ISSN 1822-427X print
ISSN 1822-4288 online

THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

http://www.bjrbe.vgtu.lt

2006, Vol I, No 1, 55–61

BRIDGES WITH LIGHTWEIGHT AGGREGATE CONCRETE STRUCTURES

Ainars Paeglitis, Genadijs Sahmenko

Department of Roads and Bridges, Riga Technical University, Azenes st. 20, LV-1048 Riga, Latvia
paeglitisa@apollo.lv

Abstract. Traditionally the lightweight aggregate concrete (LWAC) has been applied in buildings for many years. The improvement of the technology of production, mix composition and execution has considerably changed the nowadays LWAC properties. The uses of various admixtures have increased the strength, stress-strain modulus and decreased the creep that allowed the use of LWAC for the hardly loaded bridge structures worldwide. The paper describes the experience of use of LWAC for bridge structures in Latvia. The obtained results showed that the use of high-strength LWAC will decrease the dead load of bridge structures without reduction of load-carrying capacity. In many cases the use of LWAC will help the reconstruction and widening of the existing bridge structures.

Keywords: concrete, lightweight aggregate, bridge.

1. Introduction

Concrete as well as the lightweight aggregate concrete (LWAC) or lightweight concrete have been used for structural engineering for a long time. All this time concrete gives the ultimate opportunity for engineers and architects to design aesthetic, functional and safe structures.

Nowadays development of LWAC as a high-performance structural material allowed applying them in bridge structures [1, 2]. The reason of using the of structural LWAC is to reduce the dead load of concrete bridge structures, which allows reducing the size of span, piers, abutments and foundations. The structural LWAC mixes can be designed to achieve similar or higher strength than normal weight concrete, as well with the same or better durability. Structural LWAC provides a more efficient strength to weight ratio in structural elements, reduced volume of concrete, less reinforcement and lower overall costs.

In Latvia the LWAC has been applied in buildings for many years. Various admixtures have increased the strength, stress-strain modulus and decreased creep that made possible to use them for hardly loaded bridge structures.

This paper deals with experience of using the LWAC in bridge projects in Latvia.

2. Historical overview

Lightweight aggregate concrete as a structural material has been known for a long time. The natural lightweight aggregates with a volcanic origin like a pumice and scoria was well known and used long before the Christian era by Greeks and Romans.

Magnificent ancient structures, like Coliseum and Pantheon in Rome (Fig 1), Sophia Cathedral in Istanbul, were built by using the lightweight concrete elements for arch and vault structures.

Structural lightweight concrete has not been used in a general way until the 20th century, when the lightweight industrial aggregates returned to construction industry.

The developments of technological processes allowed to obtain expanding clay using a tubular kiln. The aggre-

Fig 1. Coliseum and Pantheon in Rome

Fig 2. Southwestern Bell Telephone Company and Park Plaza Hotel buildings [3]

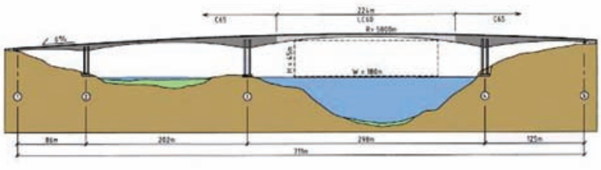

Fig 3. Elevation of Rafsunded bridge in Norway [2]

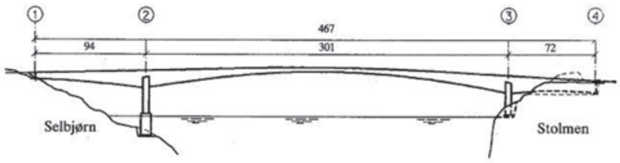

Fig 4. Elevation of Stolma bridge in Norway [2]

gates produced by this system were applied for the construction of ship hulls during World War I.

The first major project employing structural lightweight concrete was undertaken in 1928 and 1929, when the Southwestern Bell Telephone Company heightened its office building in Kansas City with additional eight floors.

