ISSN 1392 – 1231. CHEMINĖ TECHNOLOGIJA. 2009. Nr. 2 (51)

Study of the compatibility of historical stone materials of the Kuldiga brick-vault bridge across the Venta river and materials used in the restoration of the bridge

S. Igaune, I. Vitina, I. Timma, L. Lindina
Institute of Silicate Materials, Riga Technical University,
Azenes str.14/24, LV-1048 Riga, Latvia
E-mail: dekanats@ktf.rtu.lv

Received 13 February 2009; Accepted 25 February 2009

The Kuldiga bridge (1873–1874) is one of the longest brick-vault bridges in Europe (164 m). In the first world war (1915), two parts of the bridge were destroyed by the Russian army. In its previous restoration in the 1930, incompatible materials – dense portland cement based mortars and concrete – were used. In the frame of the recent restoration project (2007–2008), a scientific investigation of the old materials, corrosion products and new compatible materials developed for the restoration was carried out. Based on the obtained results, recommendations and suggestions on materials and methods to be used in the restoration were given to provide for the compatibility of materials and the sustainability of the bridge.

Introduction

The Kuldiga brick-vault bridge across the Venta river is an inseparable element of the old town, one of Kuldiga's symbols, a significant architectural monument. It is the longest (164 m) brick-vault bridge not only in Latvia, but also in Europe. The bridge was built in 1873–1874. It consisted of seven brick-vault span lengths; two of them were destroyed in the First World War (1915) by the Russian army. In 1926, instead of them, were two concrete vault span lengths erected. In the 1930, in the restoration of the bridge incompatible materials were used (concrete and as a joint material dense portland cement based mortars). In 1958, the historical stones of the pavement were covered with bituminous concrete.

To retain the uniqueness and authenticity of the bridge, in 2007–2008 the Kuldiga City Council launched a huge restoration project with the financial support from the European Regional Development Foundation.

An active part in the restoration project of the bridge was taken by scientists of the Centre for Conservation and Restoration of Stone Materials of the Riga Technical University. Stone materials and corrosion products were investigated, new compositions of materials for restoration were developed [1].

After the restoration of the bridge performed by the Kuldiga City Council, this significant success was submitted for the Europe Nostra award.

The aim of this study was to ascertain the type and properties of building materials (historical) of the Kuldiga brick-vault bridge to choose compatible materials to be used in the restoration of the bridge to provide for its sustainability.

Experimental

The methods applied were:

1. Full chemical analysis [2, 3]. The reagents used for all analyses were of "pure for analyses" (p.a.). purity grade. The chemical composition of the historical materials was detected by wet chemical analysis determining the ignition loss of samples at 1000 °C, followed by the dissolution of a sample in HCl. The obtained solution was further used for soluble SiO_2 and Al_2O_3 determination by sedimenttation.
   The next step was dissolving the samples in H_2SO_4 and HF for CaO, MgO, Fe_2O_3, Na_2O and K_2O detection:
   - CaO and MgO – by complexonometric titration with EDTA, using methyl thymol blue and calcein as indicators,
   - Fe_2O_3 by *ФЭК-56ПМ* photocolorimetry using sulphosalicylic acid forming a yellow complex with Fe_2O_3,
   - Na_2O and K_2O by flame photometry *Jenway PFP7*. Butane or propane flame was used to excite the alkalis to emit their characteristic spectrum in the visible range: the emission is proportional to alkali content at low concentrations.
2. XRD – by using X-ray *Rigaku Ultima+* diffractometer, Japan, with Cu Kα, radiation at a scanning interval 5–60 °(2θ) and speed 2 °/min.
3. Hydro tests (hydric properties, water absorption, porosity) [4].
4. Grain size distribution test [3].

Analysis of the sieve curve was done by dissolving the binder with 14% HCl and sieving the washed aggregate through gradual of finer sieves.

Results and discussion

The general visual observation of the Kuldiga bridge built of sewen vault span length has revealed a great difference among its parts: five original brick vaults are in a good state (bricks without damage), while the two restored (in 1934) vaults are in an unsatisfactory state.

The bricks are split, cracked, some dolomite plates are damaged or absent. The mortar of this part, used as joint material, also visually differs from that used in the original part of the bridge. In some places biological damage was seen.

