EXAMINING VARIOUS OPTIONS TO EXTEND SPAN RANGE OF PRECAST PRESTRESSED CONCRETE BRIDGE GIRDERS

Razaq Ferhadi, PhD Candidate, PE, Bechtel Power Corporation, Frederick, MD

ABSTRACT

Prestressed concrete I-girders have been used in bridges for over 50 years and are used for spans up to 200 ft. During the past two decades, engineering and material technologies have advanced significantly and many tools were developed to extend the span length and/or girder spacing of prestressed concrete I-girders. These tools include:

- *High Performance Concrete (with f_c' up to 15 ksi)*
- *Lightweight Concrete (with f_c' up to 12 ksi)*
- *Large Size Strands (0.6- and 0.7-inch Diameter) and High Strength Strands (Grade 300ksi)*
- *Bridges made Continuous for Slab Weight and Superimposed loads*

This paper presents a parametric study that addresses some of these tools. The study investigates the impact of using these tools individually and simultaneously on the maximum span range and the corresponding cost of the superstructure. Results of study will help design engineers to decide which tool or tools should be considered based on the project criteria.

Keywords: prestressed, concrete, bridge, girder, lightweight, strands, high performance

INTRODUCTION

Extending span length of prestressed concrete bridge girders has always been a challenge for engineers and designers who enthusiastically desire to take concrete to next level to further sharpen the competition with steel. This was never been an easy challenge and continuously require researches and studies.

There are several tools and techniques that can be used to increase the span length of precast, prestressed concrete bridge girders. Among them are:

1. Normal weight High Performance Concrete (NWHPC),
2. Lightweight High Performance Concrete (LWHPC),
3. Ultra-High Performance Concrete (UHPC),
4. Large Size and High Strength Strands,
5. Spans made continuous for superimposed loads,
6. Spans made continuous for slab weight and superimposed loads.

This paper investigates the effect of using NWHPC, LWHPC, and Large Size and High Strength Strands, on increasing the span length. A parametric study has been performed using commercial Computer Aided Design software to reach that goal.

HIGH PERFORMANCE CONCRETE (HPC)

American Concrete Institute (ACI) defines HPC as concrete that meets special combinations of performance and uniformity requirements that cannot always be obtained using conventional ingredients, normal mixing procedures, and typical curing practices[1]. A commentary to the definition states that a high-performance concrete is one in which certain characteristics are developed for a particular application and environment. These requirements may include the following enhancements:

1. Ease of placement and consolidation without affecting strength,
2. long-term mechanical properties,
3. early high strength,
4. toughness,
5. volume stability, and
6. longer life in severe environments.

ACI 363 defines HPC as a concrete having a specified compressive strength of 40 MPa (6000 psi), or greater, and it does not include concrete made with exotic materials or techniques[2]. This limit is followed in this research. Using high performance concrete in bridges has many advantages including longer spans and/or wider girder spacing, low maintenance cost, better protection to the reinforcement as it is less permeable, lower creep and shrinkage losses, shallower sections, and higher abrasion resistance to traffic.

Several states have implemented HPC for bridge construction as part of the Strategic Highway Research Program (SHRP). Applications include all bridge components: superstructures (slab and girders) and substructures (piers and abutments). The SHRP projects have proved that HPC bridges are constructible and HPC can be cost effectively used in bridges.

LIGHTWEIGHT CONCRETE (LWC)

The primary goal of using structural lightweight concrete is to reduce the weight of the superstructure, which allows reducing the size of the substructure and foundation elements. By using lightweight concrete for the slab and girders, the self-weight can be reduced by as much of 15-20% and money can be saved[3]. In addition, it can help increasing girder spacing that may result in using fewer number of girders, eliminating or decreasing sizes of substructure elements, or extending the span range of concrete girders. Structural lightweight concrete mixtures can be designed to achieve comparable strength as normal weight concrete. The same is true for other mechanical and durability performance requirements.

Structural lightweight concrete provides a more efficient strength-to-weight ratio in structural elements than normal weight concrete. The higher cost of the lightweight concrete is offset by size reduction of structural elements, and less reinforcing steel and concrete that may result in lower capital cost.

Lightweight concrete is not a new material but using it in bridges is not very old. Researchers found that LWC has lots of benefits when it is used for bridges. In their investigation, Castrodale and Harmon examined using 115 pcf and 125 pcf LWC mixes in combinations for the girders and deck and concluded that the number of strands used for girders can be reduced when LWC is used for both the deck and the girder and spans can be increased when concrete's compressive strength is increased[4].

LARGE SIZE AND HIGH STRENGTH STRANDS

To obtain high prestress level, more prestressing steel is required that makes it necessary to use large diameter strands. Today, the 0.5-inch diameter, 270 ksi strand is the most common type of strands used in highway bridges in the United States. In the last six years, some State DOTs have started using the 0.6-inch with deep girders to enhance their flexural capacity[5,6,7]. Recently, there have been some investigations to use the 0.7-inch diameter strands[8].

Typically, strands used in highway bridges are made from high strength steel with 270 ksi tensile strength. Recently, high strength strand with tensile strength in excess of 300 ksi has become commercially available. ***Figure* 1** shows the stress-strain relationship for different grades of strands. ***Figure 1*** shows that the 300-ksi strand has the same level of ductility and modulus of elasticity as the 270-ksi strand. Although large size and high strength strands have higher cost than the typical 0.5-inch, 270 ksi strand, saving can be achieved from extending the span length and girder spacing.

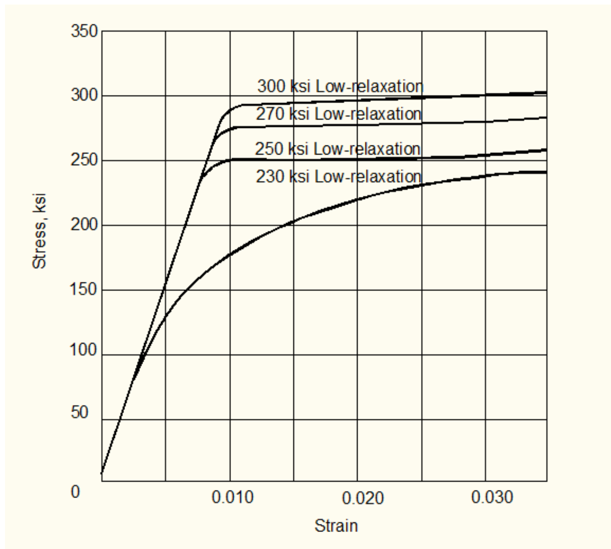

Figure 1 *Partial stress-strain curves for uncoated low-relaxation prestressing strands of different grades*[5]

Using 0.6 and 0.7 inch prestressing strands at a center-to-center spacing of 2 in allows for the optimal implementation of High Strength Concrete (HSC) in precast, prestressed concrete bridge superstructures[6]. According to Reference (6), 0.6-inch strand allows the introduction of 40% more prestressing force than the 0.5-inch strand because full pre-compression of the bottom fiber of the beam allows the largest possible service load moment to be resisted without exceeding the allowable tension stress in the concrete. "In addition, a forty-percent increase in reinforcement area can result in a comparable increase in ultimate capacity. Thus, girders reinforced with 0.6-in. (15.2 mm) strand offer significantly improved performance when considering either service or strength limit states[6]."

