POTENTIALS IN DEVELOPING LIGHTWEIGHT CONCRETE PRESTRESSED BRIDGE GIRDERS

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Summary: *Lightweight aggregate concrete is a challenge for developing bridge girders with reduced self-weight. Savings in transportation costs for precast girders can be considerable. An extensive research started in Hungary (within a cooperation with a design office and a precast plant) to develop possible concrete mixes and design rules for precast bridge girders of lightweight aggregate concrete. Particular aspects for our studies were: selection of type of lightweight aggregate, concrete mix design, adequate curing, relatively high final compressive strength and adaptation of the production process in the prefabrication plant. An additional request was the high early age strength. As part of the research project, a prototype girder has been cast with concrete strength class of LC50/55 and density class of D2.0. In the paper we concentrate on two main aspects as bond between strands and lightweight aggregate concrete and durability (especially frost resistance and chloride ion migration).The prototype girder has been produced in industrial conditions and has been loaded up to failure.*

Keywords: *LC, lightweight concrete, bridge girder, density, precast, prototype*

1. INTRODUCTION

Majority of load bearing lightweight aggregate concrete (LWAC) structures and structural elements are made of using expanded clay aggregates [1]. Therefore, most of the material research is carried out by concretes with expanded clay pellets. Consequently, new recommendations and standards for LWAC are also based on expanded clay aggregate concretes. Water absorption capacity of the lightweight aggregates with open pores is high. The high water absorption of lightweight aggregates must be taken into account in mix design which is different from that of normal weight

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concrete. In design of concrete structures there is always a target value for the compressive strength of concrete. In case of lightweight concrete, an additional criteria is the density. It often leads to an optimization.

2. DESIGN QUESTION

Live loads and environmental loads are the same concrete structures independently of the concrete type. However, there are several requirements that may need careful considerations such as: bond capacity, water tightness, freeze-thaw resistance, resistance to chloride ion penetration and durability in general. Based on requirements by environmental protection and sustainability, lot of research is directed to the possible use of supplementary cementitious materials (SCM) as part of the binder [2].

The effect of water-cement ratio is the same for both normal weight and lightweight concretes. But the particle strength of lightweight aggregates themselves is lower. Another difference is that the volumetric ratio of lightweight aggregates is lower compared to normal weight aggregates. Therefore, the properties of cement mortar plays an important role for lightweight aggregate concretes. The cement paste of lightweight aggregate concrete can be made of lightweight sand or normal weight sand. If the aggregates of lightweight concrete are used in different particle densities (lightweight course aggregate and normal quartz sand) the grading curve can be calculated in volume percent, not in mass percent [3]. The moisture content and water absorption of concrete highly influence the durability of the structure, because most of the harmful material (e.g. chlorides, sulfates etc.) can get into the concrete through the capillaries with water. In addition, water is required to corrosive reactions, like electrolytic corrosion. LWAC has higher porosity than conventional concrete and the moisture content in air-dry condition even greater, it may be unfavorable in aspect of durability.

3. HISTORICAL REVIEW

There are many examples showing the reasonable use of lightweight materials including lightweight concrete, especially if the reduction of dead load can bring considerable benefits. The significance of LWAC has been increasing with spans and heights. Its use is also advantageous in reconstruction resulting less additional loads. In cases of increase in live loads, LWAC can compensate some of the self-weight. For prefabricated structures, LWAC can simplify handling and transportation allowing smaller cranes or larger elements. Lightweight concrete is not a new material. It was used in 1st-2nd centuries AC in the Roman Empire in the construction of cupolas, pillars and vaults (e.g. Pantheon, Coliseum). The great performance of ancient Romans demonstrates that both durability and load bearing capacity of these concretes was good enough for very long periods. The Pantheon is one of the best preserved ancient buildings. Structural lightweight concrete was first used in modern times in the United States with construction of bridge and residential towers Park Plaza Hotel (Saint Louis, 1928), South Western Bell Telephone Company (Kansas City, 1928), Oakland-Bay bridge superstructure (San Fransisco, 1936), Prudenntial Life Building slabs, (Chicago), Om

Shell Plaza (Houston) [4], [5]. In the 1940s, industrial production of lightweight concrete started in Europe, appearing first in Denmark. Around this time in North America, concrete damaged by ocean (salted) air and frost were being replaced by lightweight concrete. The achieved decrease in self-weight made it possible for structures with larger concrete covers to meet new load-bearing and durability requirements [6], [7]. The use of lightweight concrete gave birth to new architectural style in the 60's in the USA, of which first example is the Marina City Towers in Chicago. The number of large lightweight concrete structures decreased with inventing the high strength and high performance concretes. The most popular area of application was the bridges (Table 1, Figures 1 and 2).