Results of chemical analyses, summarized in Table 1, show that historical mortar used for cladding dolomite stone and brick vaults was a strongly hydraulic dolomitic lime mortar with the 1 : 2.7 binder-to-filler ratio (sample 6), but in the renovated part cement mortar had been used for joining stones and bricks (samples 3, 4). For the parapet cornices, dolomite plates had been used (sample 8).

Table 1. Chemical composition of historical stone materials, % by weight

Component	Sample				
	3 (concrete)	4 (surface of concrete)	6 (old mortar)	8 (stone)	Error ± absolute %
Ignition loss: at 400 °C	9.11	8.08	7.90	3.32	0.5
at 1000 °C	13.10	13.24	12.54	38.50	0.5
Sand and gravel	41.41	41.90	60.50	4.62	0.5
SiO_2 soluble	5.04	6.48	2.11	3.80	0.1
CaO	25.21	25.37	11.88	28.30	0.3
MgO	1.93	1.28	5.82	16.19	0.3
Al_2O_3	1.06	1.04	0.96	3.22	0.3
Fe_2O_3	1.88	1.10	1.15	0.88	0.1
Na_2O	0.45	0.96	0.46	0.47	0.,1
K_2O	0.81	1.12	0.78	0.64	0.1
Summary	100.14	99.95	100.56	100.34	–
CaO/MgO	13.1	19.8	2.04	1.74	
Binder to filler ratio	1 : 1.2	1 : 1.2	1 : 2.7	–	–
Hydraulic modulus $\frac{CaO + MgO}{SiO_2 + Al_2O_3 + Fe_2O_3}$	6.8	3.09	4.19	–	–
	Cement mortar	Cement mortar	Strongly hydraulic dolomitic mortar	Dolomite stone	

Table 2 lists the contamination of brick, concrete, mortar and dolomite stone by soluble salts. It is obvious that (cleaning of the bridge in 2001) the content of soluble salts is very low and meets the requirements of uncontaminated masonry. The pH analysis of two concrete samples (2, 3) shows that the carbonation of concrete has taken place, resulting in the pH reduced from 11 to 8.5. In some places, on the surface white deposits were seen. It is possible that $CaCO_3$ formed due to water migration into concrete, washing out $Ca(OH)_2$ with the following carbonation. Partially it was cleaned up by sandblast, but this operation is not recommended because it destroys the natural protective layer and causes the further corrosion of material.

Table 2. Contamination of building materials with soluble salts, mass% and pH

Sample	Component				
	Ca^{2-}	Mg^{2-}	Cl^{-}	SO_4^{2-}	pH
1. Brick	0.23	–	0.15	–	–
2. Brick	0.47	0.03	0.12	0.49	–
3. Concrete	0.12	0.02	0.03	0.39	9.30
4. Concrete	0.30	–	0.01	–	8.50
5. Brick ~1880	0.07	1.49	0.05	–	–
6. Old mortar	0.08	0.49	0.17	–	8.25
7. Brick ~1880	0.07	1.49	0.17	0.18	–
8. Dolomite	0.26	0.10	0.07	–	–
Error ± absolute %	0.10	0.10	0.05	0.10	0.20

Table 3 presents the results of grain size distribution analysis of concrete (3, 4) and mortar (6). We see that the concrete contains above 0.7 mm about 47.8–57.0% of coarse particles, versus ~72.4% in the historical dolomite lime mortar. Dolomite mortar ensured the porosity of joints and a perfect moisture exchange in masonry with the environment, i.e. the "breathing" of masonry. It explains the preservation of this part of the bridge to our days. On the contrary, the part of the bridge restored in 1926–1930, when dense portland cement mortars and concrete boarders instead of dolomite stone boarders had been used (samples 3, 4), was in a bad state.

Table 3. Grain size distribution analysis

Grain size D, mm	Sample			
	3 (concrete)	4 (surface of concrete)	6 (old martar)	Error ± absolute %
> 0.7	57.0	47.8	72.4	0.5
0.5–0.7	22.5	25.0	15.3	0.5
0.2–0.5	9.0	14.4	5.6	0.5
0.16–0.20	2.5	4.2	1.4	0.5
< 0.16	9.0	8.6	5.3	0.5
Summary	100.0	100.0	100,0	–

The degradation of historical stone and brick buildings is known to depend to a great extent on their physical and mechanical properties. It is closely linked to the moisture-related behaviour of the material. The behaviour of the material in response to moisture is generally determined by its microstructure, especially porosity [5].

