Measurement of Moisture Fields in the Bridge Structure of Charles Bridge

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This paper describes measurements of the moisture field of Charles Bridge in Prague. The measurements were scheduled to cover a one-year cycle, including the spring, summer, autumn and winter, in order to monitor the behaviour of the bridge structure over a period of one year.

Keywords: Charles Bridge, measurement of moisture fields, heat and mass transport.

1 Introduction

Moisture of building materials and structures is very variable. It is dependent on external climatic conditions, and also on the internal conditions in each specific building structure. While external climatic conditions are independent, internal conditions may be affected by the selection of a structural system and suitable materials.

The Moisture distribution in construction materials is non-uniform, being dependent on pressure, temperature and the texture of the applied material and the structural type.

Moisture penetration into building materials and structures, including subsequent moisture transfer in them, is brought about and affected by the following factors below:

- climatic conditions
- water-vapour diffusion and capillary moisture conductivity due to temperature and moisture gradients
- capillarity and capillary absorption capacity
- sorption and de-sorption.

Moisture field changes are caused not only by different and time-dependent external conditions, but also by stable conditions, characterized by temperature, moisture and pressure gradients.

Moisture may be found in a gaseous, liquid, or even solid state.

2 Anticipated moisture effects in the structure of Charles Bridge in Prague

2.1 Anticipated moisture effects of fully functional hydroinsulation

Charles Bridge, a stone structure across the Vltava River, is exposed to climatic effects, including rain and snowfall, solar radiation an the flow of air and water vapour that arises over water level of the river, which does not freeze over in winter. Water from rain and melting snow affects the surface of the sandstone bridge blocks. The water partly drips down its spandrel and breast walls and partly soaks in, particularly at the base of the spandrel walls, and leaking through cracks in joints between the blocks.

As a result of wetting of the breast walls and spandrels by water, the sandstone blocks become soaked with water.

Fully functional hydroinsulation eliminates water leakage from the pavement surface. It creates a closed internal

Photo 1: Charles Bridge in Prague

space enclosed by the arch, breast walls and pavement, filled with hand-placed arenaceous marl, reinforced concrete slab, expanded-clay concrete and dab below the insulation. In this space, on the surface of the breast walls and below the insulation, water vapour condensates due to temperature differences, reaching dew point, and it drips down the extrados of the arch.

In winter time, the entire structure freezes through, but, the freezing process occurs more slowly at the crown of the arch towards the piers. In the hand-placed arenacous marl close to the piers, the core remains unfrozen. It can only freeze through under extremely long-lasting low temperatures. This phenomenon probably affects the moisture transfer and brings about changes in the moisture field of the structure.

The moisture field of the bridge structure is also influenced by the air flow from the wind and the impact of the free water level of the river, which continuously releases water vapour, thus maintaining a permanently high air moisture content. This moisture affects the soffit of the bridge arch, particularly at the footings close to the pier. This state is further worsened by moisture accumulating at the extrados of the arch.

Higher summer temperatures and solar radiation, which is more or less one-sided (coming from the south side), also affect the moisture field of the bridge structure.

Finally we can assume that there are some chemical effects from the acid rain and earlier bridge pavement salting on the moisture field changes.

2.2 Anticipated moisture field of poorly functioning hydroinsulation

If hydroinsulation is not applied correctly, particularly the ends and the connections to the spandrel walls, massive leakage into the bridge occurs. Water accumulates at the extrados of the arch and its level increases if not drained. At the same time, layers of the pavement and tha hand-placed arenaceous marl become to a very large extent saturated with water. The high water content brings about excessive ice formation in the winter season, which negatively affects the bridge structure at the spandrel walls and in the bridge structure itself.

Continuous thin accretion is formed on the breast walls, mostly at places of maximum leakage. On the extrados, particularly at the footings, ice wedges may even appear.