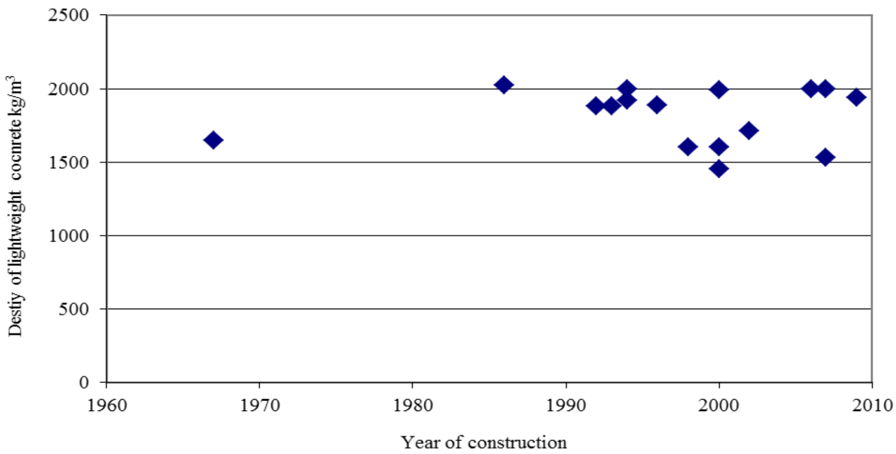

Figure 1. Density of LWAC bridges vs. the year of construction

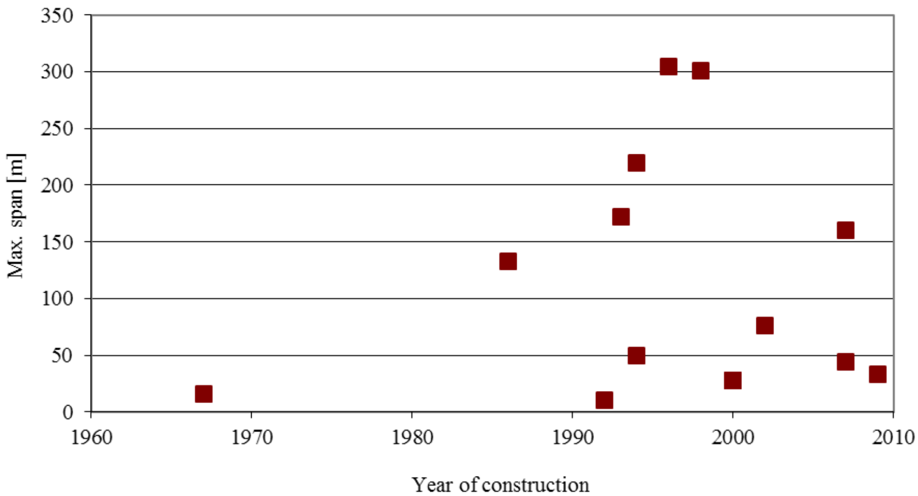

Figure 2. Max. span of LWAC bridges vs. the year of construction

Table 1 Existing LWAC bridges: name, year of construction, max. span, max. length, density and compressive strength of concrete constructed in the period of 1962 to 2010 [2, 4, 8]

