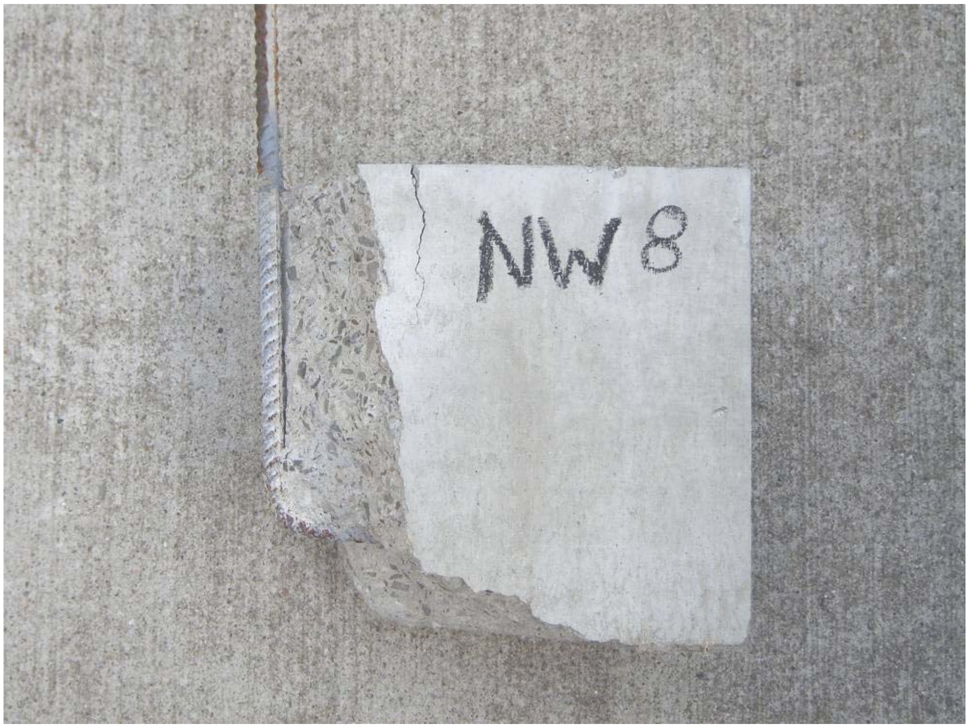

Figure 8: Concrete Bond Failure

Figure 9: Steel Failure

Test results are provided in Table 7 for the specified density concrete and Table 8 includes results for the normal density specimens. These tables include the failure load, average bar stress, failure type, and average failure load. Typically, as expected, the failure load increased with increased embedment length.

Table 7: Specified Density Load Test Results *(f'_c = 6,330 psi)*

Embedment Length	Failure Load	Bar Stress	Failure Type	Average Failure Load
2 in.	3,956 lbs	19,780 psi	Concrete/Bond	3,903 lbs
	3,849 lbs	19,245 psi	Concrete/Bond	
3 in.	8,855 lbs	44,275 psi	Concrete/Bond	7,735 lbs
	6,615 lbs	33,075 psi	Concrete/Bond	
4 in.	9,867 lbs	49,335 psi	Concrete/Bond	8,573 lbs
	7,279 lbs	36,395 psi	Concrete/Bond	
5 in.	13,006 lbs	65,030 psi	Concrete/Bond	13,248 lbs
	13,489 lbs	67,445 psi	Concrete/Bond	
6 in.	13,203 lbs	66,015 psi	Concrete/Bond	14,200 lbs
	15,196 lbs	75,980 psi	Concrete/Bond	
7 in.	16,612 lbs	83,060 psi	Concrete/Bond	17,600 lbs
	18,587 lbs	92,935 psi	Concrete/Bond	
8 in.	19,633 lbs	98,165 psi	Rebar Failure	19,064 lbs
	18,495 lbs	92,475 psi	Rebar Failure	