Therefore, high-quality, long-functioning hydroinsulation is essential for the long service life of the bridge. Moreover, continuous monitoring of the effectiveness and the condition of the insulation by continual measurement of the bridge moisture field, even after the completed reconstruction, is vital.

3 Measuring methods and the measuring system

3.1 Methods of moisture measurement

Measurement methods can invoke destructive and non-destructive procedures. They can also be classificatied, according to the manner of moisture measurement, as direct and indirect methods. Direct methods involve measuring the water content in the construction material.

The main principle of indirect methods is measurement of the functional dependence of moisture on a selected physical variable, such as electric resistance, capacity, absorption of gamma radiation, thermal conductivity, etc.

Overview of the methods

Direct methods

- Gravimetric method

Indirect methods

- Chemical method
- Thermal method
- Tensiometric method
- Gammascopic method
- Neutron method
- Electric method
    - resistance
    - capacity
    - electromotive tension, etc.

The gravimetric method is a destructive procedure, its major advantage over all the other measurement methods being that it can be used for any building material, with any moisture content, without advance calibration.

The gravimetric method is the fundamental procedure for calibrating various indirect measurement methods. It has disadvantages, though, which lead to the search for other measurement procedures. Its disadvantages include the use of sampling, which makes continuous monitoring of moisture at a certain place in the structure impossible. Further, gravimetric methods cannot be used in places with difficult access. Another weak point is the need for laboratory processing, which results in high time demands.

The gravimetric method is effective for gathering information on moisture in the monitored material at the place of sampling provided no moisture changes take place during transport and laboratory measurement. It is entirely inappropriate for monitoring moisture field changes with space and time dependency.

Indirect measurement methods enable researchers to follow changes continuously. However, practically all of them the calibration curve to be determined for the empirical dependency of moisture on a selected measured parameter, e.g. electric resistance or capacity. The accuracy of measurement is therefore limited in comparison with the gravimetric method, which is a universal and fundamental method for measuring the moistures of construction materials.

3.2 Conditions for moisture field measurement

It is necessary to make changes in temperature and moisture fields at the same measurement points and at equal time points, i.e. almost at the same time.

The temperature field and the moisture field are closely related. Moisture field measurement cannot be performed without parallel temperature field measurement.

This principle was respected during measurements on Charles Bridge. As part of the construction works done within temperature field measurement, for of moisture field sensors were placed in advance. This helped to eliminate the need for new building works, and saved costs and time.

Temperature field measurement was conducted independently throughout a one-year cycle. In the following year of experimental measurements on Charles Bridge, temperature and moisture field measurements were performed at the same time.

3.3 The measuring system and measuring probes

The measuring system was tested in an experimental construction of a feeder road in Prague – Spořilov No. E-D/47 within the project New Technologies of Hydroinsulation of Bridge Pavements. The measurements were conducted by the author.

Moisture field measurements of the structure of Charles Bridge were conducted with a digital system using devices, such as the ULTRAKUST (FRG), MULTIMETRE (UK) and SANWA ELECTRIC (Japan) systems.

A patent for the moisture field measurement methods for building structures is currently being applied for.

Photo 2 shows the moisture sensors built in rollers made of the original material together with the temperature sensors. The cable line from the moisture sensors is led along the external side of the protective tube of the temperature sensor line (see graph xy) and the cable line leading to the measuring centre.

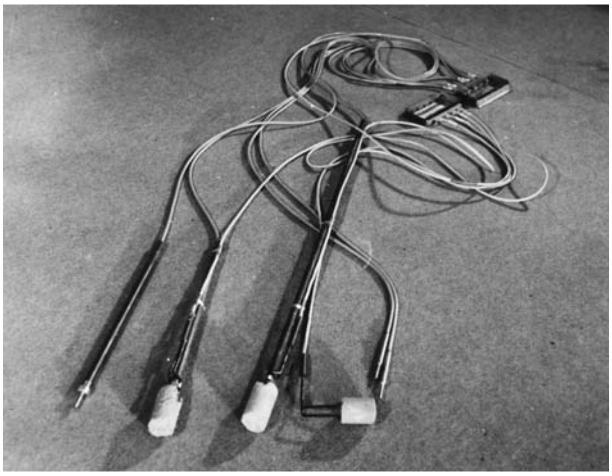


Photo 2: Arrangement of the temperature and conductivity sensors

The following table presents basic information on the placement of the moisture and temperature sensors in the structure of the bridge. The depth of placement was measured from the bottom of the working spaces of A – pier and B – arch, which were laid on insulation material.