Name of bridge and country	Year of construc-tion	Density of ligtweight concrete kg/m^3	Max. span, m	Length of bridge, m	Strength of concrete, N/mm^2
Benicia-Martinez USA	1962			2195	
Western part of The Neatherlands *Netherlands*	1967	1650	15,5	49	31.5
Koningspleij bridge *Netherlands*	1986	2020	133	760	37.5
New Eidsvoll Sund Norway	1992	1880	10	320	66.8
Nordhordland cabel stayed, Norway	1993	1881	172	172	69.9
Stovset, Norway	1994	2000	220	420	64.5
Nordhordland floating, Norway	1994	1918	50	1600	70.4
Grenland, Norway	1996	1888	305		59.8
Stolm, Norway	1998	1600	301	467	71.4
Karl-Heine, Germany	2000	1450	28	28	
Karl-Heine, Germany	2000	1600	28	28	
Karl-Heine, Germany	2000	1990	28	28	
České Budějovice *Czech Republic*	2002	1710	76		
New Benicia-Martinez ,USA	2007	2000	160	2300	69
Route 33, over Mattaponi River USA	2007	1528	44.2	133	55
Route 608, Massaponax Church Road, over Interstate 95, USA	2009			75	27.6
SR-34 Bullsboro, USA	2009	1938	33	99	

Table 1 summarizes name, year of construction, max. span, max. length, density and compressive stregtnh of concrete for some remarkable lightweight aggregate concrete bridges constructed in the period of 1962 to 2010. Figure 1 indicates concrete densities and Figure 2 maximal spans of these bridges.
Based on Table 1 as well as Figures 1 and 2 the following observations can be done:

- The density of LWAC was primarily in the range of 1500 to 2000 kg/m^3, but not limited to 2000 kg/m^3 density value,
- The largest span reached 300 m,
- The span of bridges does not show a clear correlation with the density of lightweight concrete,
- In these examples we did not realize a clear correlation between the average compressive strength of concrete and density of LWAC.

There has been already some applications of lightweight concrete for precast bridge girders. Lawrence et al. [9, 10] in his experiments tested three different LWAC compositions, which were later used as bridge girders. There experimental results indicated 20% higher shrinkage of HPLC (high performance lightweight concrete) compared to that of conventional concrete, but the creep was found to be lower.
Dunbeck in 2009 [11] continued research of Lawrence et al. (2004) and he managed to apply self-compacting concrete is easy to produce. The aim of Dunbeck was to produce prestressed, precast beams for a bridge on SR-34 over the road Bullsboro.

4. OUR EXPERIMENTAL PROGRAMME

4.1. INITIAL CONDITIONS

The following initial requirements were established for our experimental programme:
- relatively high strength with high initial strength
- proposed density class of D1.8 – D2.0,
- possibility for steam curing,
- continuous availability of the lightweight aggregate,
- constant quality of produced concrete.

The selected strength class was LC50/55 with the minimum strength of concrete of 45 N/mm^{2}at one day (with the possibility of steam curing if necessary). Due to the high strength, the density 1800-1900 kg/m^3 is realizable. The possible aggregates could be in general: expanded clay, expanded glass, slag, crashed natural tuff, and crashed clay brick. Amount of crashed natural tuff is limited and the quality must be permanently controlled.

4.2. SELECTION OF AGGREGATE

According to our previous test results, expanded glass gravel could have been reasonably used in technological, economic and environmental terms. However, at the moment no

Hungarian-made product is available (manufacturing has been suspended), and for this reason we were unable to analyse its applicability.
Crashed brick is available as waste, however, the quality is highly variable and thus in each case they need preliminary verification tests, which increases costs. Based on our preliminary test results they are suitable for achieving classes of LC35/38 or LC40/44 if combined with high-silica sand. As its stability was insufficient for the efficient prefabrication of prestressed concrete elements, no detailed analysis of the material is given herein.
Blast-furnace slag can also be used in the planned bulk density range. Its great advantage is its availability as waste in Hungary, which reduces shipping costs and environmental load to the minimum. However, it is difficult to work with it. After 10 minutes its consistency is no longer maintainable which is insufficient under industrial conditions (according to our experience, minimum 30 minutes are required even if a small beam is cast). Moreover, the material properties of approx. twice 0.5 cubic metres of blast-furnace slag of the same delivery batch can be rather different. Therefore, its application also requires continuous monitoring.
Although under laboratory conditions, the expected strength could still be achieved at a larger volume (50 volume percent) of blast-furnace slag, under the currently available conditions of manufacturing, its application is not recommended. Its subsequent use for minor structural elements requires additional analyses.
Expanded clay gravel is burnt out at high temperatures. It is developed for factory production for the purpose of lightweight concrete aggregate in several bulk density ranges. A product of strength class (Liapor HD 7n) regularly available in Hungary was chosen for our preliminary tests. This product is recommended for strength class up to LC35/38 concretes. In the course of our experiments, we could achieve this next strength class, however, this was still insufficient for efficient production of prestressed beams. For this reason, we ordered a material designated as “Liapor 8” from Germany for our experiments.
The above mentioned required parameters were only met by the Liapor 8 clay gravel aggregate. When this was used, we could achieve, and even exceed, the expected strength class LC50/55. Therefore, the detailed strength, durability and applicability tests were carried out using this material, without any additional supplementary material. Table 2 gives the characteristics of the aggregates used within this series of experiments.