The economic benefits of using 0.6 and 0.7-inch strands are not limited to NWHPC, but extend to LWHPC. "Thirty percent fewer strands may be used (compared to 0.5 in strands) to achieve the same prestress force, reducing the labor costs associated with installing strands[6]." The use of 0.6-inch and 0.7-inch strands is addressed in this research and the results are analyzed and presented in charts. As an example of using 0.6-inch strands, an increase of span range of 42 percent resulted from using this size of strands in Louetta bridges that allowed full use of concrete strengths greater than 10,000 psi in the beam design[7]. It is important to mention that U-beams are used in Louetta bridges.

Safety must come as number one priority of any job. It is important to mention that draping high strength strands can be dangerous. Strands may snap during stressing process due to significantly higher stress. In addition, most of the current prestressing tools are designed for draping of 0.5-

inch, 270-ksi strands, draping higher strength strands may force to have the anchorages suite this size of strands. For these reasons, partial debonding of 0.6-inch and 0.7-inch strands may be a better way to decrease tensile forces at the top fiber at transfer length at release than draping them. Recently, the issue of using the 0.7-inch strands with HPC has been investigated at the University of Nebraska[8]. The investigation has concluded that using 0.7-inch strands with 15 ksi HPC will lead to savings that can reach 14 percent compared to a bridge with 8 ksi concrete and 0.6-inch strands[8].

PARAMETRIC STUDY

GENERAL OUTLINE

The upper limits of compressive strength considered in this study for NWHPC and LWHPC are 15,000 and 12,000 psi, respectively. Although these limits are slightly higher than the common practice limits currently used in the United States, review of the literature and contacts made with concrete suppliers have revealed the possibility of achieving these limits in the near future.

The objective of this study is to prepare a parametric study for NWHPC and LWHPC including Large Size Strands and High Strength Strands and compare them in many aspects including cost. The parametric study is performed to determine maximum span range of prestressed concrete bridge girders using HPC in decks and beam sections. The results of the analysis have been compiled in tables and charts for further analysis and research.

The parametric study is performed on an interior girder of the simply supported bridge given in Example 9.4 of PCI Bridge Design Manual.[10] The Bridge has an overall width of 51 ft. Two girder spacing of 9 ft. and 11.25 ft. are examined in the parametric study. In both cases, an 8-inch thick slab is used including a ½ in. wearing surface (**Figure 2**). Three strand sizes of 0.5, 0.6 and 0.7-inch are considered in the study.

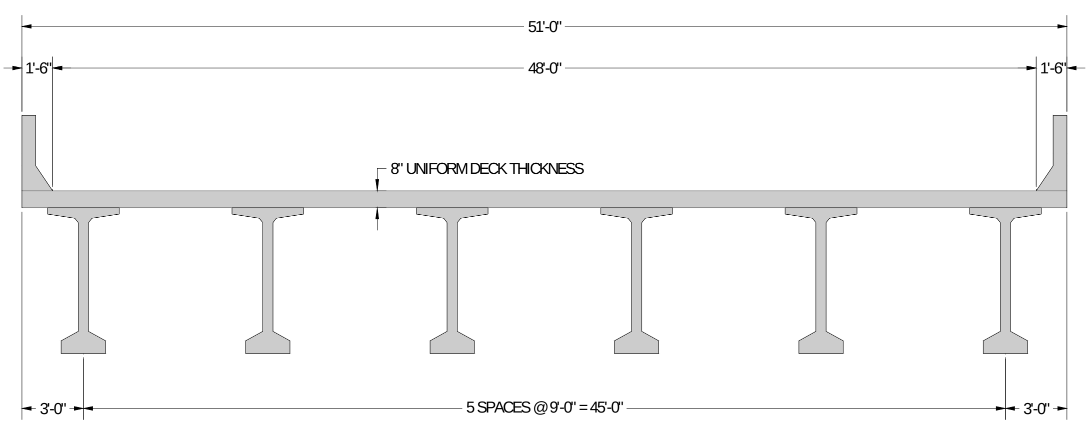

Figure 2 *The bridge model used in the analysis (with 9-ft girder spacing)*

DESIGN CRITERIA OF NWHPC

Table 1 gives the criteria of the 24 cases of NWHPC that are considered in the parametric study. 12 cases (A01 to A12) are investigated for girders with 9 ft center-to-center spacing and 12 cases (A13 to A24) are investigated for girders with 11.25 ft spacing. Three values of compressive strength are used for the deck; 4, 6 and 8 ksi. Four values are considered for the final concrete strength of the girder; 4, 6, 8 and 12 ksi, and the compressive strength at release is adjusted to 80% of the final compressive strength for all cases. Two steel grades are considered for the strands, which are 270 and 300 ksi. Three sizes are considered for the 270 ksi strands; 0.5, 0.6 and 0.7 in. diameter, and one size is considered for the 300 ksi grade strand, 0.5 in. diameter.

In order to conduct the cost analysis for these cases, cost of the NWC mixes and strands were acquired from producers in December 2008. **Table 2** shows the cost of the NWC mixes that was reported by a ready mix concrete producer in Maryland. These estimates were obtained including 6% tax and a 300-cubic yards order. **Table 3** gives the cost of the strands. It should be mentioned that the authors could not get an estimate of the 0.7-inch, 270 ksi strand because of its limited production in the United States. Therefore, the cost was estimated by linear interpolation of the 0.5 and 0.6, 270 ksi strands.

Table 1 *Cases considered for NWHPC*

Cases	**Beam Spacing (ft)**	**f'_c of the Deck (ksi)**	**Strand Tensile Strength (ksi)**	**Strand Size (in.)**	**f'_{ci} & f'_c of the girder (ksi)**
A01	9	4	270	0.5	*4.8 & 6 ksi 7.2 & 9 ksi 9.6 & 12 ksi 12 & 15 ksi*
A02		6	270	0.5	
A03		8	270	0.5	
A04		4	270	0.6	
A05		6	270	0.6	
A06		8	270	0.6	
A07		4	300	0.5	
A08		6	300	0.5	
A09		8	300	0.5	
A10		4	270	0.7	
A11		6	270	0.7	
A12		8	270	0.7	
A13	11.25	4	270	0.5	
A14		6	270	0.5	
A15		8	270	0.5	
A16		4	270	0.6	
A17		6	270	0.6	
A18		8	270	0.6	
A19		4	300	0.5	
A20		6	300	0.5	
A21		8	300	0.5	
A22		4	270	0.7	
A23		6	270	0.7	
A24		8	270	0.7	

Table 2 *Cost estimate of NWC mixes ($/yd^3)*

4 ksi	6 ksi	8 ksi	9 ksi	10 ksi	12 ksi	15 ksi
116.55	127.15	137.75	143.05	148.35	158.95	169.55

Table 3 *Cost estimate of prestress strands ($/1000 ft)*

0.5-inch, 270 ksi	0.6-inch, 270 ksi	0.5-inch, 300 ksi	0.7-inch, 270 ksi
390	560	429	730

DESIGN CRITERIA OF LWHPC

Table 4 gives the design criteria for LWHPC, where 24 cases are established and examined.

