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Fizyczne i chemiczne parametry 124-letniego mostu z betonu zbrojonego

PHYSICAL AND CHEMICAL STATE OF 124 – YEARS OLD REINFORCED CONCRETE BRIDGE

Streszczenie

Most drogowy w miejscowości Krasno nad Kysucou zlokalizowany na rzece Bystrica jest uznawany za najstarszy zachowany obiekt betonowy na Słowacji i jeden z najstarszych mostów łukowych Moniera w Europie Centralnej. Most został zbudowany pomiędzy 1891 a 1892 rokiem na terenie dawnej monarchii austro-węgierskiej i służył bez większych napraw aż do 2014 r. W latach 2014 i 2015 trzy instytuty badawcze (FCE STU, Politechnika w Żilinie i TSUS przeprowadziły kompleksowe badania fizycznych i chemicznych parametrów betonu i jego zbrojenia w konstrukcji mostu. Uzyskane wyniki badań w udanej rekonstrukcji mostu zakończonej w 2015 r. Most został ponownie otwarty na drodze, która łaczy Żilinę i Zwardoń w Polsce.
Artykuł prezentuje wyniki badań samej konstrukcji mostu w terenie oraz wyniki badań przeprowadzone w laboratoriach TSUS na 5 pobranych próbkach rdzeni w kształcie walca. Przeanalizowano mikrostrukturę i strukturę porów betonu oceniając jego aktualną żywotność i przewidując jego dalsze funkcjonowanie po pełnej rekonstrukcji.

Abstract

Road bridge Krásno nad Kysucou situated over the river Bystrica is regarded to be the oldest preserved reinforced concrete bridge in Slovakia and one of the oldest Monier Arch bridges in the region of Central Europe. The bridge was built between 1891 and 1892 in the former Austro-Hungarian Monarchy and was in service without any substantial

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repairs until 2014. Three research institutions (FCE STU, Technical University of Žilina and TSÚS) performed complex physical and chemical diagnostics of the bridge concrete and embedded steel reinforcement within 2014 and 2015. The obtained results helped to the successful reconstruction of the bridge completed in 2015. The bridge is open again on the former 1st class road between Žilina and Zwardoň in Poland.

This paper deals with material properties of concrete field tests on the bridge structure and those performed on 5 taken cylindrical cores in TSÚS laboratories, studying micro-structure and pore structure of the concrete, assessing the current concrete service-life and anticipating prediction of the life after complete bridge reconstruction.

1. Introduction

The investigation was aimed at reinforced concrete bridges older than 100 years. Neither drawings nor information has been preserved about their structure and no relevant standards existed at the time of their construction. The knowledge about material composition and properties of such old concretes and reinforcement is missing. From this point of view the progress of their deterioration is interesting and has been studied. It is believed that results of the research project should provide some general information about the mechanical properties of concretes and reinforcements used in the construction of bridges at the very beginning of applications of concrete in bridge construction in Slovakia.

For the research the following bridge structures were selected until now:

- concrete piers of the old bridge in Bratislava (age of the structure: 125 years) [1, 2];
- reinforced concrete bridge in Krásno nad Kysucou (age of the structure: 124 years) [3];
- reinforced concrete bridge in Hlohovec (age of the structure: 104 years) [3];
- reinforced concrete bridge in Ružomberok (age of the structure: 102 years) [3];
- truss bridge girder from the Nyíregyháza district in Hungary, near Slovak borders (age of the structure around: 100 years) [3];
- reinforced concrete bridge in Nižná Myšľa (age of the bridge: 103 years) [3];
- reinforced concrete bridge in Sládkovičovo (exact age of the bridge is unknown, but more than 96 years) [3].

The paper reveals technical description of the reinforced concrete bridge in Krásno nad Kysucou, the collected historical facts, the used methodology of testing and measured results of mechanical and microstructure properties of original concrete as well as descriptions of the deterioration after 124 years of the bridge in service and the reconstruction works.

