Use of High Strength Lightweight Concrete to Construct a Postensioned Segmental Beam

Jorge A. Tito[1], Luis Hernandez[2], Jaime Trujillo[3]
[1] University of Houston Downtown, Houston, TX, USA, tito-izquierdojor@uhd.edu
[2]University of Houston Downtown, Houston, TX, USA, luis.teclas.hernandez@gmail.com
[3]University of Houston Downtown, Houston, TX, USA, ptrujillo4@aol.com

ABSTRACT

A postensioned segmental beam is constructed as a project for Senior Concrete Design, which is a capstone course in the Structural Analysis and Design Program of the University of Houston Downtown. The segmental beam consists of nine hollow segments and two solid end blocks joined using postensioned cables. The segments are constructed using high strength lightweight concrete. The laboratory tests of the lightweight aggregates permit the design of trial mixes from which one mix is selected to construct the beam. The tests of the lightweight concrete show that the required strength of 8,000 psi is obtained at 14 days, and the tension strength and the modulus of elasticity compare well with the values indicated by ACI-318 for this type of concrete. The project provides valuable experience in testing, mix design, elaboration and pouring of concrete, postensioning, and the technique of segmental beam construction. The objectives of the course are fulfilled and the students show participation, motivation, and interest during the project.

This paper presents the characteristics of the lightweight concrete used, the construction methodology followed to obtain the postensioned segmental beam, and the educational objectives of the project.

Keywords: lightweight concrete, high strength concrete, segmental construction, capstone project.

1. INTRODUCTION

Lightweight concrete is used to reduce dead load, and therefore helps to obtain smaller structural elements. Since the seismic forces are proportional to the mass of the structure, then in earthquake prone areas the lightweight concrete may contribute to a safer and more economic design. In bridges and other precast construction, the lightweight concrete helps to reduce costs of shipping and crane capacity, inclusive considering a higher cost of the aggregates. It is necessary to know that the lightweight concrete has different engineering properties that must be considered during the design (Sylva et al, 2002).

In Houston, Texas, the cost of ready mix lightweight concrete varies from \$ 120 to \$ 150 per cubic yard (cy), while the normal weight concrete varies from \$105 to \$120. The price variation between lightweight and normal concrete for the same provider is about 14% to 25%. These prices, corresponding to January 2010, are for ready mix concrete delivered in a radius of 25 miles, with 28 days strength (f'c) of 8,000 psi, and a minimum of 100 cy.

The lightweight concrete was used almost 2,000 years ago by the ancient Romans to construct the dome of the Pantheon in Rome. Modern structural lightweight concrete was used for the construction of cargo ships during the First World War (WWI), followed with by buildings, and different types of bridges (Mindess et al, 2003, Murillo et al, 1994).

As a project for Senior Concrete Design, which is a capstone course for the Structural Analysis and Design at the University of Houston Downtown, a postensioned beam is built using a similar technique to that employed for segmental bridges. The beam is constructed using nine hollow segments, and two end blocks. The beam length is 21'4", with a trapeze cross section having 2'0" depth, 13" at top, 7" at bottom. The hollow segments are 2'0" long with walls of 1-3/4" thick, and the end segments are blocks having 1'8" long and designed to anchor the cables.

The lightweight concrete volume needed for the beam is 18.9 ft^3; however, the total volume mixed is 23 ft^3, considering the samples and the left over.

The beam requires a minimum concrete strength (f'c) of 8,000 psi, which is necessary to achieve at 14 days, because of time restrictions. The use of lightweight aggregates is decided to permit an easier handling of the segments, and mainly to teach the students the technique of lightweight concrete. A local manufacturer, Texas Industries Inc. (TXI-ES&C) provides the coarse and fine lightweight aggregates consisting of expanded shale and clay (ES&C). The cement used is portland type I/II (ASTM C150), and the plasticizer used is ViscoCrete 2100, from Sika.

The ES&C aggregates are manufactured by expanding minerals in a rotary kiln at temperatures over 1000 ^{o}C, conforming to the norm ASTM C330, which covers lightweight aggregates intended for use in structural concrete (TXI-ES&C, 2010).