4.3. CONCRETE MIXES

For the purposes of selecting the cement type, it was taken into account that ordinary Portland cement must be used for bridge superstructures in Hungary, and from among the latter, the product with the highest initial strength was selected and considered as a constant during the experiments. For our experiment we CEM I 52,5 R cement.
Efforts were taken at the selection of a very low water-cement ratio in a way to provide at least 160 l/m^3 actual mixing water, to obtain a mix that is still workable under industrial conditions. However, this required high cement content. In most combinations we used 460 kg/m^3.
Altogether 24 different kinds of mixes were prepared with the above-mentioned four types of lightweight aggregates in addition to the ordinary concrete used as references.

Table 2 Grain density and water absorption of ligthwight aggregates

Ligthweight aggregate	Grain fraction, mm	Grain density, kg/m^3	Water absorption in 24 hours, m%
Liapor HD 7N (expanded clay)	4/8	1185	
Liapor 8 (expanded clay)	4/8	1380	13.1
crushed clay brick	0/16	1615	23.2
expanded blast furnace slag	0/16	1875	12.8

4.4. SELECTED CONCRETE MIX

In terms of compressive strength, expanded clay gravel had the best characteristics. Therefore, we carried out tests using this material (Table 3). When Liapor 8 was used as LWA, the achieved strength was considerably higher than in the case of the other LWAs. Moreover, bulk density increased by approximately 5 percent in comparison to the concrete made with Liapor HD 7N.

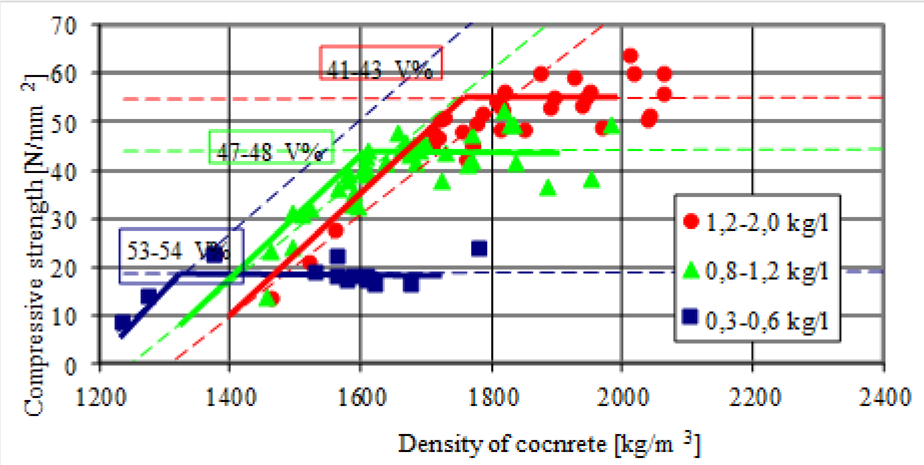

Figure 4 Relationship the density of cocnrete to compressive strength depend on particle density and amount (V%)of lightweight aggregate

By using Liapor 7N the concrete strength was below our target strength of LC50/55. Therefore, Liapor 8 was selected which has higher aggregate strength. It resulted a possible decrease of volumetric percentage of aggregates to 45 percent. In this way the strength of concrete increased with a simultaneous increase of density, but the density still remained below the 2000 kg/m^3 limit value. We also studied the effects of supplementary materials, and established that the addition of metakaolin and silica powder had a positive influence on the development of compressive strength. However, in the case of 2- and 28-day strengths, the significance of supplementary materials decreases, and for this reason, the analyses were continued with a mix not containing supplementary materials. Table 3 gives the summary of types of aggregates used altogether in our experiments. Figure 6 provides an impression of surfaces of lightweight aggregate mixes with different volumetric contents of expanded clay gravel aggregates.