2. Description of the original structure and substructure of the bridge

The bridge Krásno nad Kysucou was built by G.A. Wayss Company in the former Austro-Hungarian monarchy in 1892. Today it is one of not only the oldest reinforced concrete bridges in Slovakia but also in Central Europe region, which is still in service [4]. G.A. Wayss company built 320 bridges of this type throughout Europe within 1884 and 1891 [5, 6]. The state of this bridge before testing and reconstruction works starting in 2014 is seen in Figure 1.

Fig. 1. Bridge in Krásno nad Kysucou before reconstruction in 2013

This unique bridge with the statue of Saint John of Nepomuk placed within its railing was in a very good technical condition after 124 years in service with hundreds of cars passing it every day on the former 1st class road between Žilina in Slovakia and Zwardoň in Poland. However, due to the increased demands for its reliability, in terms of new European standards, and also due to the effort of the city administration to maintain this technical monument, it was decided to refurbish and strengthen its structure as well as its approach roads.

The bridge consists of two reinforced concrete arches built on stone abutments and stone pier, which were the part of the previous stone arch bridge. Each arch has a span of 16.8 m. The thickness of the arch is variable with 400 mm in the springs, 150 mm in the middle of the first arch, and only 130 mm at the centre of the second arch. The thickness of the arch varies also in the transverse direction, and at the both sides has a same thickness at both arches – 250 mm in the middle of the span. Above the main arch reinforced at both surfaces there is a layer of plain concrete reaching a thickness up to 600 mm nearby the springs and gradually diminishes towards the centre of the arches. The total thickness of the concrete nearby the springs is slightly over 1 000 mm. This additional layer of plain concrete is situated only between the spandrel walls, not reaching the side edges of the bridge and extends only about to one third of the span from both sides. Rise of the arches is 2.40 meters. Free width on the bridge was 6.1 m and the total length of the bridge reached 36.2 m. The substructure of the bridge consists of one stone pier situated in the middle of river Bystrica and two stone abutments. Original road layers on the bridge are shown in Figure 2. Under the asphalt cover the pavement consisting of three layers was found: 1) crushed stone made of larger flat, 2) closely packed stones stacked on their edges and 3) fine gravel-sand layer at the very bottom.

Fig. 2. Original bridge pavement found under the asphalt layer

3. Historical survey of Monier Arch Bridges

The bridge Krásno nad Kysucou was completed in 1892 as one from the series of Monier Arches built in the Austro-Hungarian Monarchy (now in Slovakia). The first reinforced concrete bridge of this type was built by Joseph Monier in 1875; however, only few of them have survived until today [7]. Most structures were designed based on previous experimental investigation, since the theory of reinforced concrete was not well known back then. The typical concrete batch of the Wayss Company for the construction of Monier

Arch Bridges consisted of 1 part of Portland cement and 3 parts of gravel with maximum coarse aggregate 25 mm [8, 9 and 10]. Data on compressive and tensile strengths were not reported. Structural analyses of vaults at the end of 19th century were made in a very simplified manner and were mostly based on experimental experience. Simple example of structural analysis of reinforced concrete vaults was described by G. A. Wayss [5]. The minimal thickness of the arch was determined from the calculated axial forces in arch springing and the defined strength of concrete and reinforcement as well as the recommended reinforcement ratio. The bending moments on the vaults were determined for uniformly distributed load from the deviations of the vault geometry from parabola. Neutral axis within the reinforced concrete cross-section was considered to be in the middle of the height of the cross section and stress-strain relationship was taken into account as linear relationship [5]. However, in reality, the design of the reinforced concrete vaults was mostly based on experimental experience that considered also an uneven (one-sided) distributed loads as well as concentrated loads from vehicle wheels [6].

4. Research methodology

The overall diagnosis of the old bridges was divided into three main phases. The first phase is concerned by visual observation of the bridge and site-determinations for non-destructive testing and taking the concrete cores for laboratory mechanical and microstructure tests.

