SEA-SALT RESISTANCE OF PRESTRESSED RPC BEAMS

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ABSTRACT

Five concrete arch bridges measuring about 200 m in span have been built along the Adriatic coast in Croatia. All these bridges are affected by the sea water salt which reaches the bridge structure through wind action. Due to influence of sea-water salt (chloride), prestressed superstructure components of such bridges are highly susceptible to heavy damage.

The research relating to the use of reactive powder concrete (RPC) in prestressed structures is described. Properties of prestressed beams in which RPC is used in combination with steel prestressing cables, were tested in laboratory conditions.

Authors present research about the load bearing capacity of prestressed RPC beams as conducted at the Faculty of Civil Engineering, Zagreb. RPC was submitted to gas permeability and capillary water absorption testing which indicated that the RPC is a material ultra-resistant to sea water action.

Results obtained in this research confirm that the use of prestressed RPC beams enables realization of structures characterized by high bearing capacity, resistant to chloride action.

Keywords: Concrete Bridges, Reactive Powder Concrete, Prestressed RPC Beams, Gas Permeability, Capillary Water Absorption, Sea-Salt Resistance.

INTRODUCTION

Five concrete arch bridges measuring about 200 m in span have been built along the Adriatic coast in Croatia [2]. All these bridges are exposed to sea water salt which reaches the bridge structure through wind action. Due to influence of sea-water salt (chloride), prestressed superstructure components of such bridges are highly susceptible to extensive damage.

Fig. 1 Maslenica Bridge, concrete arch 200m in span, Croatia, 1997, Author: J. Radic [2]

The first appearance of the Reactive Powder Concrete (RPC), an ultra-high-strength cementitious composite with advanced mechanical properties, superior physical characteristics, excellent ductility properties, very-low-porosity and extremely low permeability, opened up hopes that this material could be used on bridges located in aggressive Adriatic Sea environment.

Information about compressive strength ranging from 200 to 800 MPa, and ductility that is 250 times as high as in the case of traditional concrete [1] is admirable to say the least, but it also raises a logical question: If its properties are so fantastic, why is this material not widely used? Some of possible answers are:

- high price of RPC;
- engineers are not skilled enough to profit from exceptional performance of this new material;
- know-how required to achieve best results with RPC is lacking;
- non-existence of regulations in this field and insufficient data about some of the RPC properties.

A team of young researchers lead by Prof. D. Bjegovic has been working on a daily basis at the Faculty of Civil Engineering, Department for Materials, to develop and improve new RPC mixtures, while at the same time best ways to use this material in bridge building are being studied at the Department for Bridges and Structures, under guidance of Prof. J. Radic.

This paper provides an overview of RPC bridges recently built in the Far East, and describes latest results obtained by the complex study of RPC and its use in bridge construction, as conducted at the Faculty of Civil Engineering in Zagreb. Results obtained by submitting RPC to gas permeability and capillary water absorption testing, are also presented. These results confirm very low porosity and extremely low permeability of this material, which is highly significant for the study of RPC's resistance to sea salt.

PRECONDITIONS FOR THE USE OF RPC IN BIG STRUCTURES

LOWER PRICE

The first and the most convincing argument why the use of RPC in big structure has remained restricted is most probably its high price. However, already the first Japanese bridge made of RPC, i.e. the Sakata-Mirai bridge built in Sakata [7] in September 2002, drastically changed this misconception. On this pedestrian bridge 50 m in span, 2.4 m in width, the own weight of beams was reduced to one fourth of the weight of prestressed concrete beams. This in turn reduced dimensions of foundations so that in the end the total price of the bridge was reduced by about 8-10% when compared to the cost of a similar reinforced concrete bridge. Therefore, although the RPC is more expensive than traditional concrete, the resulting structure is less costly, simply because of savings that can be made in the consumption of materials.

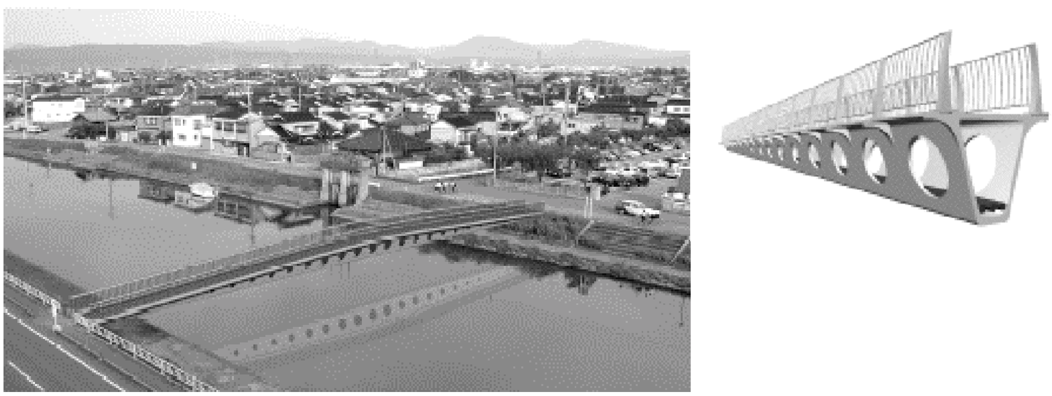

Fig. 2 Sakata-Mirai RPC bridge in Sakata, Japan, 2002 [7]