The first structural lightweight concrete high-rise building was the Park Plaza Hotel in St Louis. Built in 1929, this 28-story structure made an extensive use of structural lightweight concrete in both frame and floor systems (Fig 2).

The first application of the lightweight concrete for bridge structures was in 1936, where the upper road deck of the Oakland Bridge in San Francisco was made from lightweight concrete.

In many countries the uses of structural lightweight concrete for bridge construction considerably increased from the 60's of the last century.

We could find many good examples in bridges built in the US, Germany, Norway, the Netherlands and other countries.

Two world longest reinforced concrete cantilever bridges – the Raftsundet and Stolma bridges, both with spans of about 300 m have been built in Norway by using lightweight concrete.

Raftsundet Bridge, completed in 1998, located more than 300 km north of the Arctic Circle, provides a road connection between the Lofoten Islands and Norway's mainland highway system. The bridge is a continuous post-tensioned cast-in-place box section concrete bridge with total length of 711 m. The four spans are 86 + 202 + 298 + 125 m long respectively. The 224 m long central part of the 298 m main span is constructed from LWAC. The hardened density of the LWAC part was 19,75 kN/m^3 with a 28-day compressive strength of 60 MPa (Fig 3).

The Stolma Bridge is the free-cantilever structure with the world longest main span of 301 m completed in 2000. The Stolma bridge connects the islands Selbjorn and Stolmen. The total length of the bridge is 94 + 301 + 72 = 467 m, providing two traffic lines and one pedestrian line. The hardened density of the LWAC part was 19,40 kN/m^3 with a 28-day compressive strength of 70,4 MPa (Fig 4).

3. Materials

The nowadays structural lightweight concrete has been defined as concrete with the unit weight between 1400 and 2000 kg/m^3, corresponding to cube strengths from approx 10 to over 70 MPa.

Lightweight aggregates suitable for concrete mix can be divided into 4 groups according to the source of their raw materials:

- Natural aggregates (pumice and scoria)
- Natural materials (perlite, vermiculite, clay, shale, slate etc);
- Industrial products or by-products (glass or fly ash);
- Industrial by-products (PFA, cinder or expanded slag).

A classification of lightweight aggregate concrete could be illustrated by the diagram. You can see (Fig 5) that not all aggregates are suitable for structural concrete.

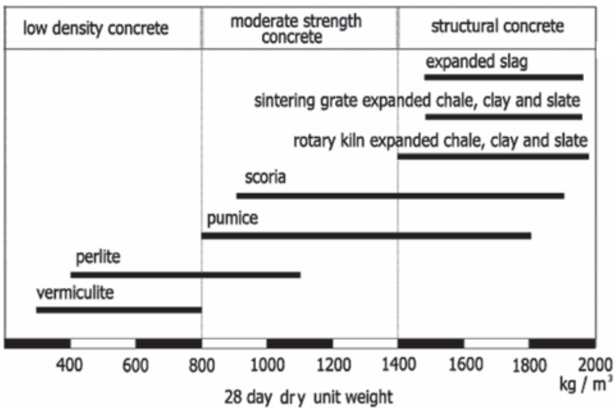

Fig 5. Classification of LWAC according to their unit weight

Present procedures for selecting the mechanical properties of lightweight aggregates rely mainly on empirical formula with two parameters – compressive strength and oven-dry density of aggregates.

The uses of the structural LWAC for bridge structures imply such advantages:

- Reduction of the dead load of concrete bridge structures, which allow reducing the size of span, piers, abutments and foundation structures.
- The structural LWAC mixes can be designed to achieve a similar or a higher strength as normal weight concrete, as well with the same or better durability performance requirements.
- Structural LWAC provides a more efficient strength to weight ratio in structural elements, reduced volume of concrete, less reinforcement and lover overall costs.

As disadvantages of LWAC, in comparison with normal weight concrete, can be mentioned:

- Lower strength
- Lower modulus of elasticity
- Higher influence of creep and shrinkage
- Increased brittleness.

4. Examples of using the LWAC in bridge structures in Latvia

In Latvia the LWAC has been applied in buildings for many years, but until 1997 it has been not used in bridge construction. In this paper four bridge projects will be presented and reasons for applying LWAC will be discussed.