The second phase consisted of in situ diagnostics. In-situ diagnostics methodology comprised of the following procedures: locating the steel reinforcement and measurement of its cover, non-destructive determination of the concrete strength by Schmidt rebound hammer [11], ultrasonic measurement of the dynamic modulus of elasticity and pull-off tests [12, 13].

Consequently, concrete core specimens with nominal diameter of 100 mm and steel reinforcement samples were taken from the bridge structures. A set of 5 drilled cores was carried out (2 from the arches and 2 from the parapets), from which were gained 5 specimens (ARCH1, ARCH2, PAR1/1, PAR1/2 and PAR2) for mechanical tests [14, 15 and 16] in laboratory. Immediately after the concrete cores were drilled out the depth of carbonation was measured by the phenolphthalein test.

The third phase was covered by laboratory tests on drilled cores. Mechanical properties (dynamic and static modulus of elasticity, compressive strength), the mineralogical, phase and chemical composition [17] as well as the basic pore structure parameters and pore size distribution of the concrete specimens were studied. The present state of concrete is assessed on the above-mentioned set of obtained results.

5. Experimental verification of material properties of concrete

5.1. Visual observations and site-determinations for testing

Localization of selected sites from the upper part of the bridge to gain cylindrical drilled cores is portrayed in Figure 3. The specimens for the consequent laboratory tests were taken by core drilling in the area of 1st and the 2nd arch and 2 parapets of the bridge Krásno and Kysucou (further are the specimens abbreviated as ARCH or PAR for the specimens of arches and parapets, respectively). This procedure gave 5 specimens of concrete having a diameter of approximately 100 mm, a height of approximately 200 mm. Alongside this activity non-destructive measurement of concrete strength, dynamic modulus of elasticity, adhesive strength of the coating to the substrate was carried out as well as the location of steel reinforcement in the bridge structure with subsequent reinforcement sampling for laboratory testing of its properties were carried out on the bridge.

Fig. 3. The upper part of the bridge and notification of 4 sites for drilling bores

5.2. Non-destructive tests

The estimated informative compressive strength of concrete from the 1st arch is reported in Table 1. The 2nd arch of the bridge structure was tested and evaluated in the same way. The results of both tests were very similar. Statistical evaluation of the measured results related to the whole bridge structure is postulated in Table 2.

Table 1. Compressive strength determination by Schmidt rebound hammer of type N

Test site*	Direction of the hit **	Individually found valid rebound values on the test sites					Calculated average rebound	Strength from the table	Estimated informative strength
		Ra,i					Ra,m	Rb,ei	Rb,inf
		[-]					[-]	[MPa]	[MPa]
		1	2	3	4	5			
1. ARCH1-U-C	ua45	47	47	48	46	46	47	49.0	39.0
2. ARCH1-U-C	ua45	48	48	47	47	50	48	51.0	40.6
3. ARCH1-U-L	ua45	46	45	45	44	48	46	47.0	37.4
4. ARCH1-U-L	ua45	48	48	46	50	48	48	51.0	40.6
5. ARCH1-O-R	vd	40	40	42	38	38	40	46.0	36.6
6. ARCH1-O-R	vd	40	40	42	38	42	40	46.0	36.6

Table 1. Con't. Compressive strength determination by Schmidt rebound hammer of type N

Test site*	Direction of the hit **	Individually found valid rebound values on the test sites					Calculated average rebound	Strength from the table	Estimated informative strength
		Ra,i					Ra,m	Rb,ei	Rb,inf
		[-]					[-]	[MPa]	[MPa]
		1	2	3	4	5			
7. ARCH1-O-L	vd	34	34	34	34	34	34	35.0	27.8
8. ARCH1-O-L	vd	36	36	36	36	36	36	39.0	31.0
9. PAR-L	h	34	34	32	36	36	34	30.0	23.9
10. PAR-L	h	34	34	33	32	35	34	30.0	23.9