Point A – Pier

Point of measurement	Material	Installation depth [m]
A	loose material	1.37
B	expanded-clay concrete	0.48
C	dab	0.10
D	reinforced concrete slab	0.56

Point B – Arch

Point of measurement	Material	Installation depth [m]
F	sandstone	0.99
G	expanded-clay concrete	0.47
H	reinforced concrete slab	0.48
I	dab	0.10
J	below the pavement of the bridge deck	
L	air temperature at the bridge deck level	
M	lower soffit of Arch No. X (depth of placement, measured from the bottom part of the arch)	0.07

4 Results of moisture and temperature field measurement

Results of measurement of the moisture field are presented graphically (see graph No. 1).

Marking of moisture sensors (in graph No. 1):

Point A – Pier

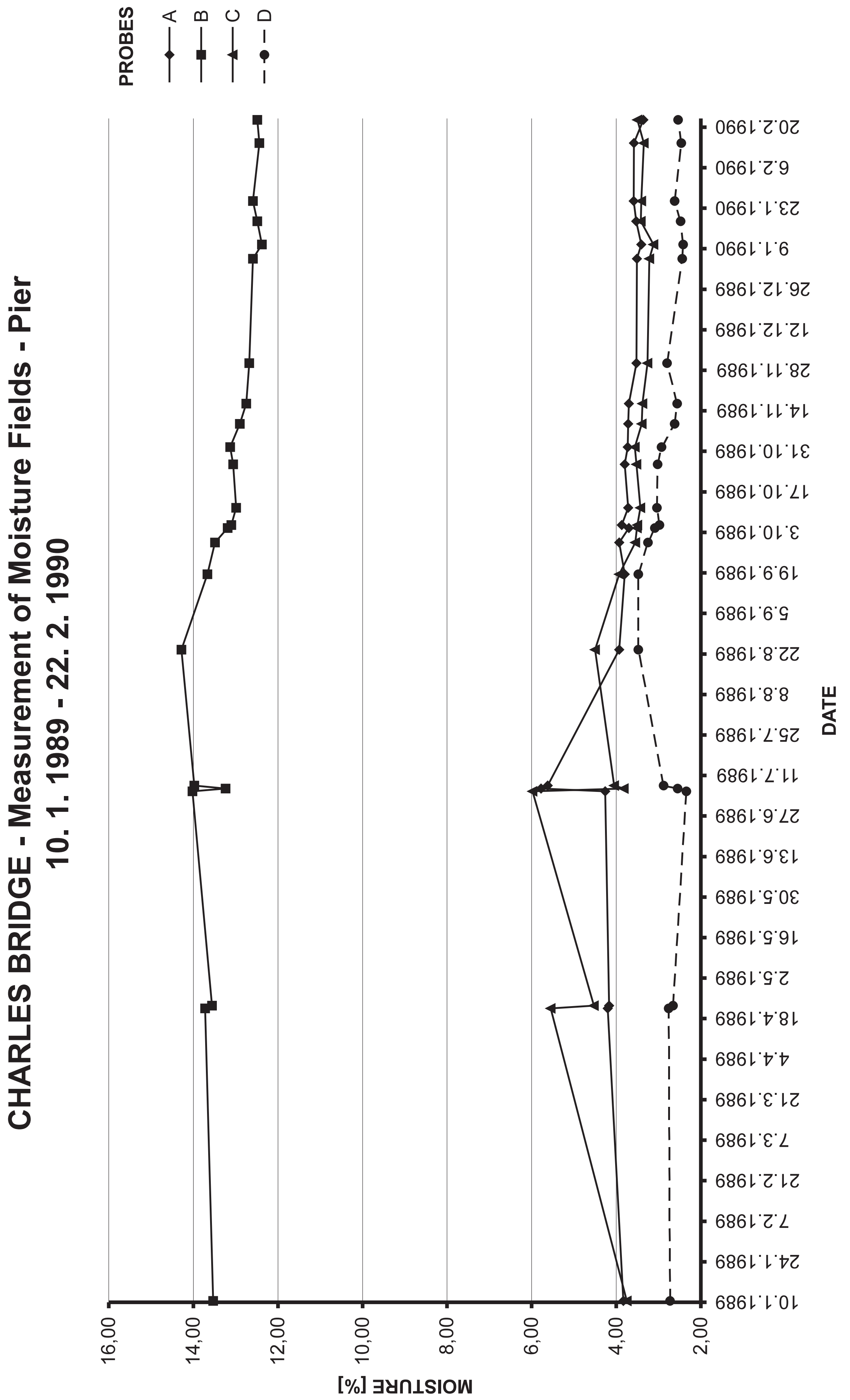
A	loose material
B	expanded-clay concrete
C	dab
D	reinforced concrete slab