The water absorption and porosity of historical and new by developed materials used in the restoration of the bridge are plotted in Figures 1–3. A comparison of these data shows that for building the original Kuldiga bridge, bricks with a high porosity (25–31%) and accordingly water absorption (12–16%) and dolomite with porosity 22% and water absorption 9% were used. As a joining material, compatible hydraulic dolomite lime mortar was used. Materials for the restoration were developed and selected with regard to these characteristics (Figs. 2, 3).

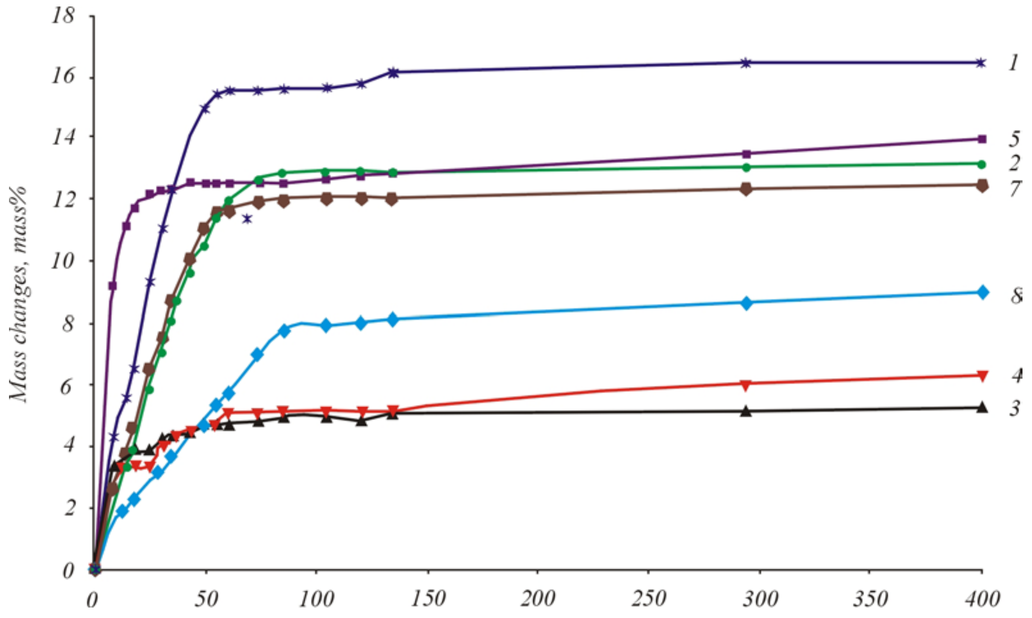

Fig. 1. Water absorption of historical stone materials: *1* – brick; 1926-1930, *2* – brick; 1926-1930, 3 – concrete; 1926–1930, *4* – concrete 1926–1930, *5* – brick; 1874, *7* – brick; 1874, *8* – dolomite; 1874