**Explanations indicating the test sites: ARCH1 – the 1st ARCH, U – measurement under the bridge, C – centre of the width of the bridge, O – measurement on the bridge, L – the left side of the width of the bridge looking at Žilina, R – the right side of the width of the bridge looking at Žilina, PAR – parapet of the bridge; **Symbols for direction of the hits: h – horizontally, vd – vertically down, ua45 – under the angle 45°*

Table 2. Statistical characteristics of determining the strength by Schmidt rebound hammer

The number of the chosen values	10
The smallest value	23.9 MPa
The highest value	40.6 MPa
The average value	33.7 MPa
The standard deviation	6.6 MPa
The variability	19.6 %
The guaranteed strength estimated as informative	21.0 MPa

**Statistics is based on the assumption of one concrete recipe used across the bridge*

The above tests give the average compressive strength value of 33,7 MPa with the variability among individual determinations up to 20.0%, which can be regarded, bearing also in mind the age of concrete, as still well-reproducible results. Values of the average and the guaranteed compressive strength found for the whole bridge structure indicate preserved concrete condition on the bridge Krásno nad Kysucou after 124-years of the service-life.

The scheme of in-situ measurements of the transit time of ultrasonic wave at the bridge structure is illustrated in Figure 4 and the obtained results are summarized in Table 3.

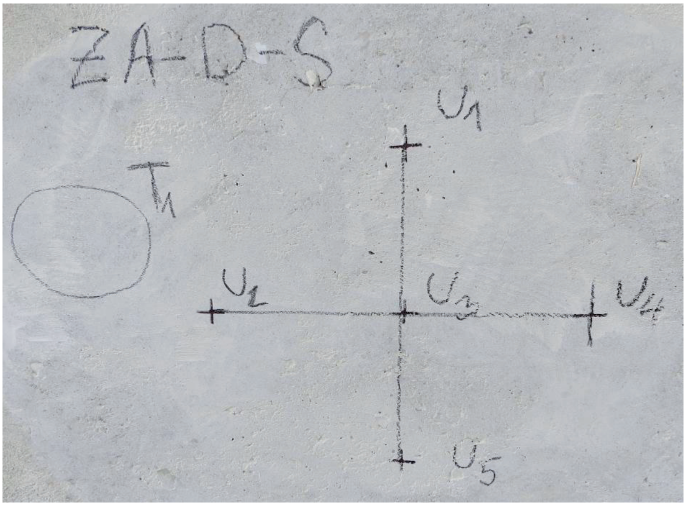

Fig. 4. Scheme of the transit time of ultrasonic wave measurement – test site ARCH1-U-C

Table 3. Dynamic modulus of elasticity estimated by in-situ measurements

Test site	**Localization of the chosen measurement sites**	**Volume density* (kg/m^3)**	**Dynamic modulus of elasticity (GPa)**
ARCH1-U-C	Arch 1, the bottom centre of the bridge width	2130	13.8
ARCH1-U-L	Arch 1, the bottom left side of the bridge width looking at Žilina	2130	12.5
ARCH1-O-L	Arch 1, the upper left side of the bridge width looking at Žilina	2080	13.3
ARCH1-O-R	Arch 1, the upper right side of the bridge width looking at Žilina	2080	16.1
PAR-L	The left-side parapet looking at Žilina	2130	12.3

**Volume density values were taken from laboratory measurements of cylindrical specimens*

The evaluated 124-years old concrete registered volume densities over 2000 kg/m^3 and dynamic modulus of elasticity at thickness of the concrete structure between 150 and 300 mm, through which penetrate ultrasonic waves between 12.3 and 16.1 GPa. The above findings are consistent with those identifying compressive strength, indicating as well as previous results the preserved state of the concrete at the bridge, which was in service for 124 years until testing.

The test of adhesion of surface concrete layer to the deeper substrate is depicted in Figure 5 and the obtained results are summarized in Table 4. Tensile strengths showing the quality of the surface concrete at the bridge exceeded in all measurements the value 1, somewhere 2. This observation gives also the evidence on the preserved state of the concrete occurring at the bridge Krásno nad Kysucou.