The TXI-ES&C representative provided consulting during the mixing, being one of his main recommendations to make the mix using the aggregates with water content close to their absorption capacity. This practice avoids the loss of water needed for hydration and also provides a reserve of water for "internal curing" of the concrete, which is important for high strength concretes, as indicated in the literature (Harding, 1995).

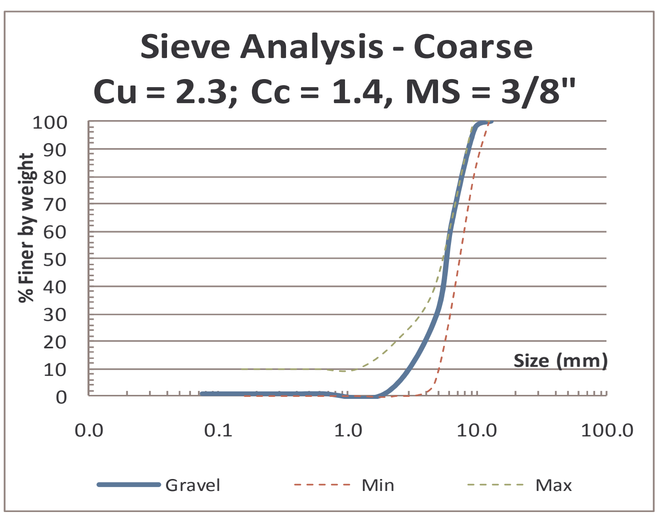
This paper presents and discusses the characteristics of the lightweight concrete used to make the segments of the beam; the construction methodology of the postensioned segmental beam; and, finally, the educational objectives of this capstone project.

2. Laboratory Test of Aggregates

The coarse and fine lightweight aggregates were tested to obtain the properties needed for concrete design, such as the sieve grain analysis, unit weight, and specific gravity.

The unit weight (M) of the coarse aggregate is 58 lb/ft^3, and for the fine aggregate the unit weight is 71 lb/ft^3. Figure 1 shows the sieve grain analysis of the coarse aggregate, which has a coefficient of uniformity (Cu) less than 4, and the coefficient of curvature (Cc) between 1 and 3, meaning that the coarse aggregate is not well graded; however, its grain size distribution is inside the recommended range. The coarse aggregate has a nominal maximum size (MS) of 3/8".

The fine material is well graded, having a Cu greater than 6 and a Cc between 1 and 3, and a modulus of fineness (FM) of 2.9, as shown in Figure 1.



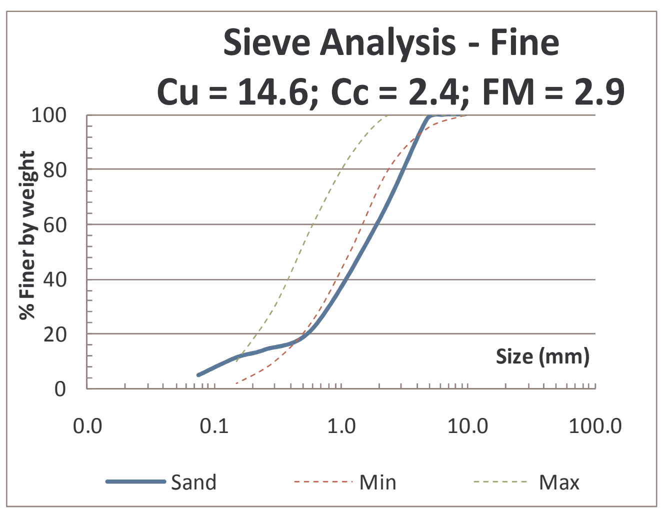


Figure 1. Sieve Analysis of Light-Weight Aggregates

Other properties obtained from the laboratory tests for the light-weight aggregates are shown in Table 1. The unit weight (M) of the gravel and sand is 58 lb/ft3 and 71 lb/ft3, respectively. The specific gravity (spg) is 1.56 for the gravel and 1.88 for the sand. Table 1 shows that the spg is lower for larger particles; inclusive, it is observed that few large particles float.