Table 8: Normal Density Load Test Results *(f'_c = 5,310 psi)*

Embedment Length	Failure Load	Bar Stress	Failure Type	Average Failure Load
2 in.	4,203 lbs	21,015 psi	Concrete/Bond	4,418 lbs
	4,633 lbs	23,165 psi	Concrete/Bond	
3 in.	7,843 lbs	39,215 psi	Concrete/Bond	7,574 lbs
	7,304 lbs	36,250 psi	Concrete/Bond	
4 in.	10,224 lbs	51,120 psi	Concrete/Bond	10,182 lbs
	10,140 lbs	50,700 psi	Concrete/Bond	
5 in.	8,772 lbs	43,860 psi	Concrete/Bond	10,715 lbs
	12,658 lbs	63,290 psi	Concrete/Bond	
6 in.	14,381 lbs	71,905 psi	Concrete/Bond	14,349 lbs
	14,316 lbs	71,580 psi	Concrete/Bond	
7 in.	15,323 lbs	76,615 psi	Concrete/Bond	15,492 lbs
	15,661 lbs	78,305 psi	Concrete/Bond	
8 in.	15,359 lbs	76,795 psi	Concrete/Bond	17,036 lbs
	18,713 lbs	93,565 psi	Rebar Failure	

ANALYSIS

The average failure loads for the specified and normal density specimens are plotted in Figure 10. The graph includes only the results for the 2 inch thru the 7 inch embedment specimens. The 8 inch embedment results were omitted from the plot due to reinforcing steel failure that occurred during testing. The plot represents increasing levels of bar stress and the ultimate stress at the concrete/bar interface. Specimens with bar failure were omitted as the ultimate bond stress was not attained and comparison could not be made with specimens where bond failure occurred. The plot of results appears to provide a good comparison of the ultimate failure loads when considering the two different types of concrete. Although a few of the average loads appear to fall outside of that expected, a reasonably good understanding of the pullout strength in the different types of concrete is provided.

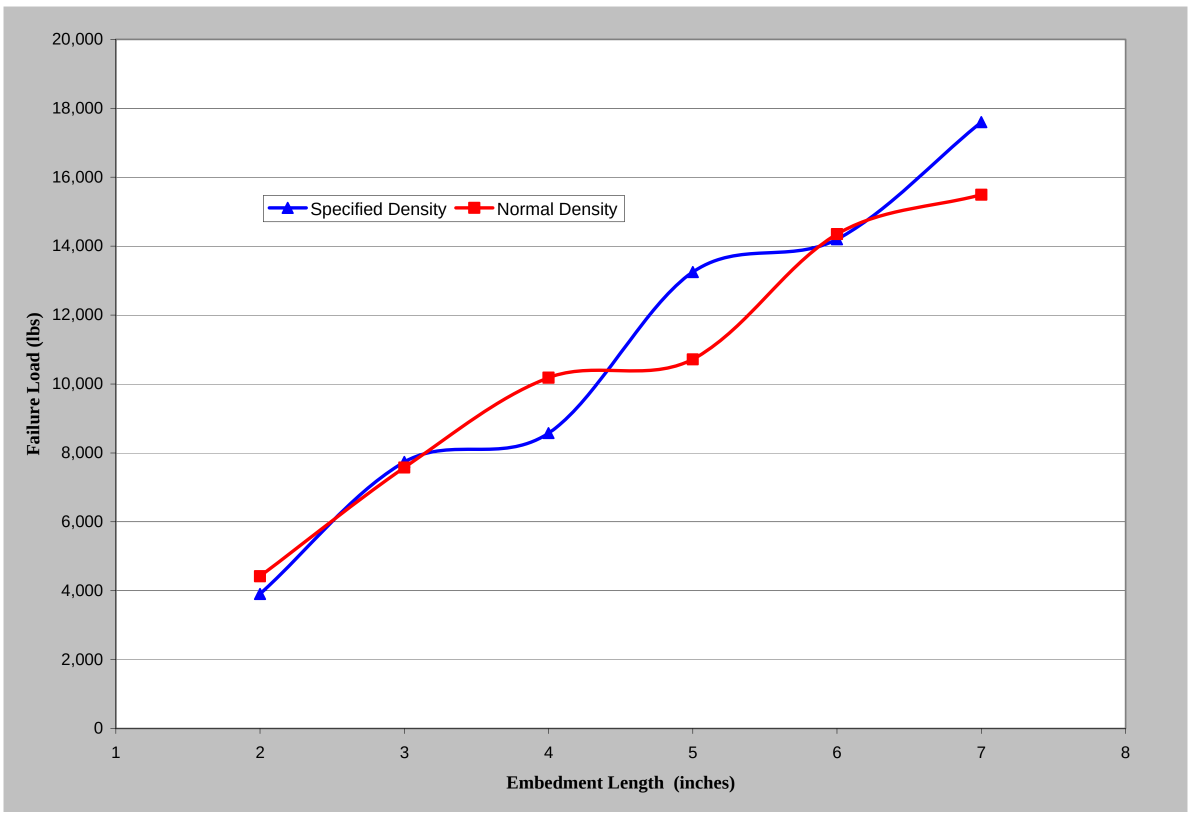

Figure 10: Average Test Results

A simple linear regression of these results was completed and is illustrated in Figure 11. The regressions were completed assuming that each line intercepted zero load at zero embedment. Although simple in nature, each line appears to match the experimental results well with coefficients of determination (R^2) of 0.967 and 0.968 for the specified and normal density concretes, respectively. Equations for both linear regressions are provided in the figure. Due to the equations intercepting at zero, they appear to diverge at higher loads and embedment length. This small error should not introduce noticeable differences in comparisons.