Fig. 5. Estimation of the adhesion – teared off surface concrete layer

Table 4. Adhesion of the surface concrete layer expressed as tensile strength of surface layer

Test site	Tensile strength of the surface layer (MPa)
ARCH-D-C	2.38
ARCH-D-L	1.81
ARCH-O-R	2.32
ARCH-O-L	1.86
PAR-L	1.06

5.3. Carbonation depth

Carbonation of concrete was determined by a simple indicating method by phenolphthalein (0.1% solution in ethanol) to observe the depth of carbonation. The depth was measured immediately after drilling concrete cores by the distance of coloured layer oriented vertically to the surface of the structure as seen in Figure 6. The observed depths of carbonation are reported in Table 5.

Fig. 6. Verification of carbonating concrete layer on the superstructure of the bridge

Table 5. Depth of carbonation of concrete (measurements were performed by TU Žilina)

Test site	**Localization of the chosen measurement sites**	**Average depth of carbonation (mm)**
1	Middle of the top of the arch No. 1 (1 200 mm from the parapet)	< 2 mm
2	Top part of the arch No. 1 in abutment no. 2 (1 700 mm from the parapet)	< 2 mm
3	Bottom of the arch No. 1 in abutment no. 1 (edge of the superstructure)	< 2 mm
4	Bottom of the arch No. 1 in abutment no. 1 (middle of the superstructure)	< 2 mm

The 124-old concrete is characterized by very surprisingly and unexpected low carbonation depth. However the previous finding on the well preserved state of concrete at the bridge structure is confirmed by this way. Contrary, the found low carbonation depths open the duty or at least the attempt to explain such "anomaly" in the terms of today´s concretes susceptible to carbonating. Low carbonation could be caused either by the type of cement, resistance of concrete itself due to concrete composition, method of making concrete and early curing storage and also long-acting external conditions. The research on this topic is focused in 2016 for taking smaller concrete cores from the bridge to study in a more detail carbonation of the concrete. The repeated verification of carbonation depth from May 23 to 24, 2016 confirms previous findings of negligible carbonation of concrete of the arches and parapets.

Comprehensive verification of the current state of the concrete by in situ testing at the structure of bridge Krásno nad Kysucou brought the following knowledge, important for the management of reconstruction works: the concrete is specified by the least guaranteed compressive strength value of 21.0 MPa but the measured average strength value is 33.7 MPa, dynamic modulus of elasticity approximately between 12.0 and 18.0 GPa, tensile strengths confirming the adhesion of surface layer to deeper concrete substrate always over 1.00 MPa, sometimes over 2.00 MPa and extremely low carbonation depth up to approximately one-two millimeters. The above findings gave the evidence on still well-preserved state of concrete on the 124-years old bridge.

5.4. Laboratory tests

Figure 7 shows the necessary work for gaining core. Cylindrical specimens intended for laboratory tests are seen in Figure 8.

Fig. 7. Drilling the concrete core with diameter of 100 mm

Fig. 8. The taken concrete specimens for dynamic and Young´s modulus of elasticity and compressive strength testing in the laboratory

The values of important utility properties of the studied concretes are presented in Table 6.

Table 6. Modulus of elasticity and compressive strength of in-laboratory tested concretes

Designation of concrete	**Dynamic modulus of elasticity (GPa)**	**Young´s modulus of elasticity (GPa)**	**Compressive strength**	
			Cylindrical (MPa)	**Cube (MPa**
ARCH1	29.3	20.9	22.7	28.2
ARCH2	37.1	23.7	30.5	36.4
PAR1/1	35.2	24.1	20.2	24.8
PAR1/2	31.9	16.5	22.4	27.6
PAR2	29.5	15.1	19.2	23.8

The studied concretes are specified by relative high values of dynamic modulus of elasticity moving around 30.0 GPa. Young´s modulus of elasticity and compressive strengths can be attributed to the today´s concrete class of C 20/25 [18].

According to the obtained results the anticipated strength class C 20/25 of 124-years old concrete in the present days answers then-technological possibilities of a production and achieved quality of concrete that were available in 1892.