Table 1: Aggregate Properties from Laboratory Tests

Property	Light-weight Aggregates (ES&S)	
	Coarse	Fine
Unit Weight (M)	58 lb/ft^3	71 lb/ft^3
Average Specific Gravity (spg)	1.56	1.88
spg for 3/8"	1.27	-
spg for 1/4"	1.46	-
spg for #4	1.43	-
spg for #10	-	1.51
spg for #30	-	1.59
spg for #60	-	1.65
spg for #100	-	1.86
spg for #200	-	2.40
Absorption	15 to 20%	20 to 25%
Water Content (before mixing)	12 to 19 %	11 to 23%

3. MIX DESIGN

The trial mix design is performed using a spreadsheet that computes the quantities of the concrete components using the laboratory results, recommendations from ACI (ACI-91, ACI-2001), and previous experience in the Laboratory of Concrete Technology of the University of Houston Downtown.

The batch done by the students is hand mixed and it is proportioned to fill approximately 20 cylinders of 3" diameter and 6" height. Three mix designs are tested previously to decide the most suitable mix to make the segments of the beam. The proportions for each mix design are indicated in Table 2.

The workability of Mix 1 and Mix 2 is appropriate to pour the form for the segments. Mix 3 contains plasticizer in the same proportion than the others; however, it is very flowable and presents segregation. Avoiding the use of plasticizer in Mix 3 might make the mix behave well. The Fly Ash has rounded particles that cause the excess of flowability. It is interesting to indicate that for lightweight concrete, the segregation makes the coarse aggregate go to the top of the concrete mass. This type of segregation is because the coarse particles have less specific gravity than the fines, as appreciated in Table 1.

Table 2: Concrete Mixes for One Batch and Equivalent Mix for 1 m^3 of Dry Aggregates

Material	Concrete Mix					
	[1]Mix 1 (lb / batch)	[2]Net Mix 1 (lb / yd^3)	[1]Mix 2 (lb / batch)	[2]Mix 2 (lb / yd^3)	[1]Mix 3 (lb / batch)	[2]Mix 3 (lb / yd^3)
Water	7.34	356	7.32	357	7.28	349
Cement	17.86	1011	26.14	1436	19.60	1057
Fly Ash Class "C"	0.00	0	0.00	0	6.54	352
Gravel	16.27	775	16.27	752	16.27	737
Sand	18.71	861	14.11	630	14.11	619
Plasticizer	0.044	2.49	0.064	3.51	0.066	3.44
w/c ratio		0.35		0.25		0.25

Notes:
1. Materials for 1 batch make 20 cylinders 3" diameter and 6" height
2. The Net Mix is obtained calculating the corresponding dry material using their moisture and absorption properties.

Figure 2 shows how the concrete compression strength along the time for different mixes. All the concrete tests are done using cylindrical samples with 3" diameter and 6" height. Mix 2 is selected to construct the segmental beam; principally, because this mix is workable and reaches the required strength before 28 days, permitting the application of the first postensioning force when the last segment is 14 days old.