Table 4 *Cases considered for LWHPC*

Cases	**Strand Size & Strength**	**Concrete Density of the Deck (pcf)**	f_c' **of the slab (ksi)**	**Concrete Density of the Girder (pcf)**	f_{ci}' & f_c' **of the girder (ksi)**
B01	0.5 inch 270 ksi	150	4 ksi	150	*4.8 & 6 ksi* *6.4 & 8 ksi* *8 & 10 ksi* *9.6 & 12 ksi*
B02				130	
B03				115	
B04		130		150	
B05				130	
B06				115	
B07		115		150	
B08				130	
B09				115	
B10	0.6 inch 270 ksi	150		150	
B11				130	
B12				115	
B13		130		150	
B14				130	
B15				115	
B16		115		150	
B17				130	
B18				115	
B19	0.7 inch 270 ksi	150		150	
B20		130		130	
B21				115	
B22		115		150	
B23				130	
B24				115	

Only 4 ksi slab is used with all the cases of LWHPC. This decision was made based of the results of NWHPC, which has shown that slabs with concrete strength greater than 4 ksi have very little effect on increasing the span length. The LWHPC cases cover all types of strands that are used for NWHPC. While LWC can be manufactured with different values of concrete density (90 to 130 pcf), only two values are chosen in this research, which are 115 and 130 pcf. This decision was made after searching the literature. It should be mentioned that the cases with 0.7-inch strands are established with criteria to match only the successful cases of 0.5 and 0.6-inch strands. In other words, 0.5-inch and 0.6-inch strands were analyzed and the cases that resulted in significant span range increase are chosen for 0.7-inch strands. In addition, only beam spacing of 9 ft is used in this section. Also, 300 ksi strands that were studied for NWHPC and proofed inefficiency in increasing the span length are not considered here. **Table 5** gives the cost estimate of the LWHPC mixes. The cost of different compressive strength LWC mixes was acquired in February 2009. It was found that the115 and 130 pcf LWC mixes are $39 and $18.00 more than the NWC mix for the same $f_c^{'}$, respectively.

Table 5 *Cost estimate for LWC ($/yd^3)*

Concrete Density (pcf)	4 ksi	6 ksi	8 ksi	9 ksi	10 ksi	12 ksi
115	155.55	166.15	176.75	182.05	187.35	197.95
130	134.55	145.15	155.75	161.05	166.35	176.95

RESULT ANALYSIS OF NWHPC

Results from 24 cases of NWC are compiled and presented in **Figures 3 to 5**.

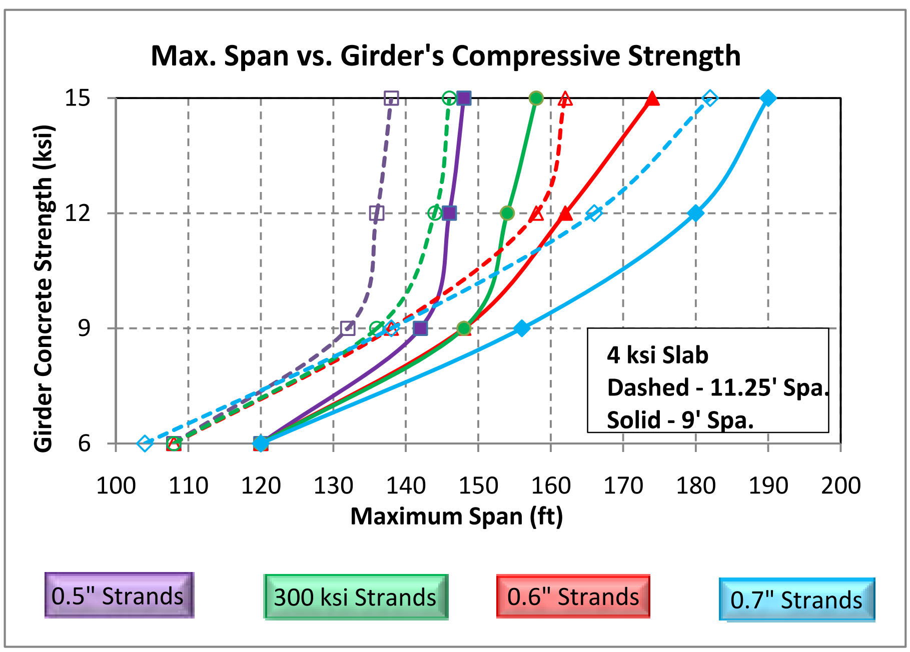

Figure 3 *Maximum achievable span versus girder's compressive strength (f_c' of the slab = 4 ksi)*

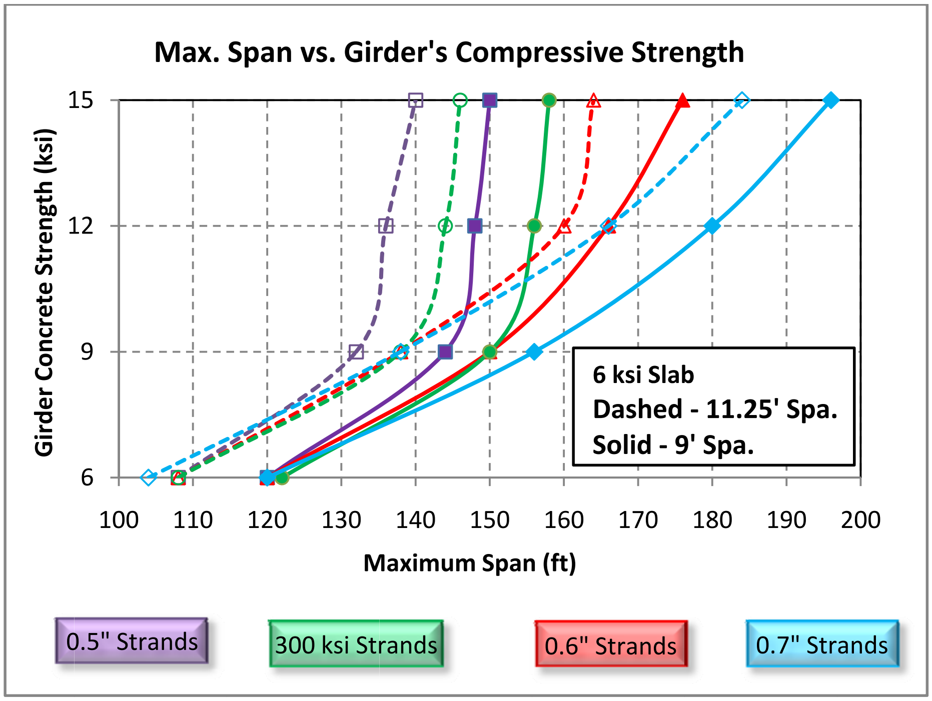

Figure 4 *Maximum achievable span versus girder's compressive strength (f'_c of the slab = 6 ksi)*