6. Microstructure and pore structure

6.1. Sample preparation and procedures

For the mineralogical, phase and chemical characterization, the concretes were crushed to smaller bulk samples, consequently dried for several days at temperature 60°C in an oven to the constant weight and then milled for 60 minutes for homogenization. The grounded products were sieved through 0.063 mm meshes to receiving the powder applicable for testing. Chemical analysis of the bulk concrete matrix (without large aggregate grains) was realized in concordance with STN EN 196-2. The X-ray diffraction data were collected on the STOE X-ray diffractometer equipped with programme of the record´s estimation Bede ZDS. The overall measurements of the samples were carried out in a 2Θ range of 10–60°. CuK_α radiation and Ni-filter was used. Thermal analysis (TG-DTA) was performed on the NETZSCH apparatus (STA 449 F3 Jupiter). Samples weighing 100 mg were heated in flowing air and ceramic crucibles within the heating range 20–1100°C, at heating rate 10°C/min. Basic parameters of the pore structure were identified on the high-pressure QUANTACHROME porosimeter Poremaster 60 GT.

6.2. X-ray diffraction analysis and thermal analyses

XRD records and TG-DTA plots are shown in Figures 9 to 12. Concrete from arch is specified by the presence of $Ca(OH)_2$ (CH) and negligible content of $CaCO_3$ (calcite Cc).