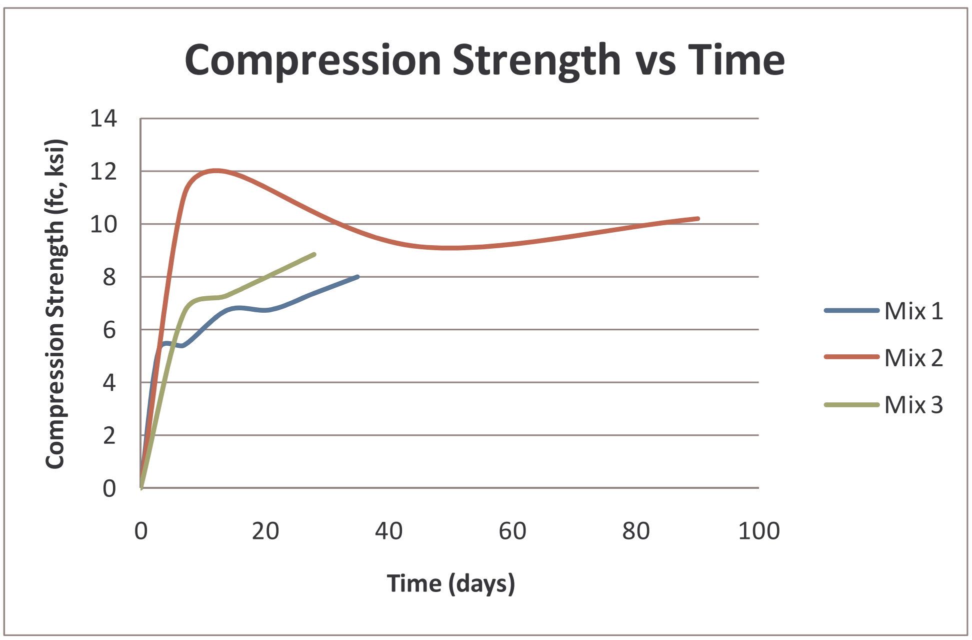


Figure 2. Compression Strength vs. Time

Additional tests are done to the selected Mix 2 using the samples obtained during the pouring of the segmental beam. The Brazilian test for samples aging 40 to 45 days provides an average splitting tension strength of 690 psi, with a minimum value of 570 psi. The test is repeated for cylinders 90 days old, obtaining an average splitting tension strength of 970 psi, with a minimum of 900 psi. Figure 3 shows a split sample with good distribution of the coarse aggregate.

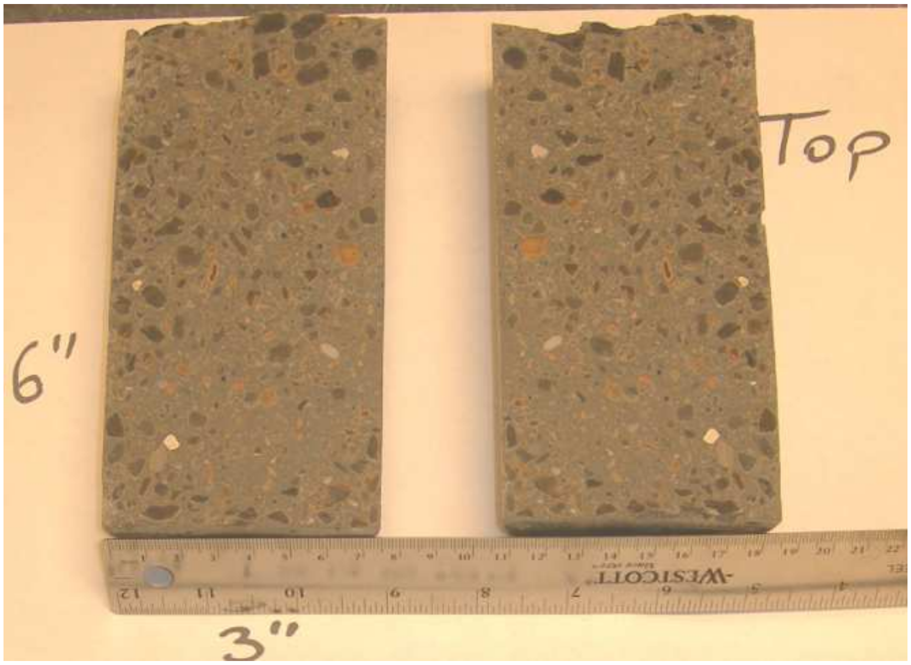


Figure 3. Typical failure after Brazilian Tension test

The splitting tension strength may be compared with the following equation provided by ACI-318 (ACI, 2008):

$f_{ct} = 6.7\ \lambda\ \mathrm{sqrt}(f'c)$ (Eq. 1)

For lightweight concrete, λ shall be 0.75, and the f'c is 9,000 psi. Then the f_{ct} from ACI-318 equation is 480 psi, which is lower than the splitting tension strength obtained experimentally.