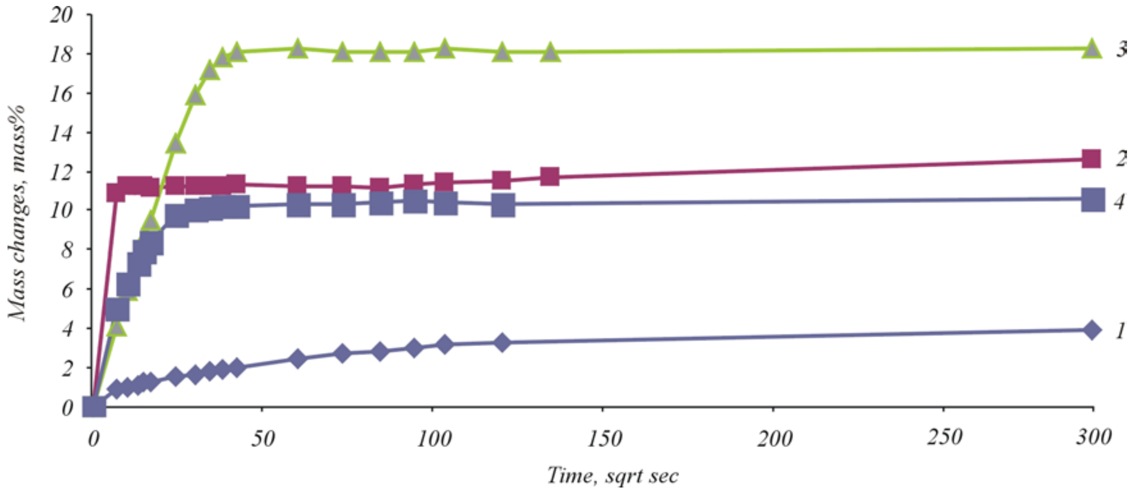

Fig. 2. Water absorption of stone materials used in the restoration: *1* – Estonian dolomite 2008, *2* – brick „Sencis” , *3* – calsitic mortar 2008, *7* – dolomitic mortar 2008

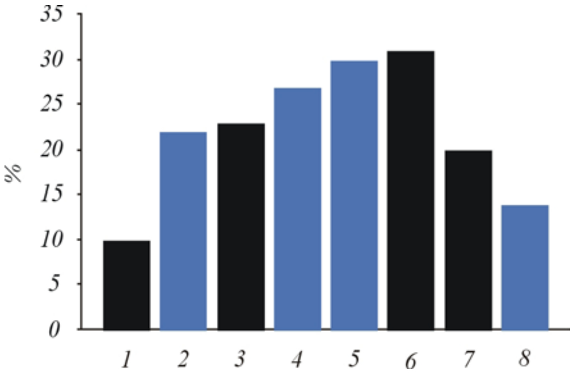

Fig. 3. Porosity of historical and new materials: *1* – Estonian dolomite 2008, *2* – dolomite 1874, *3* – brick „Sencis” 2008, *4* – brick 1880, *5* – brick 1926-1930, *6* – calsitic mortar 2008, *7* – dolomitic mortar 2008, *8* – concrete 1926-1930

Figure 4 presents bridge historical mortar XRD used for joints (1) and the newly developed calcium lime mortar for restoration of the Kuldiga bridge (2). It is evident that SiO_2 (quartz), $CaCO_3$ (calcite), $2CaO{\cdot}SiO_2{\cdot}{\cdot}2H_2O$ and $CaO{\cdot}SiO_2{\cdot}H_2O$ are present in both samples. The differing phases of samples are $MgCO_3$ (magnesite – sample 1) and $Ca(OH)_2$ (portlandite – sample 2). Chemical analysis (Table 1) and XRD pattern 1 confirm that the historical mortar is based on dolomite lime. This explains the preservation of the old brick vaults (1873–1874) to our days, unlike the brick vaults restored in 1926–1930. The presence of $Ca(OH)_2$ in sample 2 indicated that the carbonization process while forming $CaCO_3$ had not been complete.