Table 3 Characteristics of the LWAC mixes

Sign of mix	Type of aggregate	Density (kg/m^3)	Average compressive strength (28 days) (N/mm^2)
14	mortar without course aggregate	2240.0	69.2
15	polystirol pellet	1505.0	21.8
6	crashed clay brick	2142.5	49.6
12	exp. blast furnice slag	2119.0	49.5
13		1833.3	17.4
1	expanded clay gravel Liapor HD 7N	1904.0	52.1
2		1817.0	47.6
5		1785.0	47.2
7		1850.0	59.2
8	expanded clay gravel Liapor 8	1997.3	66.8
9		2019.0	67.7
10	expanded clay gravel Liapor 8 +supplementary material	2018.0	76.9
11		1981.3	71.9

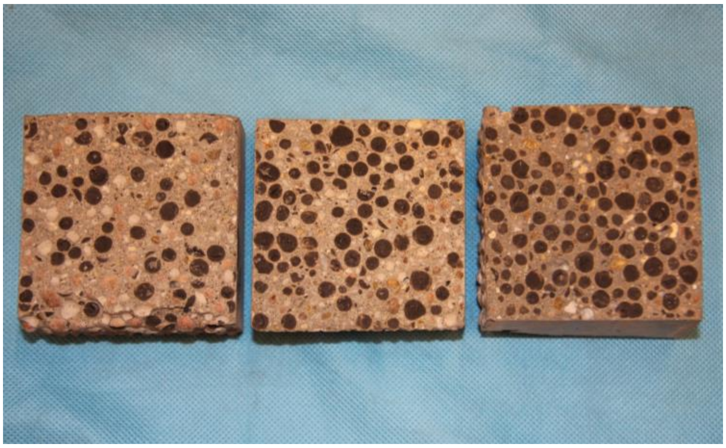

Figure 6. LWAC concrete surfaces with different volumetric contents of expanded clay gravel aggregates after material testing

5. PROTOTYPE TESTING

Based on the selected mix design a prestressed girder was manufactured at industrial conditions in the Dunaújváros plant of Ferrobeton Co. (Figure 7).

Figure 7. Precast LWAC girder before load testing

The concrete was cast according to the specified mix, but with wet LWA (water content 9.3 percent by mass). The required amount of concrete could be mixed in two batches and compacted by concrete formwork vibrators. It was demoulded after one day. The beam behaved in the test in accordance with the calculations. Figure 8 gives an indication of bond of 7 wire strands in the LWAC girder as well as the distribution of lightweight aggregates around the prestressing wires.

Figure 8. Bond of 7 wire strands in the precast LWAC girder (photo was taken after failure)

Bond strength is one of the key issues for prestressed, prestensioned element in order to provide enough anchoring capacity of prestressing tendons. Development of bond strength versus the age of concrete with light weight aggregates (Liapor 7N and Liapor 8 as well as the reference mortar) is presented in Figure 9 in addition to the development of concrete compressive strength versus age of concrete (Figure 10).

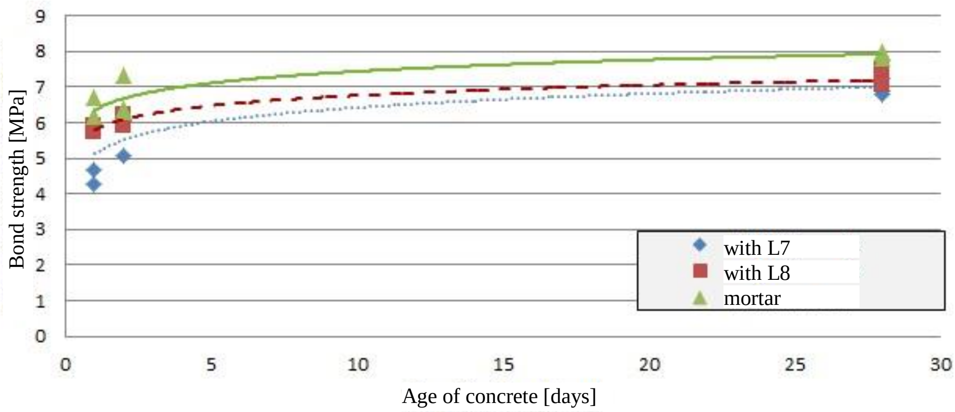

Figure 9 Bond strength vs. age of concrete [12]