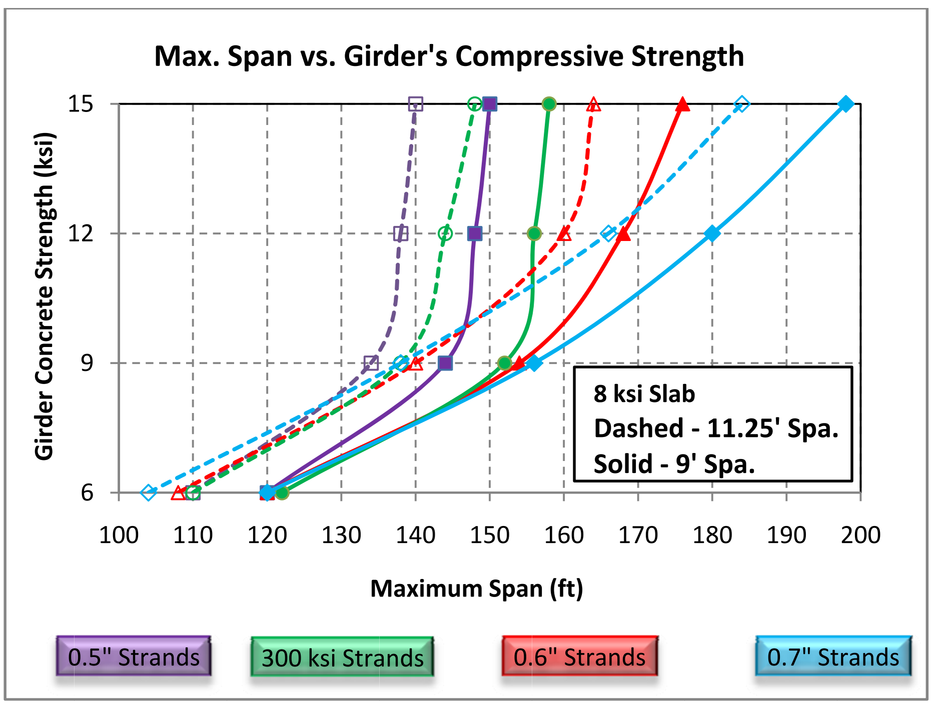

Figure 5 *Maximum achievable span versus girder's compressive strength (f'_c of the slab = 8 ksi)*

The charts are prepared such that to optimize benefit for engineers and designers who want to use BT-72 in their bridges. Checking **Figures 3 to 5**, the following conclusions can be reached:

1. Regardless the compressive strength of the slab and the girder spacing, all relationships follow almost the same trend.
2. Increasing the compressive strength of the slab from 4 to 6 ksi or from 6 to 8 ksi does not have a significant impact on increasing the span range. This phenomenon is clearly illustrated in **Table 6** that was extrapolated from **Figures 3 to 5**, where the case of f_c' = 6 ksi of the girder with 0.5-in., 270 ksi strands is taken as the base line of comparison.
3. Increasing the compressive strength of the girder f_c' from 6 to 9 ksi has higher impact on increasing the span length more than the cases of increasing f_c' from 9 to 12 ksi and from 12 to 15 ksi. This phenomenon can be seen from **Figures 3 to 5** where the relationship between f_c' and the span length has a mild slope for f_c' = 6 to 9 ksi and a steep slope for f_c' = 9 to 15 ksi. The only exception to this phenomenon is the case where the 0.7 in. diameter, 270 ksi strands are used, where almost the same rate of increase in the span is detected when f_c' is increased from 6 to 12 ksi.

Table 6 *Percent Span Increase Compared to Baseline*

f_c' of Girder (ksi)	f_c' of Slab (ksi)	Percent Span Increase Compared to the Baseline							
		0.5-inch, 270 ksi		0.6-inch, 270 ksi		0.5-inch, 300 ksi		0.7-inch, 270 ksi	
		9 ft	11.25 ft	9 ft	11.25 ft	9 ft	11.25 ft	9 ft	11.25 ft
6	4	0*	0**	0	0	0	0	0	-4
	6	0	0	0	0	0	0	0	-4
	8	0	2	0	0	0	2	0	-4
9	4	18	22	23	28	23	26	30	28
	6	20	22	25	28	25	28	30	28
	8	20	24	28	30	27	28	30	28
12	4	22	26	35	46	28	33	50	54
	6	23	26	38	48	30	33	50	54
	8	23	28	40	48	30	33	50	54
15	4	23	28	45	50	32	35	58	69
	6	25	30	47	52	32	35	63	70
	8	25	30	47	52	32	37	65	70

* Baseline case for the 9 ft girder spacing
** Baseline case for the 12 ft girder spacing

4. **Figures 3 to 5** can be used to determine the ideal compressive strength of the girder. Ideal compressive strength is the point on the curve that gives the most economic value of f_c' that can be used for the girders. If a higher value of f_c' is used for the girders, then the benefit from using HPC is decreased dramatically as the higher value of f_c' cannot offer much span increase. For example, if the BT-72 girders are spaced at 11.25 in. and 0.5-in., 270 ksi strands are used, the ideal compressive strength for the girder will be around 10 ksi. When

0.6-in., 270 ksi strands are used with 11.25 ft girder spacing, the ideal compressive strength rises to approximately 13 ksi.

5. Regardless the girder spacing or the compressive strength of the slab, if f_c' of the girder = 6 ksi, using larger size of strands or strands with higher tensile strength has almost no effect on the span length. This phenomenon can be seen from **Figures 3 to 5** where all the relationships start almost at the same point.
6. Using larger strand size (i.e. 0.6 or 0.7 in. diameter) has higher impact on the span length than using higher grade of strands.

COST ANALYSIS OF NWHPC

The cost analysis presented in this section considers only the material cost of the girders and slab using the cost of concrete and strands given in the introduction section of this paper. Cost of the barriers, wearing surface and reinforcement provided in the slab are not included in the analysis. Also, the labor cost is not included.

Figure 6 shows the cost per linear foot of an interior girder with the associated portion of the deck. This figure presents selected results from the two-girder spacing, 9 and 11.25 ft. For clarity, **Table 7** gives the design criteria for the cases covered in **Figure 6**. All the cases shown in **Figure 6** are for 4 ksi slab. The 4-ksi slab is chosen for the cost analysis because the span length analysis has shown that 6 and 8 ksi slab do not provide significant increase of the span.

As shown in **Figure 6**, the cost per linear foot increases when f_c' of the girder increases. However, the relationship is not linear. There is a significant cost increase for the 11.25 ft. spacing for the cases where 0.6-in. and 0.7-in. strands are used (Cases A16 and A22), and f_c' of the girder is raised from 12 ksi beam to 15 ksi. Meanwhile, the cost does not change for the case with 300 ksi strands (Case A19) for the same change in f_c'.

Incorporating **Figures 3 and 6** draws a very useful and practical path to choose the right compressive strength for the girder and the right strand type that optimize both span length and cost per linear foot. For example, if 300 ksi strands are chosen with 15 ksi concrete girders, this case offers 32% span length increase and costs approximately $93 per linear foot. Comparing this case with the case where 0.6-in. strands and 12 ksi concrete girders are used that offers 35% span length increase and costs approximately $87 per linear foot, a direct saving of $6 per linear foot and extra length of 2% can be achieved. More comparisons can be drawn if the cost analysis is developed for all the cases presented in the span length analysis.

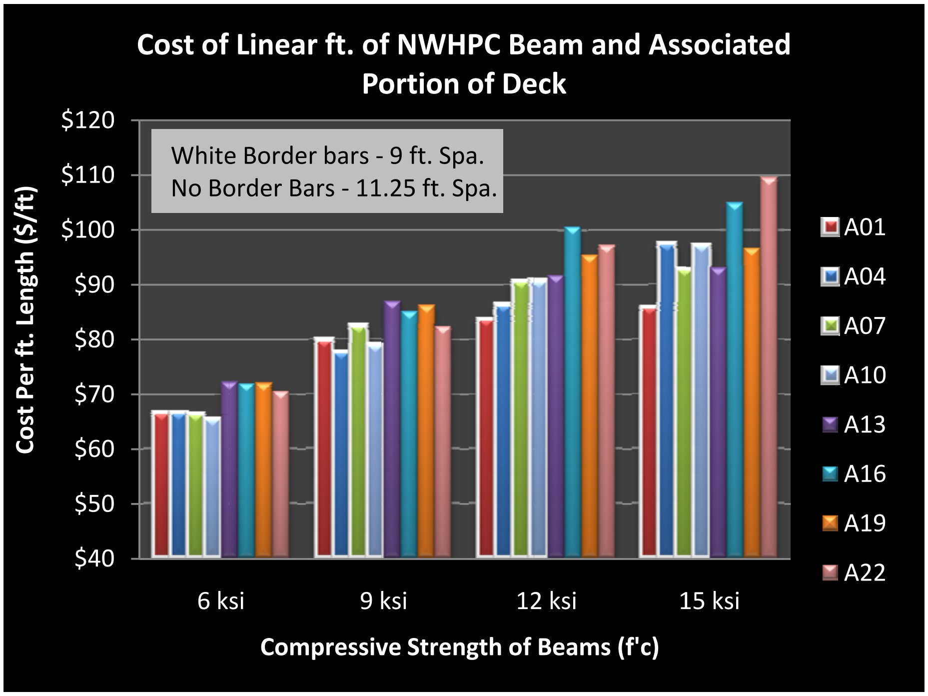

Figure 6 *Cost of linear foot of NWHPC beam with associated portion of the 4 ksi deck (see **Table 6**)*