For reconstruction of a more than 125 years old stone arch bridge in Kandava town the LWAC was used as fill material for the over arch structure to hold a constant dead load and obtain enough hard basements for the wearing course.

By reconstruction of the bridge over the Lielupe River in Jelgava-town the ribbed over-arch structure from LWAC has been used for decreasing the self-weight of superstructure and ensure that the increase of traffic load does not increase the stresses under the foundation slab.

At the new overpass over road A2 the LWAC have been used to achieve a more slender superstructure for aesthetic reasons.

At the new pedestrian overpass over road A2 the LWAC has been applied in a composite structure to ensure the stiffness of steel tubes used for the load bearing structure.

4.1. Reconstruction of 125 years old stone arch bridge

The bridge over Abava River was completed in 1873. It consists of four 8,60 m long and 8,70 m wide stone vaults and 12,00 m long side wings (Fig 6). The width of piers at water level reached 2,10 m and the thickness of vault in top point was 1,20 m. The bridge facades and icebreakers were made from split stones. The bridge has 6,30 m wide carriageway with two 1,25 m sidewalks.

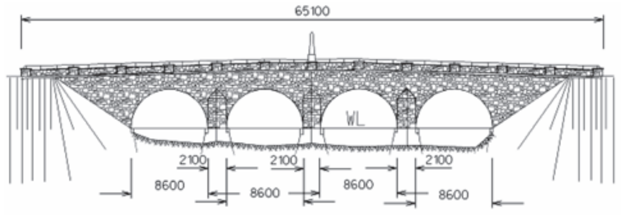

Fig 6. Elevation of stone arch bridge

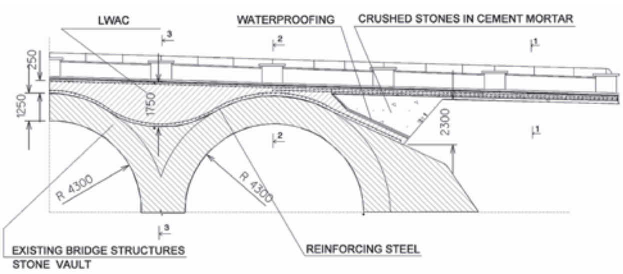

Fig 7. Longitudinal section

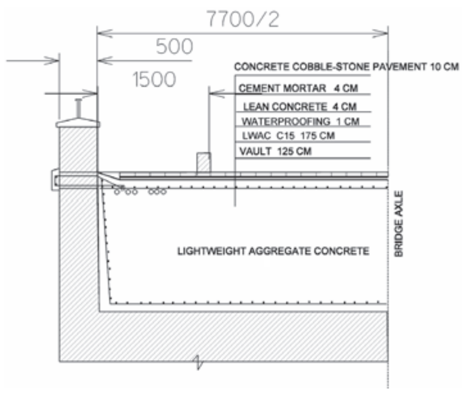

Fig 8. Cross-section of the pier

The assessment of the existing bridge structures indicated that the basic structures need repair. The restoration works should preserve the original quality of the structures and respect, as far as possible, for the historical look of the bridge. The design provide for the reconstruction of the existing carriageway structures, strengthening and waterproofing the upper side of the vaults, injection of cracks, and replacement of the sand backfill in the upper arch part with LWAC (Figs 7 and 8).

As backfill, LWAC class LC16/18, with density of 17 kN/m^3 was used. The use of LWAC decreases the total dead load of the span structures and allowed to avoid strengthening of foundations [4].