Point B – Arch

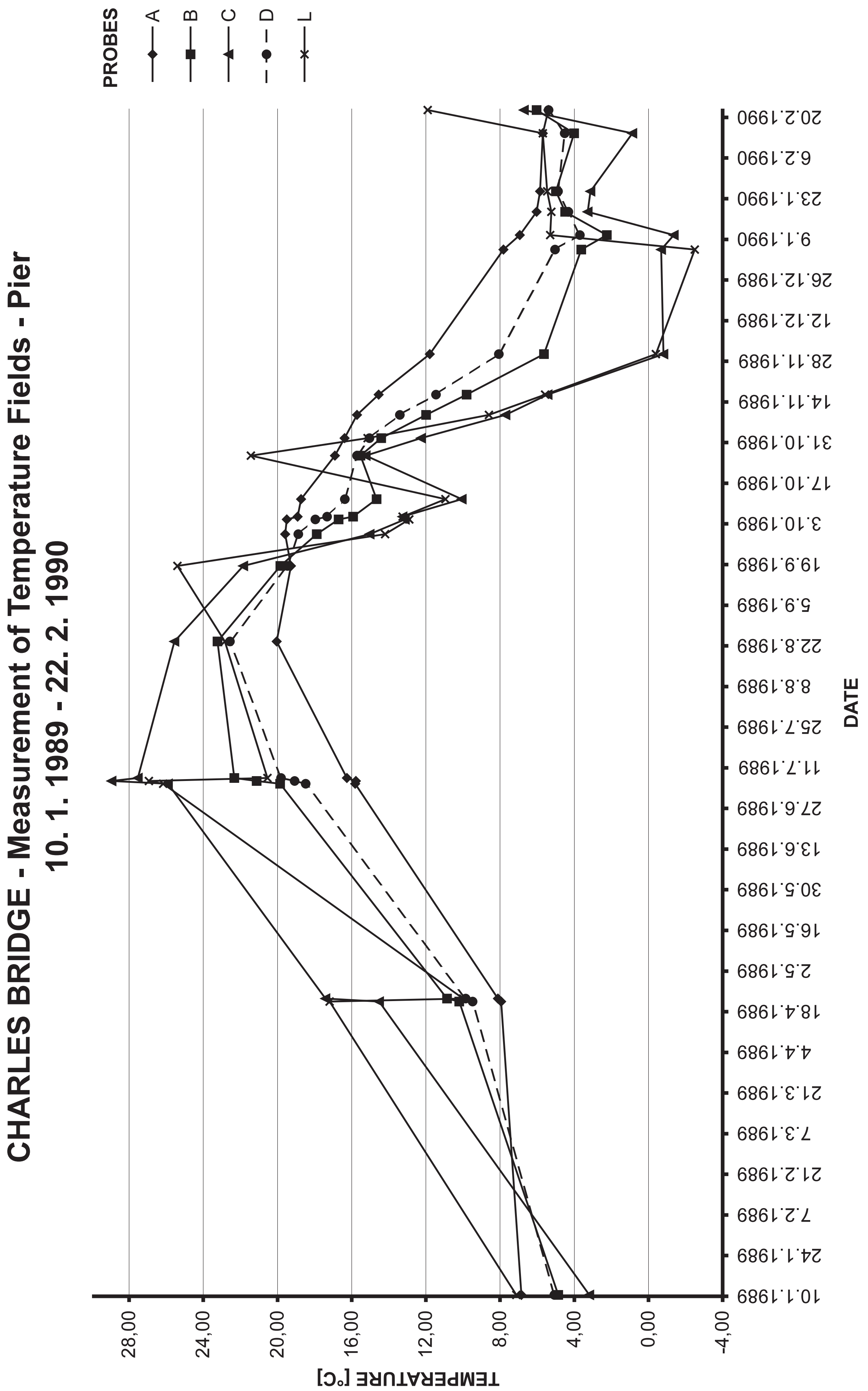
F	sandstone
G	expanded-clay concrete
H	reinforced concrete slab
I	dab
J	below the pavement of the bridge deck