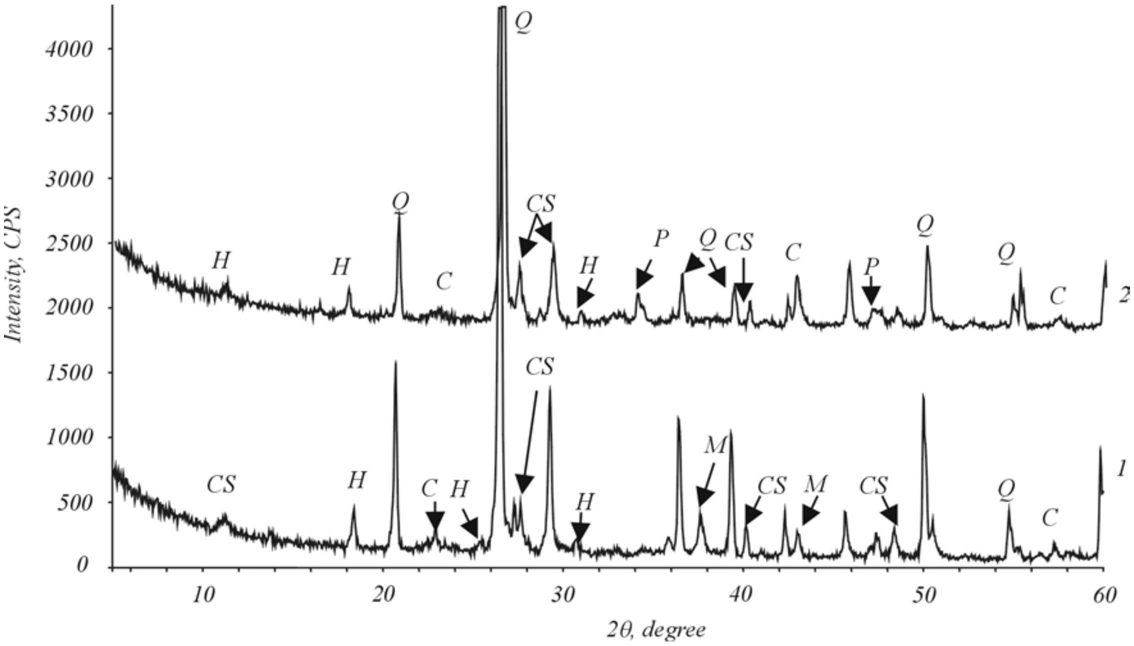

Fig. 4. XRD patterns of historical (*1*) and newly developed calcium lime mortar (*2*). Q – quartz, SiO_2; C – calcite,$CaCO_3$; P – portlandite, $Ca(OH)_2$; M – magnesite, $MgCO_3$; H – hydrosilicate, $2CaO{\cdot}SiO_2{\cdot}2H_2O$; CS – low- basic hydrosilicate, $CaO{\cdot}SiO_2{\cdot}H_2O$

Conclusions

1. In 1930, the restoration of Kuldiga brick-vault bridge built in 1873–1874 was not successful because of incompatibility of old bricks and mortars used for restoration. The main cause of the incompatibility was the different porosity of bricks (25–31%) and cement mortar (13–14%), resulting in the damage of bricks.
2. In 2007–2008, the restoration of the damaged brick vaults was carried out with replacing those hand-made bricks "Sencis" produced at the SIA "Lode", which were compatible in colour, dimensions and properties with the old bricks.
3. For joining bricks, compositions of calcium and dolomite lime mortars were developed at the laboratory of the Centre for Conservation and Restoration of Stone Materials of the Riga Technical University.
4. The similar porosity and water absorption of both bricks and mortars provides for their compatibility and the sustainability of the renovated bridge.

References

1. **Krage L., Vitina I.** // Proceedings of 7th Triennal Meeting for Restorers of the Baltic States. Riga, 2005. P. 204–209.
2. LVS EN 196-2:2005. Test methods of cement.
3. **Teutonico J. M.** A Laboratory Manual for Architectural Conservators. ICCROM, Rome, 1988. P. 35–52.
4. pr EN 1936:1998E. Determination of real density and apparent density and total and open porosity.
5. **Palomo A. et al.** // Historic Mortars: Characterisation and durability. New tendencies for research. European Research on Cultural Heritage. State-of-the-Art Studies. Vol. 3, ARCCHIP, Prague, 2004. P. 167–184.

S. Igaune, I. Vitina, I. Timma, L. Lindina

ISTORINIO KULDĪGOS SKLIAUTINIO TILTO PER VENTOS UPĘ MŪRO IR NAUDOTŲ JO RESTAURAVIMUI MEDŽIAGŲ SUDERINAMUMO TYRIMAS

Santrauka

Kuldīgos skliautinis tiltas (1873–1874 m.) yra vienas iš ilgiausių mūrinių tiltų Europoje (164 m). Pirmojo pasaulinio karo metais (1915) du jo skliautai buvo susprogdinti besitraukiančios Rusijos armijos. Restauruojant 1930 m. šį tiltą buvo naudojamos netinkamos tam medžiagos – portlandcemenčio skiediniai ir betonai. Pagal 2007–2008 m. Restauracijos projektą buvo moksliškai ištirta senų medžiagų, korozijos produktų ir restauracijai naudotinų naujų medžiagų suderinamumas. Remiantis gautais rezultatais pasiūlytos rekomendacijos ir restauracijos metodai užtikrinantys medžiagų suderinamumą bei tilto tvirtumą.