The density of the concrete, w_c, recently extracted from the cylinder is 117 lb/ft^3 and after 54 days drying it is 112 lb/ft^3, which compares well with the literature that indicates a typical unit weight of 115 lb/ft^3.

The concrete modulus of elasticity, Ec, is defined as the slope of the curve stress vs. strain shown in Figure 4, which corresponds to a sample obtained from the segment to be placed at the beam center. The test is done using a strain gage attached to the cylinder. The load is applied up to 70% of the estimated f'c to permit the test repetition at different ages of the cylinder without damages. Two sets of tests are presented, the first one (test-1 to test-5) is done for 39 days age resulting in an average modulus of elasticity of 3'200,000 psi. The second set (test-6 and test-7) is done when the cylinder is 91 days old presenting a modulus of elasticity of 3'700,000 psi, or 17% greater than the first one.

ACI-318 provides the following equation to estimate the modulus of elasticity for lightweight concrete (ACI, 2008):

$E_{c1} = w_c\hat{}1.5 * 33 * \mathrm{sqrt}(f'c)$ (Eq. 2)

The density, w_c, for this Mix 2 is 112 lb/ft^3, and the f'c obtained is 9,000 psi.

Then, using the ACI-318 equation, the modulus of elasticity, E_{c1}, is 3'710,000 psi, value that compares well with the measurements.

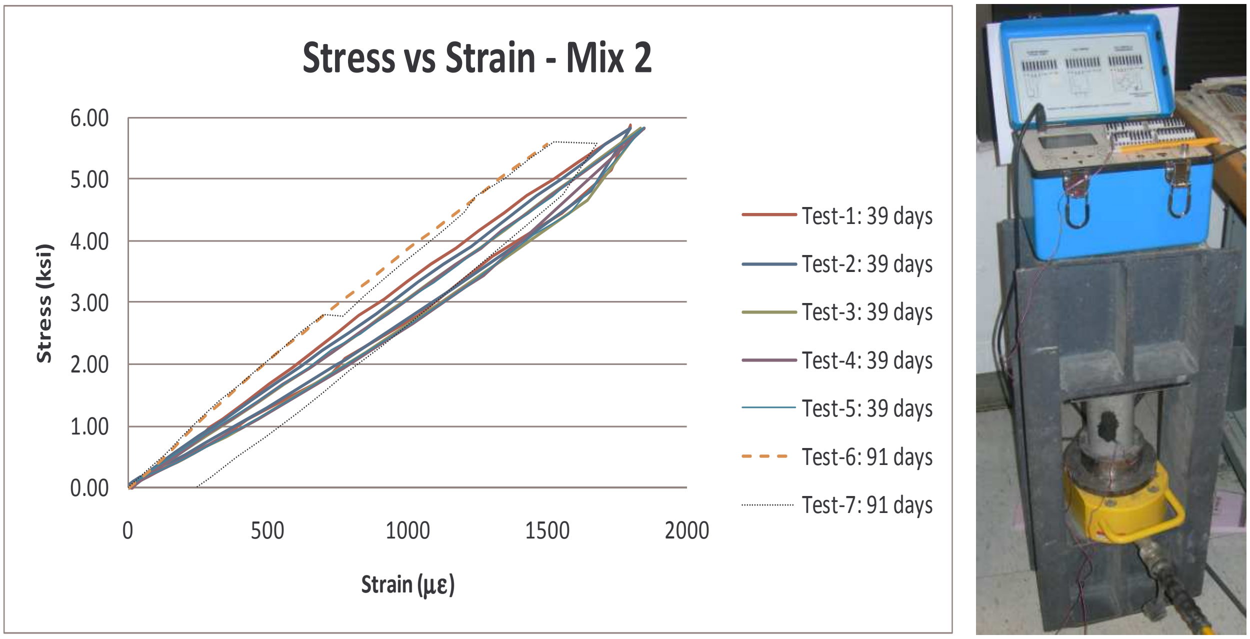


Figure 4. Curve Stress vs. Strain for Mix 2 and setup showing the cylinder, strain gage, strain reader and jack.