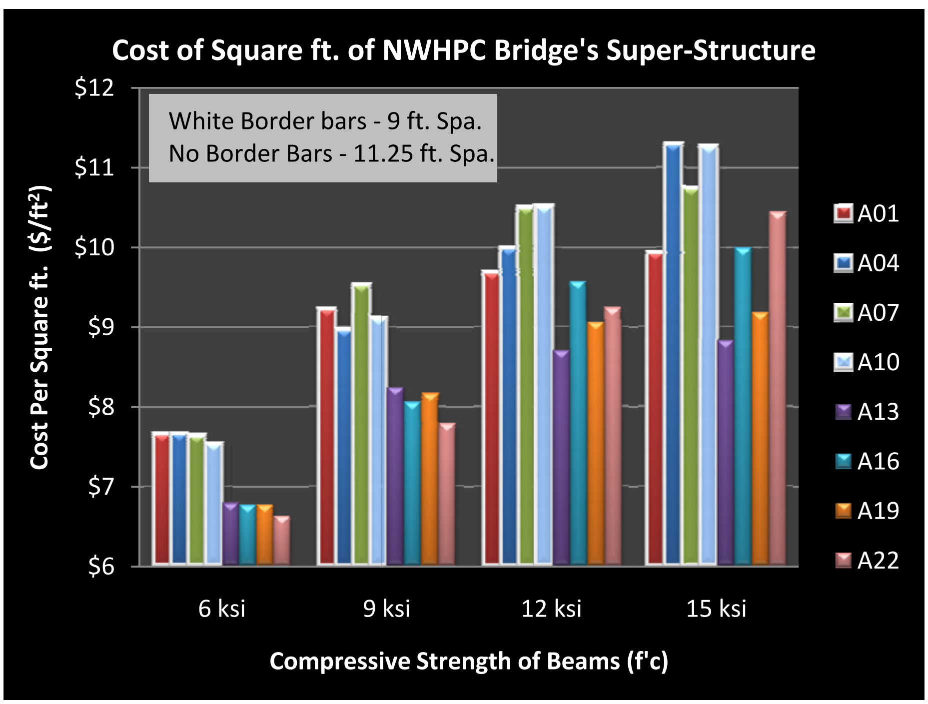

Figure 7 *Cost per square foot of the NWHPC bridge's superstructure not including barrier and wearing surface*

Table 7** Design criteria of cases presented in **Figure 6

Beam Spacing	The Cases with 4 ksi Slab							
	A01	A04	A07	A10	A13	A16	A19	A22
9 ft. Beam Spacing	0.5-inch 270 ksi	0.6-inch 270 ksi	0.5-inch 300 ksi	0.7-inch 270 ksi	NA	NA	NA	NA
11.25 ft. Beam Spacing	NA	NA	NA	NA	0.5-inch 270 ksi	0.6-inch 270 ksi	0.5-inch 300 ksi	0.7-inch 270 ksi

Figure 7 shows cost per square foot of the bridge's superstructure excluding the barrier and wearing surface costs. The trend is the same as in **Figure 6** except that the bars in **Figure 7** are much shorter for 11.25 ft. beam spacing due to shorter beam spans.

RESULT ANALYSIS OF LWHPC

Twenty four cases of LWHPC are analyzed and the result data are compiled in charts and tables. **Figure 8** represents the maximum achievable span length of the LWHPC girders according to f_c' of the girder.

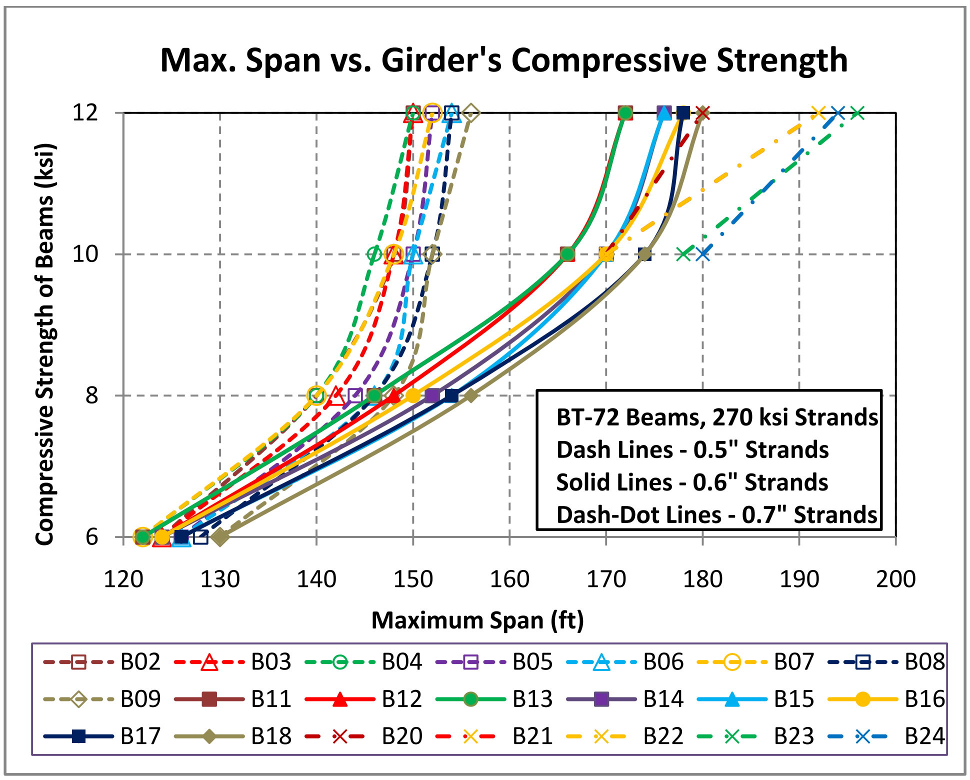

***Figure 8** Maximum achievable span length of LWHPC according to various values of f_c' of the girder*

Figure 8 is comparable to **Figure 3** of NWHPC and ideal compressive strength values can be determined for each case. It can be noticed that the ideal compressive strength values for 0.5-inch strand cases are between 8 ksi and 9 ksi, while 0.6-inch strands can take more advantage of HPC to increase the span range and can go up to 10 ksi. 0.7-inch strands take advantage of even higher values of f_c' because they are capable of increasing span range beyond the value that obtained from 10 ksi. Therefore, the ideal compressive strength for 0.7-inch strands is 12 ksi.