In order to solve transfer differential equations describing mass and heat transport applied to Charles Bridge, it is necessary to know a number of material constants. Further, it is essential to determine the initial and limit conditions and time courses of the temperature and moisture fields. Temperature field measurements therefore had to be conducted parallel to moisture field measurements of the Charles bridge structure. The results of the temperature field measurements are shown in graph No. 2.

Markings of temperature sensors in the temperature field graph (graph No. 2):


CHARLES BRIDGE - Measurement of Moisture Fields - Pier
10. 1. 1989 - 22. 2. 1990
PROBES
A
B
C
D
MOISTURE [%]
16,00
14,00
12,00
10,00
8,00
6,00
4,00
2,00
DATE
10.1.1989
24.1.1989
7.2.1989
21.2.1989
7.3.1989
21.3.1989
4.4.1989
18.4.1989
2.5.1989
16.5.1989
30.5.1989
13.6.1989
27.6.1989
11.7.1989
25.7.1989
8.8.1989
22.8.1989
5.9.1989
19.9.1989
3.10.1989
17.10.1989
31.10.1989
14.11.1989
28.11.1989
12.12.1989
26.12.1989
9.1.1990
23.1.1990
6.2.1990
20.2.1990

Graph No. 1


CHARLES BRIDGE - Measurement of Temperature Fields - Pier
10. 1. 1989 - 22. 2. 1990
PROBES
A
B
C
D
L
TEMPERATURE [°C]
28,00
24,00
20,00
16,00
12,00
8,00
4,00
0,00
-4,00
DATE
10.1.1989
24.1.1989
7.2.1989
21.2.1989
7.3.1989
21.3.1989
4.4.1989
18.4.1989
2.5.1989
16.5.1989
30.5.1989
13.6.1989
27.6.1989
11.7.1989
25.7.1989
8.8.1989
22.8.1989
5.9.1989
19.9.1989
3.10.1989
17.10.1989
31.10.1989
14.11.1989
28.11.1989
12.12.1989
26.12.1989
9.1.1990
23.1.1990
6.2.1990
20.2.1990

Graph No. 2

Point A – Pier

A	loose material
B	expanded-clay concrete
C	dab
D	reinforced concrete slab

Point B – Arch

F	sandstone
G	expanded-clay concrete
H	reinforced concrete slab
I	dab
J	below the pavement of the bridge deck
L	air temperature at the bridge deck level
M	lower soffit of Arch No. X (in the middle of the arch)

5 Conclusion

High mass moisture values of expanded-clay concrete (see Graph No. 1) indicate water leakage into this structural layer placed above the reinforced concrete slab. The material retains the gained moisture over a longer period of time.