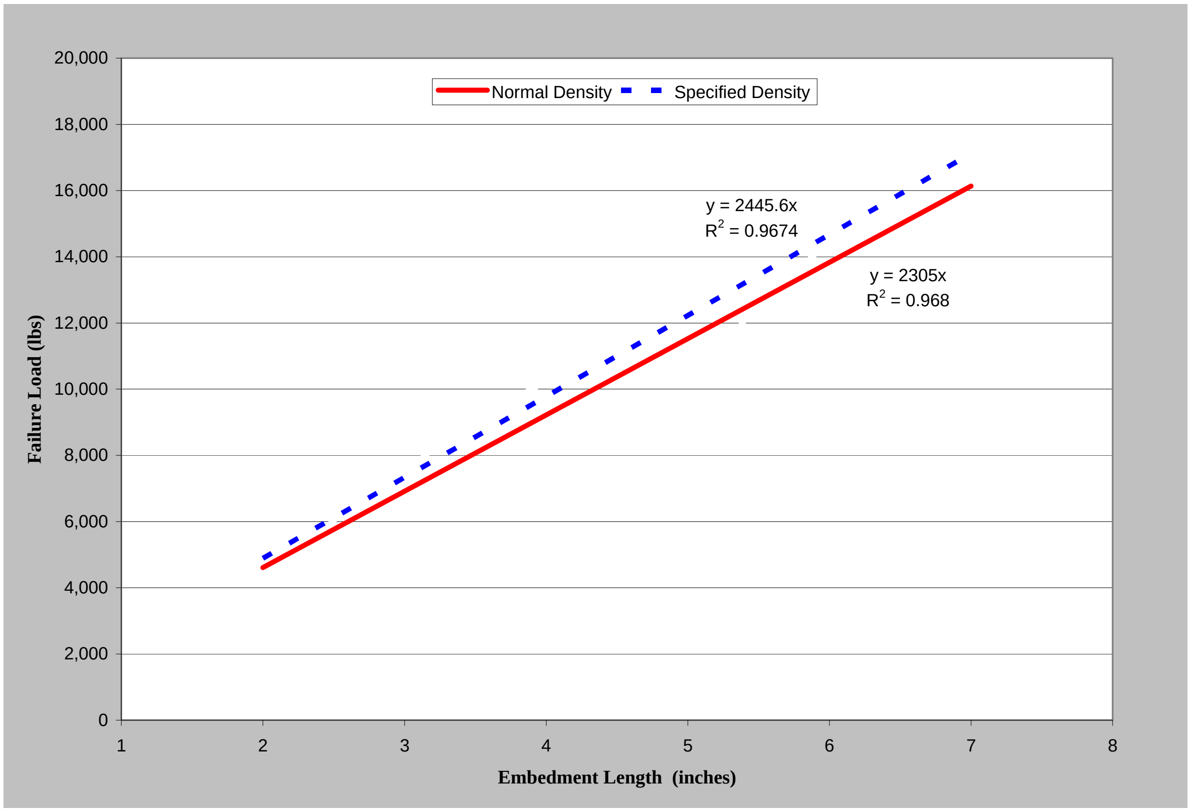

Figure 11: Linear Regression of Results

Based on the code requirements of increasing the development length of standard hooks in lightweight concrete, a decrease in failure load would be expected when comparing test results from similar strength samples. To compare the two sets of test results from different strength concretes to see if this decrease in failure load was apparent, the specified density test results were normalized to the normal density results to provide an opportunity to make the comparison. Since the code equations for development length are based on the relation of the inverse of the square root of the compressive strength, the results of the specified density tests were translated to a similar strength based on a ratio of these inverse relations. The results (Normalized Specified Density) of this normalization are provided in Figure 12 and result in failure loads very similar to that of the normal weight specimens.