Table 8 *Percent span length increase of LWHPC cases based on 6 ksi NWHPC with 0.5-inch, 270 ksi strands*

Cases	Compressive Strength of Beams			
	6 ksi	8 ksi	10 ksi	12 ksi
B01	0	8	18	22
B02	3	17	23	25
B03	3	18	23	25
B04	2	17	22	25
B05	5	20	25	27
B06	5	22	25	28
B07	2	17	23	27
B08	7	22	27	28
B09	8	23	27	30
B10	0	17	27	35
B11	2	22	38	43
B12	3	23	38	43
B13	2	22	38	43
B14	3	27	42	47
B15	5	28	42	47
B16	3	25	42	48
B17	5	28	45	48
B18	8	30	45	50
B19	0	20	35	50
B20	-	-	42	50
B21	-	-	42	60
B22	-	-	42	60
B23	-	-	48	63
B24	-	-	50	62

As in NWHPC, the difference of span length between the cases is negligible when low values of f_c' are used. Almost all the cases have the maximum span range of 120 ft. despite the type of strand used. This is the same value that obtained from the NWHPC when 6 ksi concrete is used. This means that there is no need to use LWC when using low values of f_c' for the girders.

When 8 ksi is used for the girders, the span values are still be close to each other and LWC is not a wise choice if this value of f_c' is chosen; or at least, there is no good reason to switch to bigger strands than 0.5-inch when 8 ksi LWHPC concrete is used for the girders. Likewise, when 10 ksi concrete is used, a case with 0.6-inch strands can be chosen to offer the same length that 0.7-inch strand can offer and money be saved. For example, Case B15 where the concrete density of the girder is 115 pcf and the deck is 130 pcf can offer a span length of 170 ft. that is the same length as the one offered by Case B21, which has NWHPC girders and 115 pcf slab with 0.7-inch strands.

Table 8 shows the percentage of span range increase based on 6 ksi NWHPC with 0.5-inch, 270 ksi strands. Notice that a 63% increase is possible for a beam with 0.7-inch strands when 130 pcf concrete is used for the girder and 115 pcf is used for the deck. This comparison is more useful when it is combined with the cost analysis that is discussed later in this section.

Figures 9, **10**, and **11** show maximum achievable span length when LWHPC is used and compared to the case of 6 ksi NWHPC beam with 0.5-inch, 270 ksi strands. **Figure 9** shows maximum span length per f_c' of the LWHPC beams with 0.5-inch, 270 ksi strands compared to the similar case of NWHPC. It is clear that 0.5-inch, 270 ksi strand is not a rational choice with LWHPC because there is no big difference in span length when it compared to NWHPC. As the size of strand increases to 0.6-inch, using LWHPC makes more sense because it offers significant span length increase compared to the case of NWHPC with same strand type as shown in **Figure 10**. In other words, NWHPC loses the competition when 0.6-inch strands are used. On the other hand, **Figure 11** shows that the difference in the span length increase between NWHPC and LWHPC is not significant when 0.7-inch strands are used. This can be noticed by comparing Case B19 (that is for NWHPC) with the vertical bars.

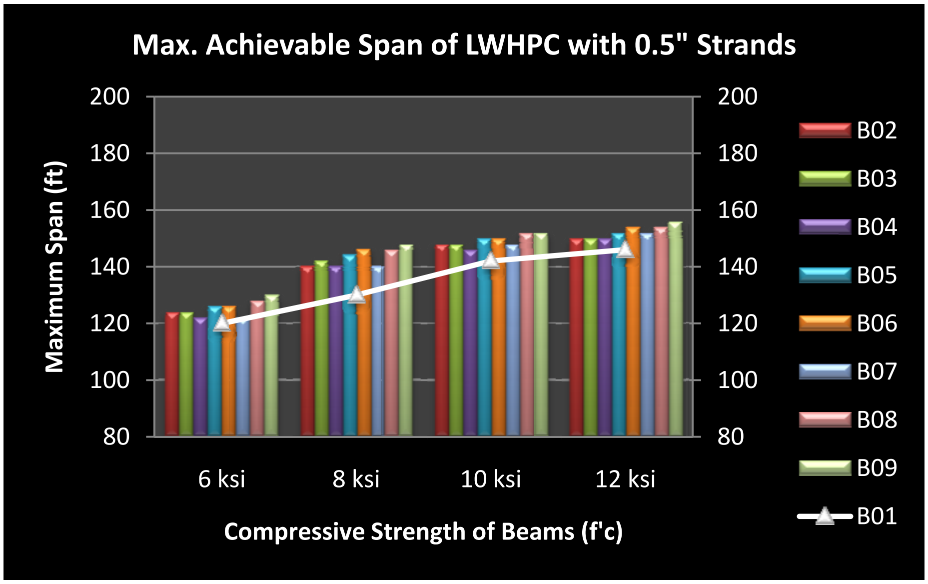

Figure 9 *Maximum achievable span length of LWHPC cases that have 0.5-inch, 270 ksi strands compared to NWHPC with 0.5-inch, 270 ksi strands (Case B01)*

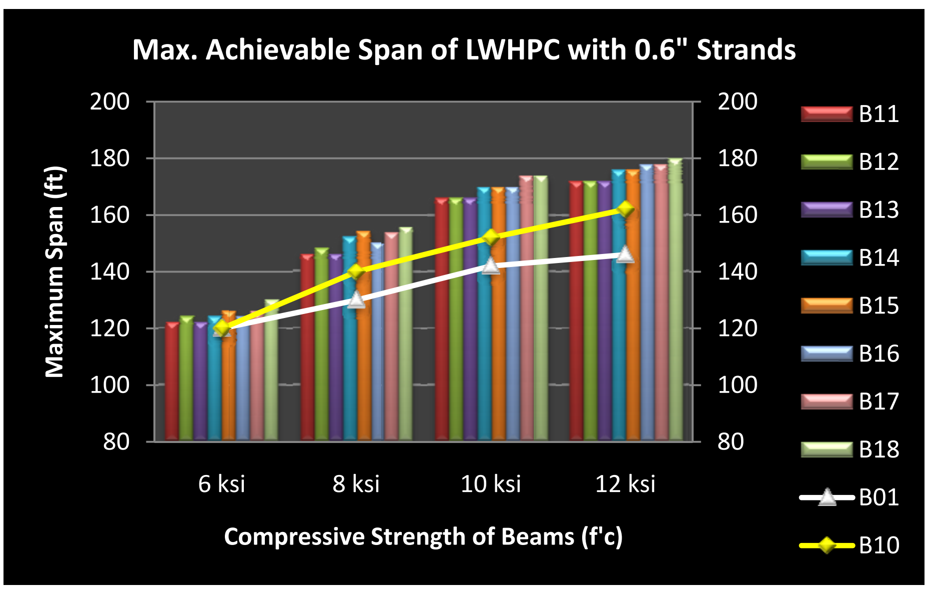

Figure 10 *Maximum achievable span length of LWHPC cases that have 0.6-inch, 270 ksi strands compared to NWHPC with 0.5-inch, 270 ksi strands (Case B01) and NWHPC with 0.6-inch, 270 ksi strands (Case B10)*