4. CONCRETE POURING

The beam is constructed using nine hollow segments and two solid end blocks. Each hollow segment requires 1.5 ft^3, which is obtained using three and a half batches. The end blocks require 6 batches each one. The concrete mix is prepared using a plastic container, measuring the materials carefully and hand mixing thoroughly until a homogeneous and consistent concrete is obtained. A total 23 ft^3 is prepared for the beam which required a net volume of 18.9 ft^3.

The steel mold used for the segments was constructed by a student. The mold consists of welded or bolted steel plates, permitting the removal of the segment without difficulty. After the segment is removed, the form should be cleaned, bolted and oiled to be ready for the next segment. The hollow segments use a foam block to obtain the interior trapeze shape. The foam block is provided by a local manufacturer with the measurements indicated. The foam block is installed using spacers consisting of a screw and a thin plate.

Figure 5 shows the preparation of the mold, and pouring of the lightweight concrete. The concrete exhibits good workability; however, the supply of concrete shall be continuous because the setting time is short, and the concrete becomes hard almost after 30 minutes to be poured. Cylinders of 3" diameter by 6" height are extracted as samples from each segment. A 3/4" vibrator and a vibrating table are used to ensure a good concrete compaction, avoiding the honeycombs. The segment is demolded after 12 hours and it is covered with wet paper for curing. The interior foam block is removed before the postensioning.

A temperature test is used as an additional control of the mix quality, consisting in measuring the temperature of a concrete sample during the hydration period. One sample is taken from each batch and it is placed inside an insulated box to read its temperature during the hydration process. Figure 6 shows a typical curve of temperature vs. time during the hydration process, and the setup necessary for reading and recording of the temperature. The peak temperature varies from 50 to 60 ^{o}C, and occurs at 10 to 12 hours after pouring. The similitude of these curves indicates that the different batches the same mix composition.

After form removal, the segments present homogeneous dimensions, smooth finishing, and are free of shrinkage cracks. One segment was rejected because excessive honeycombs, probable due poor vibration.

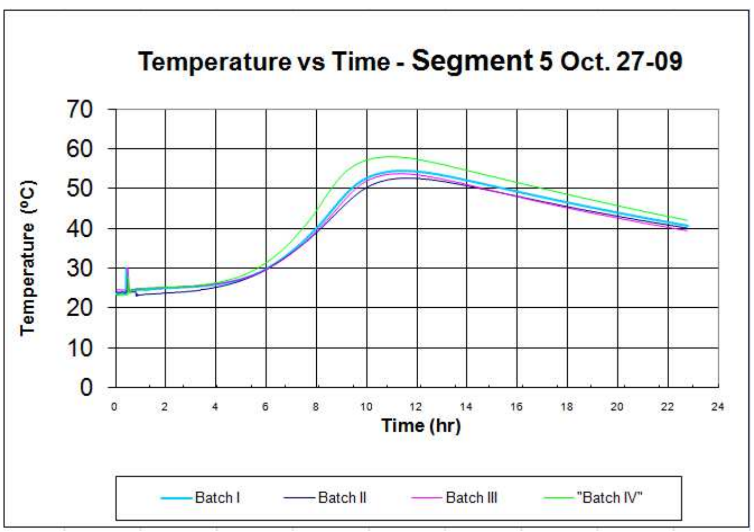
The resulting segmental beam is initially postensioning when the concrete of the last segment was 14 days old, and the final postensioning was applied when the last segment was 1 month old. The segmental beam is constructed on the testing equipment, facilitating the handling of this 21'3" long beam. Figure 7 shows the segmental beam constructed and with the initial postensioning. The final postentioning is done after the beam is positioned in the definitive supports, which span 20'6" center to center. The testing is performed applying a force in the beam center. The discussion of the testing results is not in the scope of this paper.

a. Preparing the steel mold and the foam block

b. Verification of the wall thickness

c. Pouring Mix 2

Figure 5. Construction of a hollow segment



Setup: cylinders with fresh concrete, temperature data logger, insulated boxes, and computer.