4.2. Reconstruction of multi-span arch bridge

The bridge over the Lielupe River with the common length of 160 m is located in the central part of Latvian town Jelgava (Fig 9). In includes three 41,42 m long and

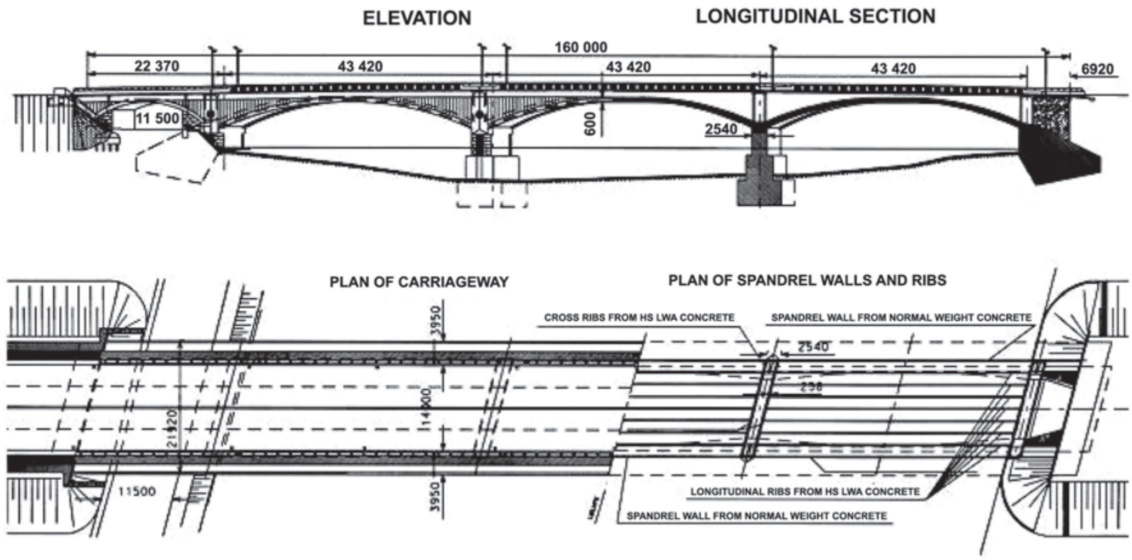

Fig 9. Elevation and section of the bridge structure after reconstruction

13,90 m wide flat reinforced concrete arches; spandrel walls with variable width; 9,00 m wide carriageway based on sand infill and 2×2,25 m wide sidewalks (Fig 10). The actual bridge condition was qualified as precarious and needing for a major reconstruction and widening.

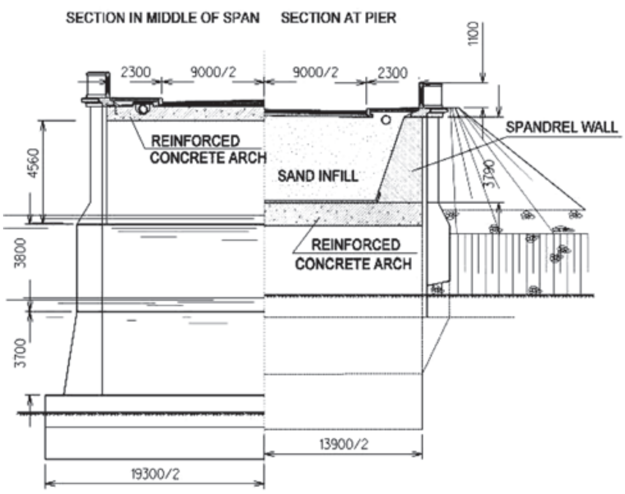

Fig 10. Cross-section of span structure before reconstruction

The results of inspection indicated that the condition of concrete in the arches was acceptable for reconstruction and further strengthening, the spandrel walls were evaluated as unacceptable, and piers and abutments, including foundations, were in an appropriate condition. The results of assessment and analysis pointed that the foundations of the pier and abutment were heavily utilised and an increase of load on foundations were not welcome.

After some discussions it was decided to widen and strengthen the arch structures and to rebuild the overarch structure with LWAC. The use of ribbed over-arch structure by LWAC (Fig 11) allowed to decrease the self-weight of the superstructure and to balance the increase of live load and to ensure that the increased traffic load according to Eurocode 1 does not increase the stresses under the foundation slab [3].

The ribs in the middle part of over-arch structure have been made of LWAC LC30/35, but from sides – of normal weight concrete. Composition and properties of LWAC are shown in Table 1.