Finally, if an approximate thirty percent increase is required by the codes and design guidelines, a similar relation may also be seen in test data that would indicate failure loads of the same approximate difference between the normal and specified density concrete. To visualize this, the normal weight results were reduced by this thirty percent factor and are also plotted (Theoretical Specified Density) in Figure 12. As shown, these results fall well below that of the normalized line for the specified density concrete.

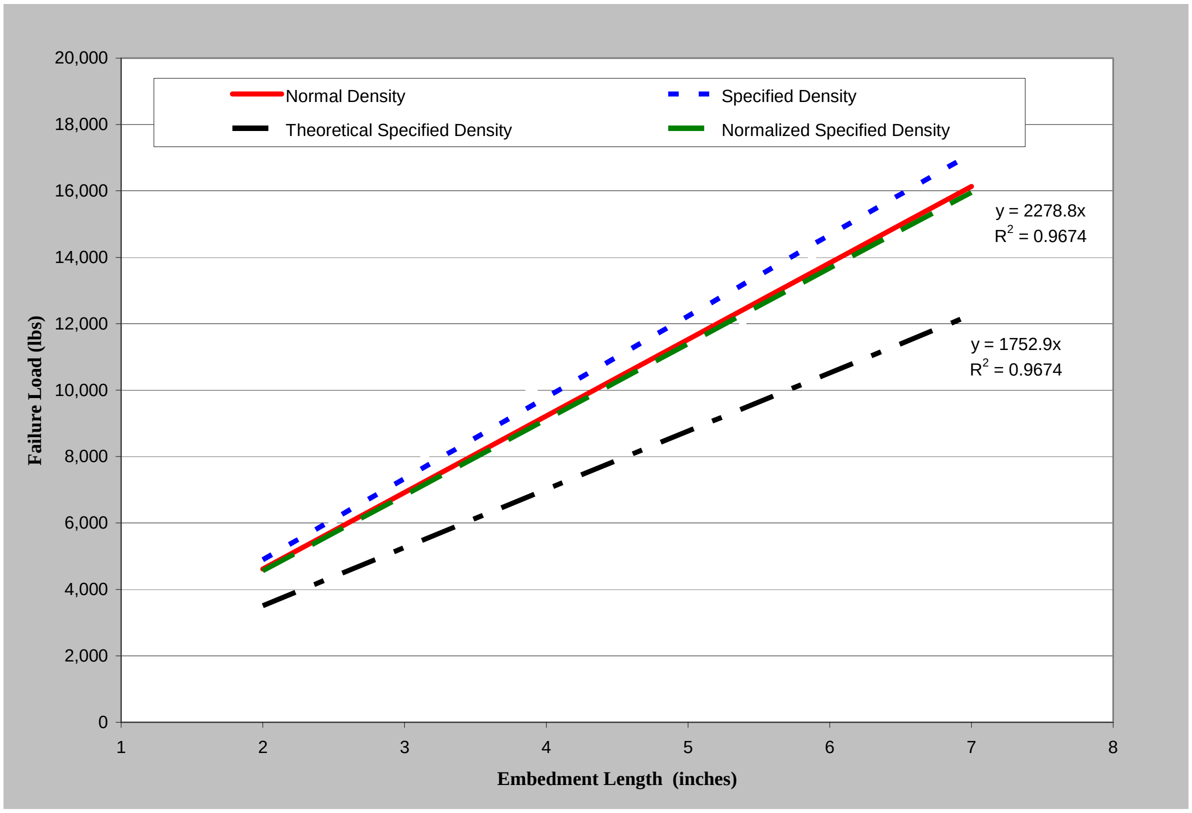

Figure 12: Normalized and Theoretical Comparison

CONCLUSIONS

Conclusions are based solely on the results of the tests completed on the two different mixes tested in this study. The results of the testing on each different mix design appear to follow the expected pattern of increasing levels of failure load correlated with increased length of embedment.

Based on the previously discussed analysis and visual representations in Figures 10 thru 12, the results of the study do not support the need for the current code required increase in development length when using specified density concrete. In fact, the results presented indicate that no increase may be needed for the particular specified density concrete tested.

Additional research is suggested that considers additional reinforcing bar sizes, varied specified density unit weights, and varied compressive strengths. Tight quality control is suggested to ensure that the compressive strengths of the different mixes are very similar to avoid any misinterpretation when comparing results. Also, comparisons with concrete tensile strength may provide additional insight into the relationship between unit weight, component material properties, pullout load, and development length.

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