Figure 6. Temperature vs. Time curve obtained during the hydration process and test setup.

Figure 7. High-Strength Lightweight Concrete Segmental beam constructed over the testing beam

5. EDUCATION OBJECTIVES

The segmental beam is constructed as a project for the course of Senior Concrete Design, which is a capstone course of the Structural Analysis and Design Program. The selection of the aggregates, mix design, and posterior elaboration of the concrete are essential parts of this project, permitting the students to apply different skills and techniques learned during their studies and from their work experience. The logistics of providing the materials, contacting the suppliers, organizing, and other activities are done by the students with good coordination with the faculty. The objectives of the course are fulfilled, which is reflected in the survey done ending the semester to assess the compliance of the course objectives. Figure 8 shows that 98% of the students consider that the objectives of the class were satisfied.

6. CONCLUSIONS

Lightweight concrete is used to construct a segmental bridge, which is a project for students of Structural Analysis and Design of the University of Houston Downtown. The lightweight concrete is done with expanded shale and clay, an industrial material provided by a local industry. As part of the student project, the most important properties of the aggregate are obtained in the laboratory and used for the trial mix design. The resulting concrete has a density of 112 lb/ft^3, design strength of 9,000 psi, and modulus of elasticity of 3'700,000 psi, values that compare well with the literature. A total of 23 ft^3 is prepared in the laboratory to make the 21'3" long postensioned beam.

The students accepted the project with enthusiasm and full participation, the assessment of the course showed a high acceptance of the project.

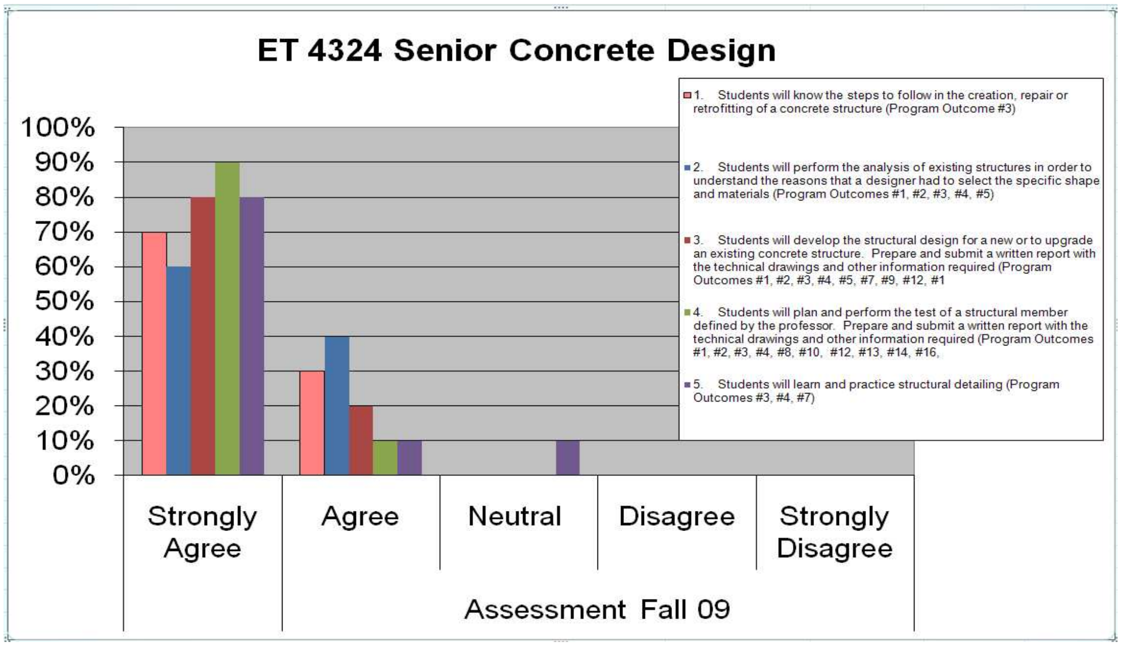


Figure 8. Assessment of the course verifying compliance of its objectives

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