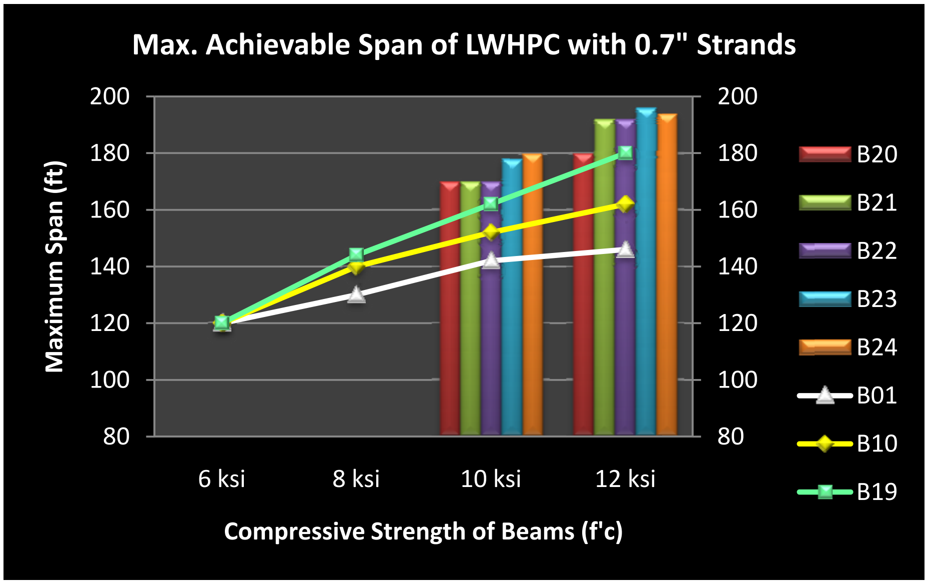

Figure 11 Maximum achievable span length of LWHPC cases that have 0.7-inch, 270 ksi strands compared to NWHPC with 0.5-inch, 270 ksi strands (Case B01), NWHPC with 0.6-inch, 270 ksi strands (Case B10), and NWHPC with 0.7-inch, 270 ksi strands (Case B19)

A big difference can be noticed in **Figure 11** between using 0.5-inch, 270 ksi strands (Case B01) and the vertical bars. It is clear that the span length can be increased more than 60% when 12 ksi is compared to 6 ksi. This is what shown in **Table 8**.

COST ANALYSIS

As in NWHPC, a cost analysis is performed for LWHPC to include only material costs for the superstructure without barrier and wearing surface costs. **Figures 12**, **13**, and **14** show the cost analysis.

Figure 12 shows the cost per linear foot of LWHPC beams with 0.5-inch strands compared to a similar case of NWHPC, which is Case B01 (see **Table 2**). It can be noticed that the cost per linear foot of the beam with the associated portion of the slab (beam spacing of 9 ft. is considered) of Cases B03, B06, B08, and B09 are the highest. In general, wherever 115 pcf LWHPC is used the cost increased. This chart can be compared to the chart in **Figure 9** to determine whether is worthy to switch to LWC or not. For example, in the case of B09 that has 115 pcf concrete for both the slab and the beams, there is approximately 17% increase in cost compared to the similar case of NWHPC when 10 ksi concrete is used and can extend the span range by only 10% (see **Figures 9** and **12**).

It can be noticed that there is very little difference in the cost per linear foot between the three NWHPC cases that has 0.5-inch, 270 ksi, 0.6-inch, and 0.7-inch strands (Cases B01, B10, and

B19 respectively). However, they offer different span range extension at 10 ksi and 12 ksi. A look at **Figures 11** and **14** proofs that 0.7-inch strands are more reasonable with NWHPC than with LWHPC because of the small difference between Case B19 (which is for NWHPC) and the vertical bars in **Figure 11** and the big difference in cost in **Figure 14**.

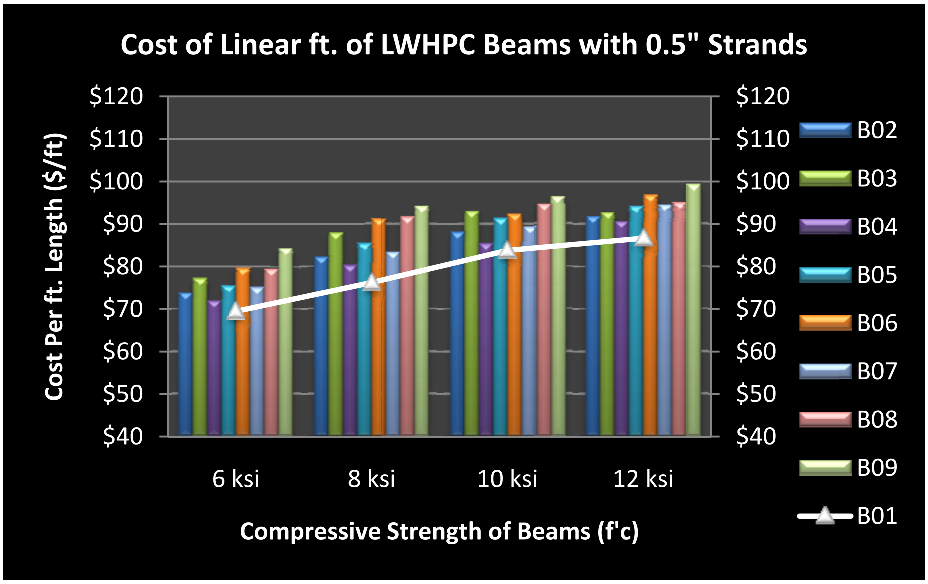

Figure 12 *Cost of linear foot of LWHPC beams with associated portion of the deck with 0.5-inch, 270 ksi strands compared to NWHPC beam with 0.5-inch, 270 ksi strand (Case B01)*

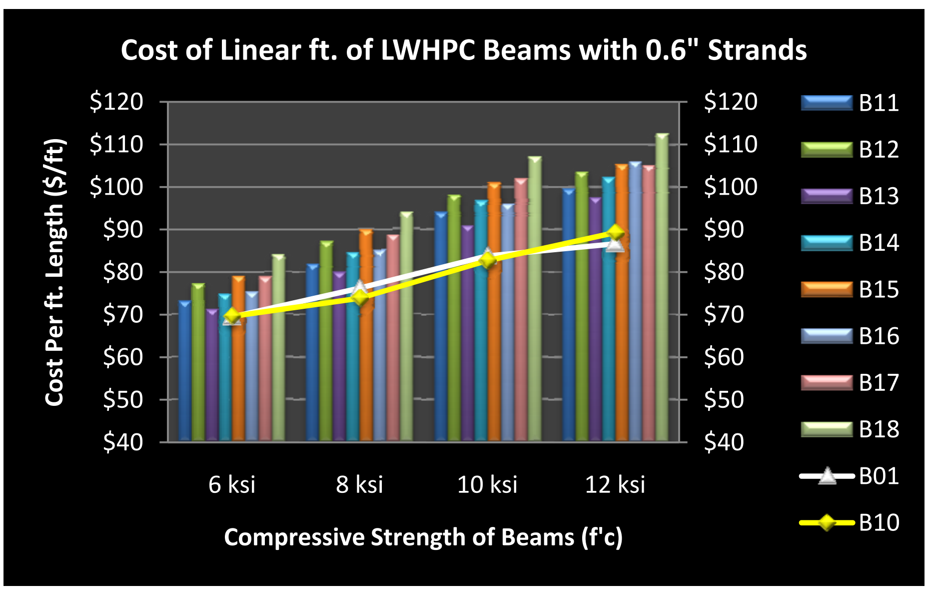

Figure 13 *Cost of linear foot of LWHPC beams with associated portion of the deck and 0.6-inch, 270 ksi strands compared to NWHPC beam with 0.5-inch, 270 ksi strands (Case B01) and 0.6-inch strands (Case B10)*