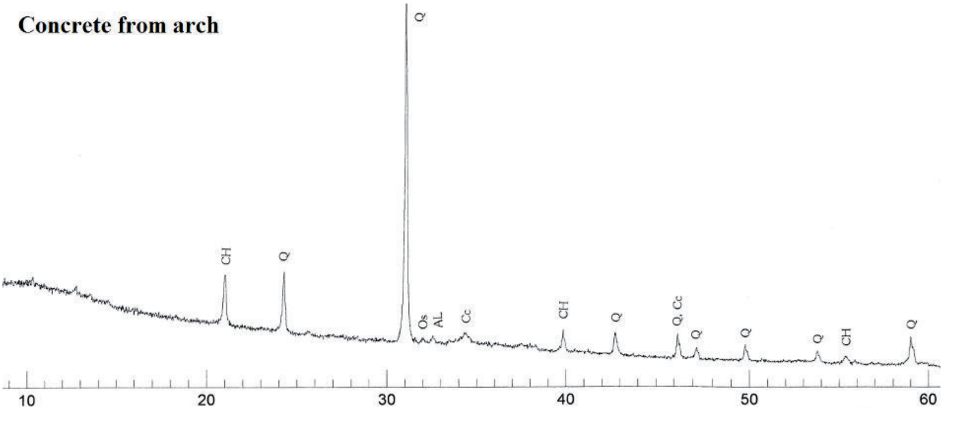

Fig. 9. X-ray diffraction analysis of concrete from arch 2

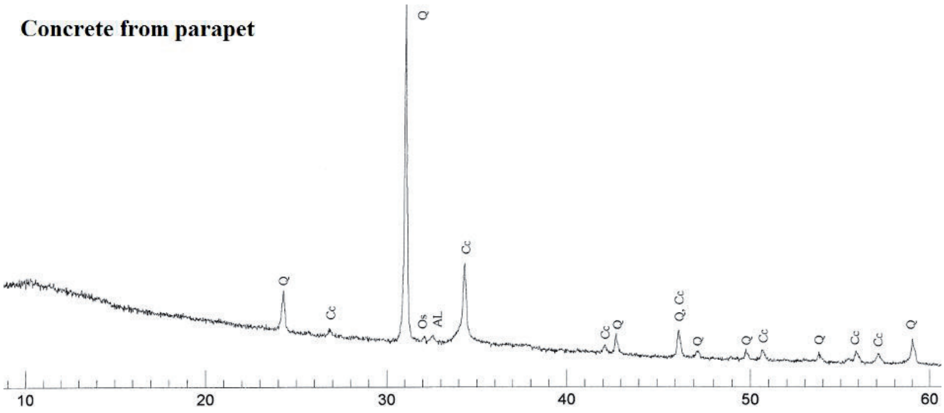

Fig. 10. X-ray diffraction analysis of concrete from parapet 2

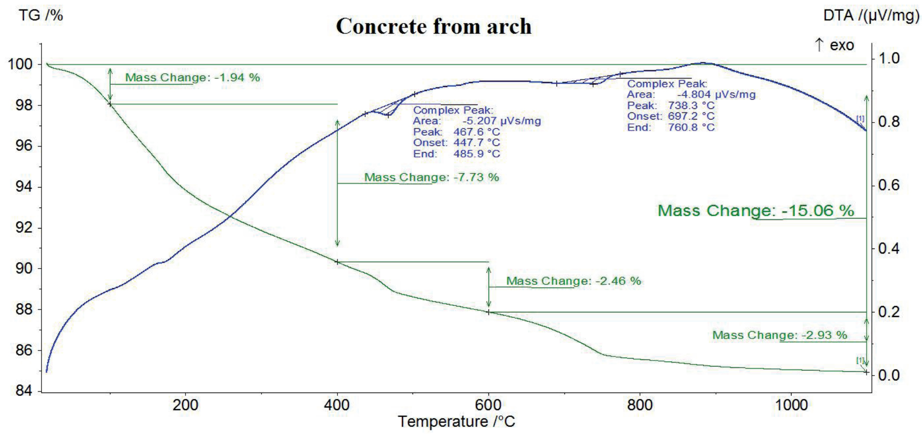

Fig. 11. Thermal analysis of the concrete from arch 2

High diffraction intensity for SiO_2 (quartz Q) indicates the use pure quartz aggregate for making the concrete. By contrast, CH diminished in parapet concrete, which is also slightly carbonated as confirmed by weak endotherm with maximum at around 805°C. The difference in ignition losses between 600 and 800°C, indicating the $CaCO_3$ dissociation, in the concrete of arch and parapet is about 5 wt. %. This result confirms a bit more of calcite content in parapet concrete but no evident carbonation.

DTA plot of concrete from arch displays two thermal effects, that from parapet only one and TG curves show the associated CH dehydroxylation and Cc decarbonation as the weight loss.

Concrete from arch contains CH and minimum of Cc, while that from parapet only calcite. The results of thermal analysis are in full concordance with those of X-ray diffraction study.

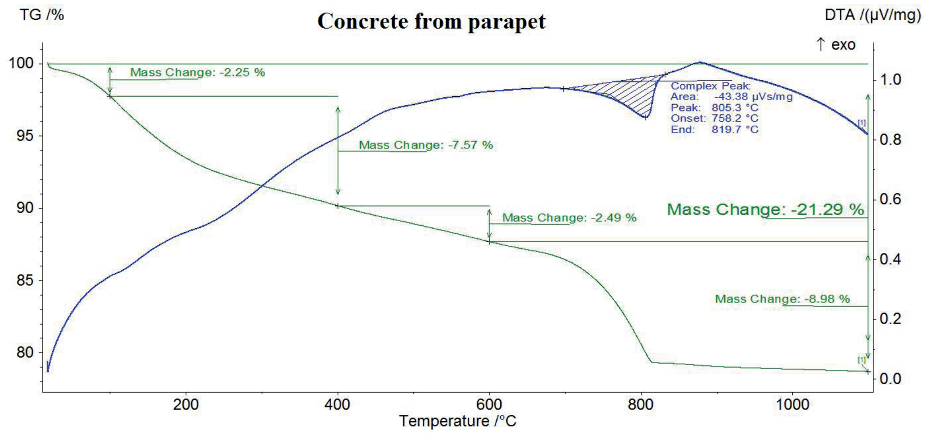

Fig. 12. Thermal analysis of the concrete from parapet 2

6.3. Chemical analysis and pore structure

Chemical composition and the pore structure of the concretes are reported in Tables 7 and 8.