MAKE FULL USE OF RPC PROPERTIES AND PERFORMANCE

The next problem lies in the fact that many engineers do not know in which way they could use such high compressive strength offered by RPC. When compared to traditional concrete, the compressive strength of this new material is 4 to 15 times higher, so that its use can not be considered cost-effective if shapes typical for reinforced-concrete and prestressed structures are applied. Thus, in many cases the compressive strength of the new material is not fully used. In fact, it is reasonable to use RPC only if the shape of structure in which the material is incorporated is modified in accordance with properties of the new material. This issue has been tackled in the papers [4], [5] in which some new bridge shapes, more appropriate for this material, are presented. In this respect, the shape of the very shallow arch of the Seonyu Bridge [8] 120 m in arch span, built in Seoul, Korea in April 2002, is really encouraging. The shape of the arch is defined by the relationship f/L = 0.125 (f…arch rise; L… arch span), and is hence very close to an optimum shape presented in paper [5] and Fig. 3.

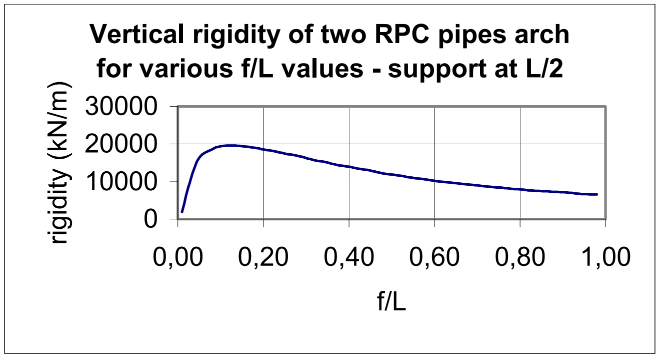

Fig. 3 RPC arch rigidity in correlation with f/L ratio [5]

Fig. 4 Seonyu RPC Bridge in Seoul, Korea, 2002 [8]

A study [6] of the RPC based arch bridge destined to road traffic, 432 m in arch span (Fig. 5), was made at the Department for Structures of the Faculty of Civil Engineering in Zagreb.

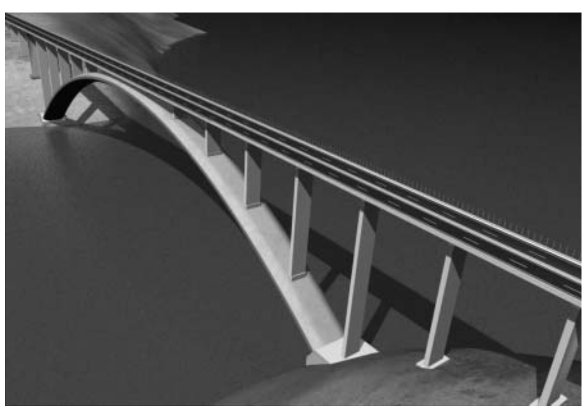

Fig. 5 Design of the Bakar RPC Bridge, 2001 [6]

DEVELOP KNOW-HOW IN RPC FABRICATION

All mix designs that have so far been published with respect to RPC fabrication are unfortunately insufficient for attaining potential performance values of this new material. A lot of experimenting with the proportioning of individual components is needed. Authors show in Fig. 6-15 choice of materials, preparation of RPC mix, the process of pouring RPC in the formwork and load testing of the prestressed RPC beam in one developing center near Zagreb. The fact that some European companies have protected with patent rights their achievements in the study of RPC is an additional proof that the production of this novel material is far from simple, despite apparent transparency of manufacturing information given in literature or over the Internet. High significance of know-how in the manufacture of RPC is additionally confirmed by the fact that both RPC bridges built in 2003 in the Far East [7], [8] were realized using patented RPC mixes ordered from the same European producer. The authors of this paper are fully aware that general use of RPC in large span structures can not be achieved without an appropriate investment in know-how. Patenting of significant information related to this production does not favor development of research in this field.

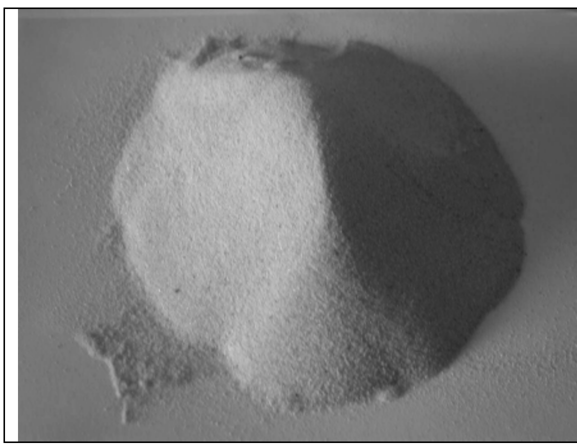


Fig. 6 and Fig. 7 Principal RPC components: quartz sand and steel fibers


Fig. 8 and Fig. 9 Adding RPC components to the mixer (Pojatno, Croatia, May 2003)