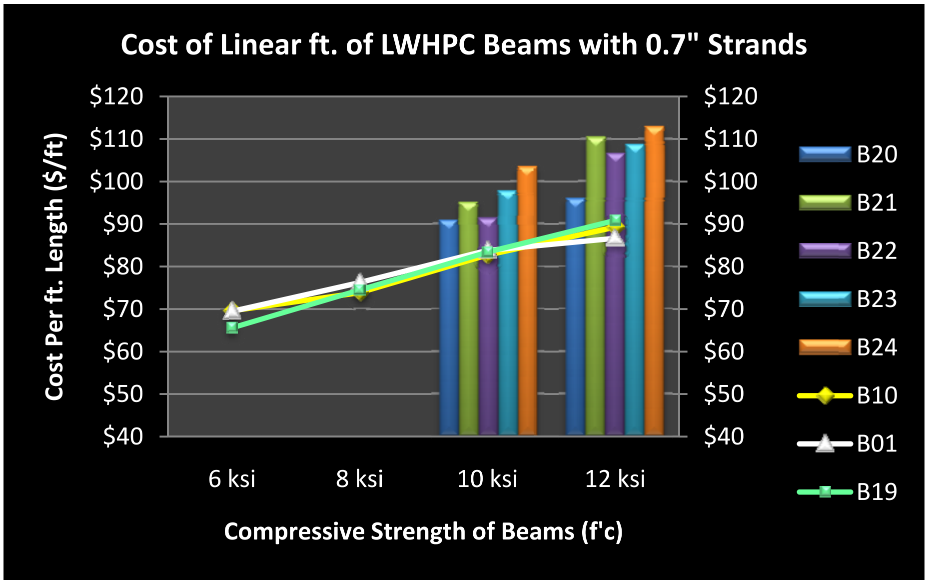

Figure 14 *Cost of linear foot of LWHPC beams with associated portion of the deck and 0.7-inch, 270 ksi strands compared to 6 ksi NWHPC beam with 0.5-inch, 270 ksi strands (Case B01), 6 ksi, 0.6-inch strands (Case B10), and 6 ksi, 0.7-inch strands (Case B19)*

Also, using 0.6-inch strand with LWHPC offers a significant advantage for extending span range when it is used with 10 ksi and 12 ksi concrete compared to 0.5-inch strands.

When the cases of LWHPC are compared using **Figure 9** through **Figure 14**, it can be concluded that the cases B14 (130 pcf concrete for both the deck and the girder), B16 (115 pcf deck on NWC beams), and B17 (115 pcf deck on 130 pcf beams) are rational choices.

CONCLUSION AND RECOMMENDATIONS

From what explained above, the following bullets are conclusions and recommendations as outcome of this research:

- Using high performance concrete for the deck does not result in increasing span length significantly. If durability factor is not considered, then the value of 4 ksi is rational for the deck.

- Using 6 ksi and 8 ksi concrete are not capable of increasing span length significantly even when high performance strand is used. Therefore, producing lightweight high performance concrete that results in these values of f_c' and using high performance strands with these values are waste of money and time.

- Ideal compressive strength for normalweight concrete with 0.5-inch, 270 ksi strands is 9 ksi; with 0.6-inch strands is 12 ksi; and with 0.7-inch strands is 15 ksi.

- It is more beneficial to use 0.6-inch strands than using 0.5-inch, 300 ksi strands because it can offer significantly longer span lengths and is not much more expensive.

- It is more beneficial to use bigger strand size than 0.5-inch when the compressive strength used for the beam is higher than 9 ksi.

- It is more economic to use 0.7-inch strands with normalweight concrete than with lightweight concrete, meanwhile, 0.7-inch strand with normalweight high performance concrete can offer span range increase close to a value where lightweight concrete can offer.

- Lightweight high performance concrete is better choice than normalweight high performance concrete when 0.6-inch strand is used.

- When lightweight high performance concrete is used, the concrete density of 130 pcf for the deck and 115 pcf for the beams is the ideal configuration that results in the maximum increase of the span length possible.

- Cases where lightweight high performance concrete of 130 pcf concrete for both the deck and the girder, 115 pcf deck on normalweight high performance concrete beams, and lightweight high performance concrete of 115 pcf deck on 130 pcf beams are good choices that offer span range extension and they are economic compared to the other configurations.

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REFERENCES

1. **ACI Committee 116.** *Cement and Concrete Terminology.* s.l. : ACI Committee 116, ACI 116R-00, Reapproved 2005.

2. **ACI Committee 363.** *Guide to Quality Control and Testing of High-Strength Concrete.* s.l. : ACI Committee, ACI 363.2R, 1998.

3. **Heffington, J. A., et al.** *Summary: High Performance Lightweight Concrete Prestressed Girders and Panels.* s.l. : Center for Transporation Research, The University of Texas at Austin, 2001. Project Summary Report 1852-S, Prestressed Structure Lightweight Concrete Beams.

4. *Increasing Design Efficiency Using Lighwtweight Concrete for Prestressed Girder Bridges.* **Reid, Castrodale W. and Harmon, Kenneth S.** s.l. : NBC, 2005, Natonal Bridge Conference.

5. **Libby, James R.** *Modern Prestress Concrete: Design Principles and Construction Methods.* s.l. : Taylor & Francis, 1990.

6. **Barnes, R W, Burns, N H and Kreger, M E.** *Development Length of 0.6-inch Prestressing Strand in Standard I-Shaped Pretensioned Concrete Beams.* Austin : Center of Transportation Research, Bureau of Engineering Research, The University of Texas at Austin, 1999. Research Report 1388-1.

7. *Louetta Road Overpass - Lessons Learned.* **Ralls, Mary Lou.** [ed.] HPC Bridge Views. 1, s.l. : FHWA, January/February 1999, Bridge Views, p. 3.

8. **Akhnoukh, A. K.** *Development of High Performance Precast/Prestressed Bridge Girders.* Construction Systems, University of Nebraska. Lincoln : UNL, 2008. Ph.D. Dissertation.

9. **FHWA.** *High Performance Concrete Structural Designers' Guide.* [ed.] Federal Highway (FHWA) Administration. Fifth. s.l. : U.S. Department of Transportation, High Performance Concrete Technology Delivery Team, 2005.

10. **PCI.** *Bridge Design Manual.* s.l. : Precast / Prestressed Concrete Institute (PCI), 2002.

11. *Analysis and Structural Benefits of High Performance Concrete for Pretensioned Bridge Girders.* **Kahn, Lawrence F and Saber, Aziz.** 4, s.l. : PCI JOURNAL, July-August 2000, Vol. 45.

12. *Design of Prestressed Girder Bridges Using High Performance Concrete - An optimization Approach.* **Hassanain, Mostafa A and Loov, Robert E.** 2, s.l. : Precast / Prestressed Concrete Institute (PCI), March-April 1999, PCI Journal, Vol. 44, pp. 40-46.

13. **Nawi, Edward G.** *Prestressed Concrete, A Fundamental Approach.* Fifth. Upper Saddle River : Pearson Prentice Hall, 2006.

14. **LEAP CNOSPAN Rating.** *CONSPAN Software Version 8.0.0.* Tampa, FL : Bentley Systems, Inc., 2008.

15. **(PTC), Parametric Technology Corporation.** *Mathcad Engineering Calculation Software 14.0 M011.* Needham, MA : PTC.