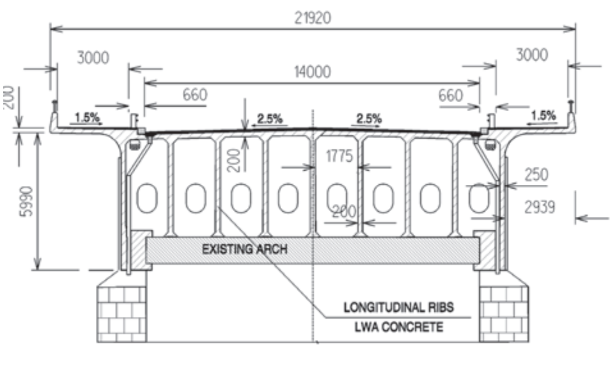

Fig 11. Cross-section of span structure after reconstruction

Table 1. Mix composition of the LWAC LC30/35 used for over-arch structure

Mix design		
Portland cement CEM 42,5 SR	kg/m^3	495
Natural sand 0,5–4 mm	kg/m^3	860
Limestone powder	kg/m^3	25
Lightweight aggregate 1–5 mm	kg/m^3	310
Superplasticiser	%	1
w/c		0,47
Mechanical properties		
Mean cube strength $f_{c,mean}$	MPa	35,1
Density, dry	kg/m^3	1803

4.3. Overpass over road A1

The bridge over the road A1 Riga – Sigulda – Estonian border (Veclaicene) is located on the main road E77 Riga – Estonian border (Ainazi) km 0,00. The new structure has replaced the existing bridge with severe deteriorations in main structures.

Based on economical, esthetic and architectural aspects, the Client selected for the final design the solution with the board-stayed system and the span structure made of LWAC [5]. The bridge consists of 3 spans, 18 + 40.55 + 18 m (Figs 12 and 13) with total length 84,27 m and 15 m wide carriageway.

The total bridge length was determined by requirements of under passing road width and the structure balance. The superstructure of the overpass consists of slab, pylon and pull board.

Due to the exposed location of the overpass, it was decided to use a slender superstructure with a nice appearance. This was made by using LWAC LC 45/50 for the slab structures and the normal weight concrete C 35/45 for pylons and board-stayed sections. The slab is pre-stressed by the 3 cables on pylons via boards.

Five pre-stressed cables are located across the slab and 2 cables are located in the edge beam between the ends of the board sections. These post-tensioned cables consist of 12 strands with 15,2 mm in diameter and are prestressed with 2360 kN each.

LWAC class LC 45/50 mix composition was elaborated in the Riga Technical University by using the optimal packing theory of the aggregates. Composition and properties of LWAC are shown in Table 2. Some correction was introduced in cooperation with the ready-mix concrete producer and supplier. The concrete mix was delivered by truck mixers with a minimum drum rotation rate.

Concrete mixes are characterised by good workability, homogeneity and high flowability (cone slump >