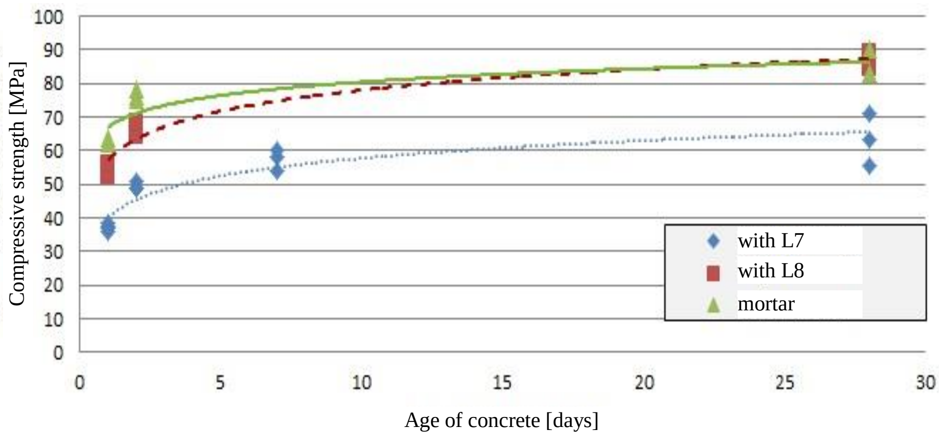

Figure 10. Concrete compressive strength vs. age of concrete [12]

6. CONCLUSIONS

An extensive research started in Hungary (within a cooperation with a design office and a precast plant) to develop possible concrete mixes and design rules for precast bridge girders of lightweight aggregate concrete. Particular aspects for our studies were: selection of type of lightweight aggregate, concrete mix design, adequate curing, relatively high final compressive strength and adaptation of the production process in the

prefabrication plant. An additional request was the high early age strength. We optimized the concrete mix from technical and economic aspects from four types of LWAs and two types of supplementary materials. The choosen mix was with Portland-cement, with Liapor 8 (d_{max}=8 mm) without supplementary material, with water cement ratio 0.35, with strength class LC50/55 and density class D2,0.
The prototype girder has been produced in industrial conditions and has been loaded up to failure. The beam behaved in accordance with the calculations.

ACKNOWLEDGEMENT

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MOGUĆNOSTI U RAZVOJU PREDNAPREGNUTIH MOSTOVSKIH NOSAČA OD LAKOG BETONA

Rezime: *Lakoagregatni betoni predstavljaju izazov u razvoju mostovskih nosača sa smanjenom sopstvenom težinom. Uštede u troškovima prevoza montažnih nosača mogu biti značajne. U Mađarskoj su započeta opsežna istraživanja (u saradnji sa projektnim biroom i proizvodnim pogonom za izradu montažnih elemenata) u cilju razvoja mogućih betonskih mešavina i pravila projektovanja montažnih mostovskih nosača od lakoagregatnog betona. Posebni aspekti naših studija su bili: izbor vrste lakog agregata, projektovanje betonske mešavine, adekvatna nega, relativno visoke konačne čvrstoće i prilagođavanje procesa proizvodnje u proizvodnim pogonima. Dodatni zahtev je bio da se postigne i visoka rana čvrstoća. Kao deo istraživačkog projekta, urađen je prototip nosača od betona klase čvrstoće LC50 / 55 i klase gustine d 2.0. U radu se fokusiralo na dva glavna aspekta: veze između kablova i lakoagregatnog betona i trajnost (posebno otpornost na mraz i migraciju jona hlorida).*
Prototip nosač je proizveden u fabričkim uslovima i opterećen do loma.

Ključne reči: *LB, laki beton, mostovski nosač, gustina, montažni, prototip*