Table 7. Chemical composition of the concrete

Sample	Component (% weight)									
	I.R.	L.O.I.	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Cl^-	Na_2O eqv.
ARCH1	38.73	14.44	49.84	24.75	5.03	2.43	1.20	0.20	0.01	0.54
ARCH2	40.39	14.29	50.40	25.17	4.85	2.43	1.09	0.31	0.01	0.63
PAR1/1	35.27	20.45	41.49	29.53	4.08	2.02	1.18	0.23	0.02	0.32
PAR2	30.64	19.85	42.34	21.19	4.45	2.10	0.97	0.20	0.01	0.29

Explanations: I.R.: insoluble residue, L.O.I.: loss on ignition

The observations of chemical composition confirm high CaO and SiO_2 portions in all studied concretes indicating sufficient amount of cement and SiO_2-rich aggregate used at their manufacture bearing in mind that carbonation is extremely low in arches and weak in parapets. The average difference 5.79 wt. % between L.O.I values indicates a higher degree of carbonation in parapets opposite to arches; as consistently confirmed by XRD and TG-DTA.

A bit coarser pore structure found in parapet concretes compared to arches is confirmed mainly by higher pore specific surface areas, total pore- and micropore volumes as well as total porosity values. The coarser pore structure in parapets is attributed to very slight carbonation effect.

Table 8. Pore structure parameters of the concrete

Sample	*SSA (m^2/g)	V_{MP} (cm^3/g)	V_{TP} (cm^3/g)	M_{TP} (nm)	M_{MP} (nm)	TP (%)	Permeability coefficient K (m/s)
ARCH1	21.45	0.074	0.110	55.95	8.98	22.04	3.0×10^{-11}
ARCH2	25.35	0.080	0.110	15.65	8.30	21.59	2.0×10^{-11}
PAR1/1	36.60	0.110	0.150	11.13	6.77	27.20	2.0×10^{-11}
PAR2	33.03	0.100	0.140	13.79	6.49	26.00	2.0×10^{-11}

**Explanations for Table 8: SSA: specific surface area of pores; V_{TP}: total pore volume (1.82 nm - 0.534 mm); V_{MP}: micropore volume (1.82 nm - 5 250 nm); M_{TP}: total pore median radius (1.82 nm - 0,534 mm); M_{MP}: micropore median radius (1.82 - 5 250 nm); TP: total porosity (1.82 nm - 0.534 mm); K: coefficient of permeability (calculated)*

The results of in-situ and laboratory testing of the physical and chemical state of the concrete served as serious knowledge base for initiating and carrying out reconstruction of the bridge.

The current view of the renovated bridge is shown in Figure 13.

Fig. 13. View of the bridge after reconstruction

7. Conclusions

Performed tests enabled to postulate the following conclusions:

1) Based on non-destructive tests 124-years old concrete at the bridge Krásno and Kysucou is specified by average informative strength 33.7 MPa, dynamic modulus of elasticity approximately between (12–16) GPa at the thickness of concrete structure between 150 and 300 mm and adhesion of surface concrete layer to deeper substrate between (1–2) MPa regarded as tensile concrete strength.
2) Based on destructive strength concrete is specified by average volume density 2 110 kg/m^3, dynamic and Young´s modulus of elasticity approximately between (29–37) GPa and (15–24) GPa, respectively.

3) The compressive strength values indicate today´s strength concrete class of C20/25.
4) Presence of portlandite was recognized in the concrete of the arches but not parapets.
5) Depth of carbonation verified in 2014 during reconstruction works and repeatedly in May 2016 was found less than 2 mm in concrete of arches and parapets.
6) These findings enabled the less demanding and less extensive reconstruction than was originally anticipated.
7) The observations give evidence on properties-still well preserved 124-years old concrete.
8) Negligible carbonation extent, found also at a couple of other old bridges of age around 100 years, is the subject of the present research aiming to figure out the cause of the essence of this phenomenon.

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