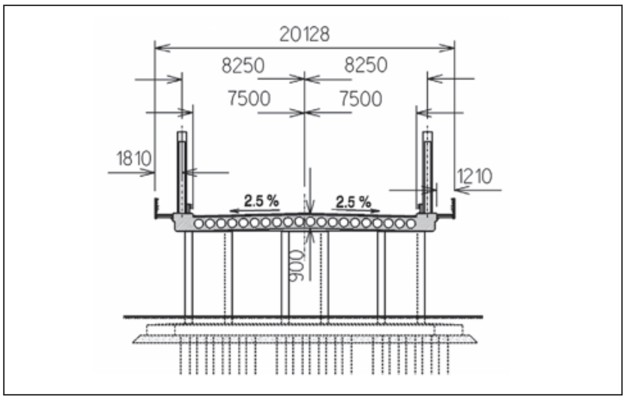

Fig 13. Cross-section of overpass span structure

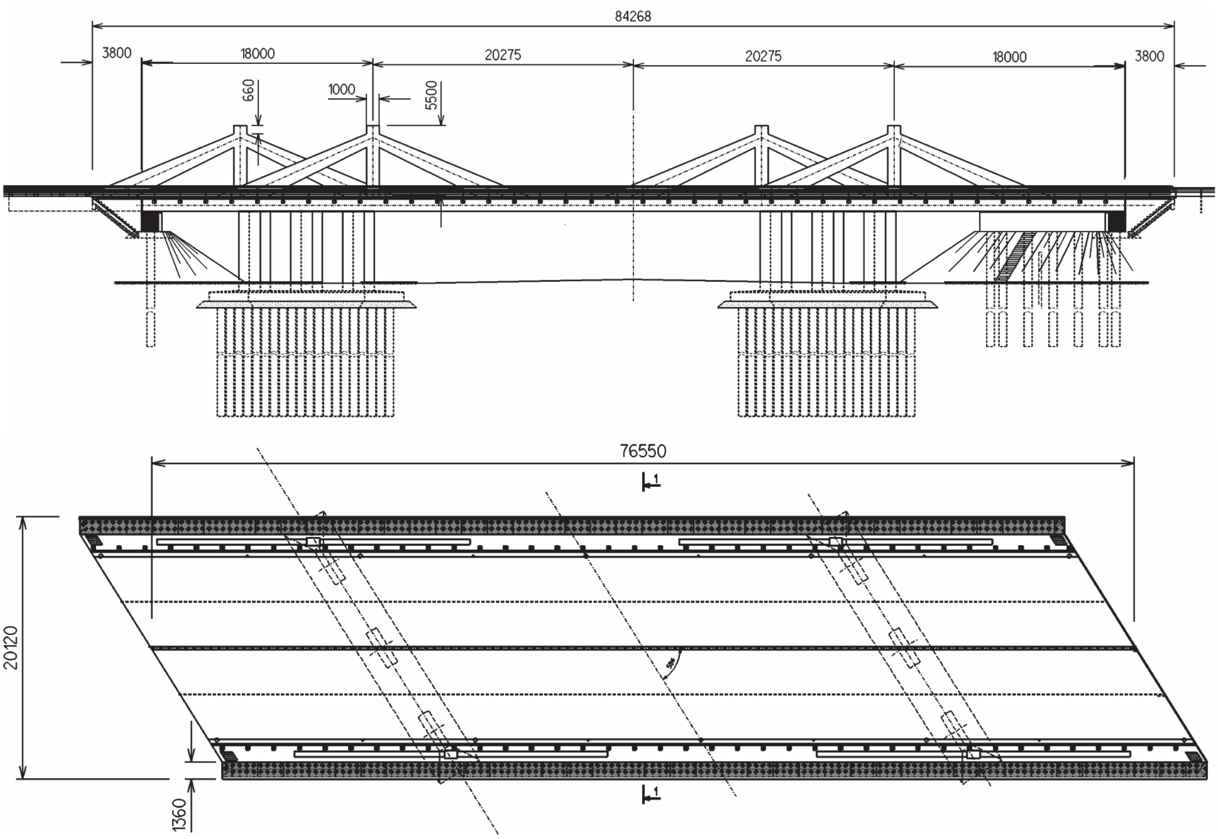

Fig 12. Elevation and plan of overpass

Table 2. Properties of the lightweight aggregate concrete LC45/50

Mix design		
Portland cement 52,5 SR	kg/m^3	396
Lightweight aggregate 4–8 mm	kg/m^3	166
Lightweight aggregate 6–12 mm	kg/m^3	284
Sand 0,5–4 mm	kg/m^3	995
Superplasticiser	kg/m^3	4,7
Silica fume	kg/m^3	26
Water	kg/m^3	179

25 cm, cone flow 60 cm, it almost corresponds to the Self-Compacting Concrete). A preliminary method of the concrete pumping was discussed. Experimental pumping indicated a non-controlled behaviour of LWA concrete mix in the system under a high pressure (up to 8 MPa). In spite of a high flowability, the mix was very viscous and blocking took place. Therefore for concreting the crane and the concreting tanks were used. Duration of the concreting works was 52 h without interruption, the total amount of concrete – 1100 m^3. The problem of pumpability of the high-strength LWA concrete is the subject for future investigations. The pumps should increase the rate and quality of concreting works as well as they should have an economical effect.