The revealed high value of the mass test for expanded-clay concrete is a worrying finding of the moisture field measurement experiment. It is suggested to that a detailed analysis of this should be made and that further experimental testing should be carried out in order to find out the suitability of applying expanded-clay concrete in the forthcoming reconstruction of Charles Bridge.

Measurement of the moisture field and of the changes in the moisture field allow researchers to judge the impact of moisture on the bridge structure, its durability, and to specify the causes of failures brought about by moisture. As a result, the main aim remains to collect of information on the quantity of water present in the structure and on changes in the moisture field related to changes in the temperature field.

Experimental results suggest interaction and interrelation between the moisture and temperature fields. The graphical documentation shows the temperature and moisture behaviour of the materials due to climatic changes within a time dependency in a one-year season. It is recommended that measurements of the temperature and moisture field of Charles Bridge should be continued, using all the measuring methods, until conclusions are finalized for the reconstruction of Charles Bridge in Prague.

The temperature and moisture field sensors remain in their places in the Charles Bridge structure and can be reactivated to facilitate continuation of the experiment. This fact is very significant for the current situation of Charles Bridge after the floods in August 2002.

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References

[1] Římal, J.: *Measurement of Temperature Fields in Long Span Concrete Bridges*. Acta Polytechnica, Vol. 41, No. 6, CTU in Prague, 2001, ISSN 1210-2709, p. 54–65.

[2] Naďľ.: *Development, Design and Load Test of an "Experimental" Partially Prestressed Concrete Bridge*. Proceedings "Challenges for Concrete in the Next Millennium", XIIIth FIP Congress 1998, Amsterdam, Netherlands, p. 503–510.

[3] Římal, J., Klobouček, B.: *Reconstruction of Bridge Decking of Nusle Bridge*. Measurement of Thermal Fields, research report, CTU in Prague, 1981.

[4] *Final Report on the Measurment of Displacements in Cracks and Arches of Charles Bridge*. PÚDIS 1991.

[5] Hejnic, J.: *Charles Bridge Repair, Calculation of Temperature Effects*. Assessment of the Function of the RC Slab, and Structural Repairs Project, General Report, PÚDIS 1988.

[6] Bažant, Z. P., Křístek, V., Vítek, J. L.: *Drying and Cracking Effects in Box-Girder Bridge Segment*. Journal of Structural Engineering, 1992.

[7] Římal, J.: *The Measurement of Thermal Fields in the Bridge Deck and Bridge Structure of Nusle Bridge in Prague*. Proceedings of the Conference New Requirements for Materials and Structures, CTU in Prague, 1998.

[8] Římal, J.: *Evaluation of Temperature Fields on the Reinforced Concrete Slab and Bridge Structure of Charles Bridge*. CTU Reports 2001, CTU in Prague, 2001, p. 846.

[9] Witzany, J.: *Preservation of Structural Monuments – Charles Bridge*. IABSE Symposium "Structures for the Future – The Search for Quality", Rio de Janeiro, 1999.

[10] Witzany, J.: *Structural and Technical Condition and Reconstruction of Charles Bridge*. The Czech Chamber of Certified Engineers and Technicians 1997, p. 8–19.

[11] Josef, D., Mencl, V., Šmerda, Z., Witzany, J.: *Charles Bridge*. Commemorative publication "The Bridge of The Millenium and the Bridges of the Century in the Czech Republic", international symposium "Bridges 2001", Brno.

[12] Witzany, J. et al: *Assessment of Structural and Technical Condition of Charles Bridge*. Bulletin of Civil Engineering, CTU in Prague, No. 8, 2002, p. 226–249.

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