4.4. Pedestrian overpass

The terms of reference for the pedestrian bridge provided a integrated pedestrian and cyclist footpath with a total width of 2,75 m.

The composite system consisting of steel pipes filled with LWAC and the concrete slab as main girders was selected for the final design (Fig 14). Such systems with good results are studied and analysed in Japan and China [6, 7].

The overpass consists of one 30 m long central span and the approach structures. The total length of the bridge is 136,50 m. The pipes are filled with LWAC classes LC40/44 (Fig 15). The concrete was placed from the holes equipped at the steel pipe upper part. These filling holes were set up in about 3 m intervals.

The LWA concrete LC 40/44 mix composition as before was elaborated in the Riga Technical University and was based on the aggregate optimal packing theory. The concrete was delivered by truck mixers.

The choice of such a structure allowed decreasing the construction costs, ensuring the effective use of the material, created a good visual appearance.

5. Study of the properties of LWA concrete

Different aspects of proposed LWA concrete mix composition before placing were studied at Riga Technical University [8]. The obtained optimal mix composition is given in Table 2.

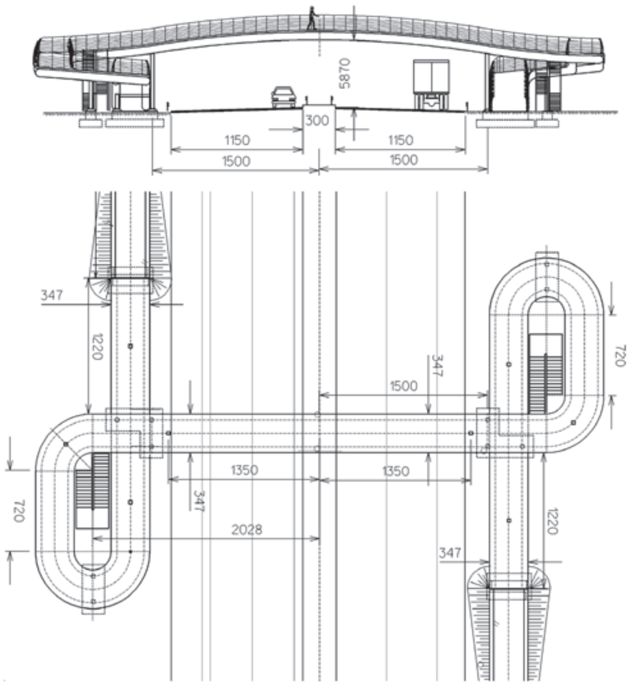

Fig 14. Elevation and plan of the pedestrian overpass

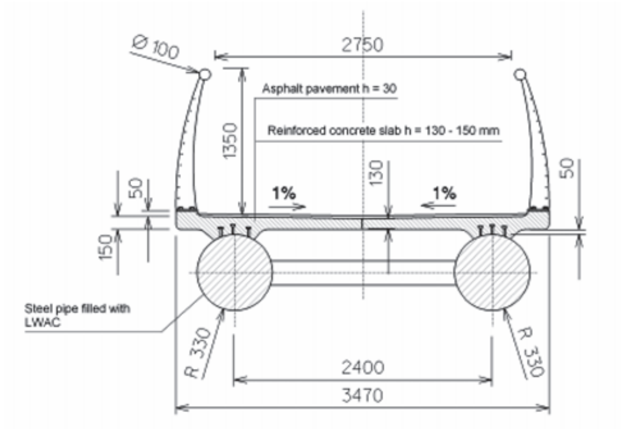

Fig 15. Cross-section of the pedestrian bridge

The concrete was homogeneous and binding with a good texture. The lightweight aggregates take up 33 % of the total volume.

The hardening kinetics is shown in Fig 16 and the stress-strain diagram in Fig 17.

After 28 days the test cubes had a density of 2045 kg/m^3. The 112 days density was 2006 kg/m^3, air content 4 %.

After 2 days the compressive strength of test cubes achieved 39,9 MPa, that is 63 % of the 28 days strength – 63,4 MPa. After 112 days the cubic compression strength achieved 74,1 MPa (Fig 16) and tensile strength 3,15 MPa.

By quantifying the modulus of elasticity in verification range of 0–10 MPa, the linear stress and strain relationship was established (Fig 17). The average modulus of elasticity of the test beams was 30,1×10^3 MPa.

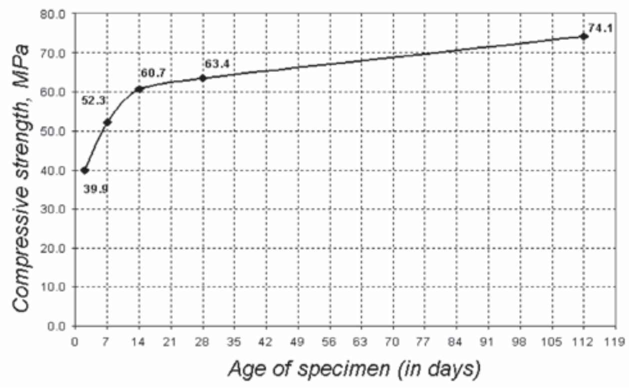

Fig 16. Compressive strength versus age

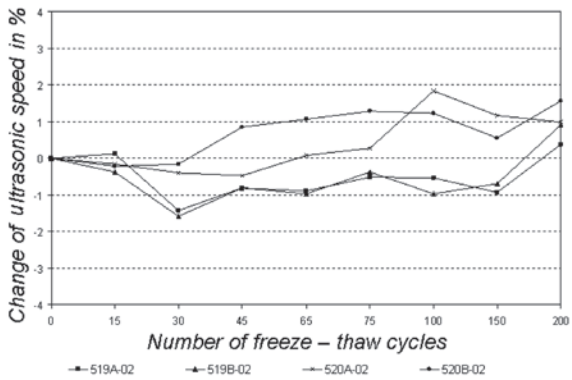

Fig 18. Change of ultrasonic speed depending on the number of freeze-thaw cycles

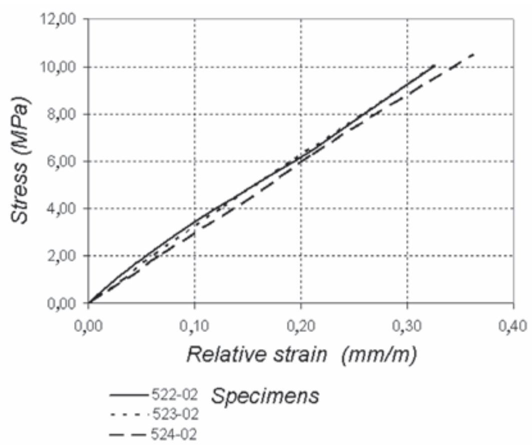

Fig 17. Stress–strain diagram

The test samples showed a good watertightness (average penetration 17 mm) and an excellent resistance against freeze-thaw and freeze-deicing-salt attack.

The freeze-thaw resistance was investigated with the ultrasonic method the samples saturated with 5 % NaCl. The obtained results (Fig 18) showed that the concrete could withstand more than 200 freeze-thaw cycles in 5 % NaCl solution. It corresponds to 600 cycles in normal water.

6. Conclusions

Structural lightweight concrete is a perfect structural material for all types of bridge structures.

The lower self-weight of LWAC requires less reinforcing, prestressing and structural steel, reduces the need for an extensive falsework, speed erection and allows the use of smaller and more economical equipment.

Investigation of properties of LWAC samples shows a high durability, high freeze/thaw resistance, good resistance to de-icing salts and chemicals.

The use of structural lightweight concrete in renovation and repair of bridges often increases the live load capacity of older bridge structures, thus meeting the current load specifications.

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Submitted 16 Dec 2005; accepted 13 Feb 2006