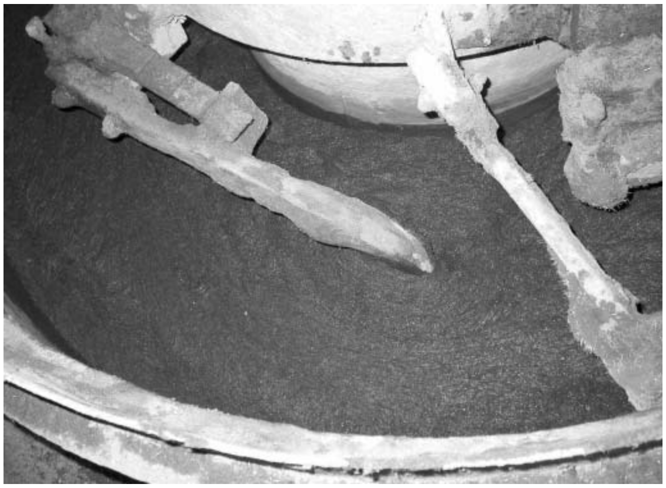


Fig. 10 and Fig. 11 Prepared RPC mix and the process of pouring RPC in the formwork (Pojatno, Croatia, May 2003)


Fig. 12 and Fig. 13 Prestressed RPC beam (Pojatno, Croatia, May, 2003)


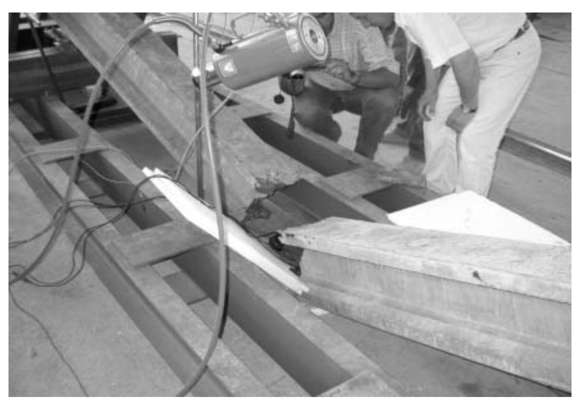

Fig. 14 and Fig. 15 Prestressed RPC beam load testing (Pojatno, May 2003)

STUDY RPC PROPERTIES AND PASS NATIONAL REGULATIONS

RPC is still subject to extensive research and analyses. Unfortunately, discoveries made so far in this research are protected by patent rights which does not facilitate speedy development in this area. In addition, this material is not standardized so that its performances can only be roughly estimated. There are no national regulations with respect to its application, except for instructions for use that have been issued by a French manufacturer. Most development centers are located in Europe and Canada.

All mechanical and physical properties of RPC must be studied with proper care, particularly those that are crucial for the durability of completed structures. Engineers are rightly concerned about future performance of RPC-based structures, i.e. after years of continuous use. There is a fear of subsequent occurrence of unknown deficiencies in this new material, i.e. of defects that have not as yet been sufficiently studied. On the other hand, studies conducted so far with respect to this ultra performance composite [11] show that this material is almost in every respect better than the high performance concrete. One of its shortcomings is its autogenous shrinkage. Hence, an appropriate emphasis should be placed on the study of this phenomenon, and suitable structural measures should be proposed to eliminate undesirable side effects.

In Croatia, it is expected that RPC will mostly be applied on large-span bridges in coastal areas of the Adriatic Sea. Five concrete arch bridges [2] measuring about 200 m in span have been built along the Adriatic coast in Croatia. All these bridges are exposed to sea water salt which reaches the bridge structure through wind action. Due to influence of sea-water salt (chloride), prestressed superstructure components of such bridges are almost always highly affected by aggressive action. It may be expected that ultra high performance concretes, such as RPC, will enable development of advanced solutions for the realization of large span structures that are very durable and capable of withstanding intensive exposure to aggressive environment and influence of salty sea water, and resistant to freezing and thawing cycles.

The following section is consecrated to the analysis of gas permeability and capillary water absorption, during which it was established that porosity and permeability values of RPC are extremely low, which is of course highly significant for its resistance to sea-salt action.

GAS PERMEABILITY AND CAPILLARY WATER ABSORPTION OF RPC

MIX PREPARATION

Five micro-reinforced concrete mixes were analyzed. The first mixture is made of hybrid micro-reinforced concrete with two different fiber types as shown in Table 2 (Type SF1: 40 ± 3 mm with radius 0.5 ± 0.02 mm; Type SF2: 13 ± 2 mm with radius 0.2 ± 0.02 mm; both tensile strength min. 2600 MPa), produced in Belgium, while the remaining four mixtures contain only one fiber type (SF2). A special attention is paid to the compatibility among components, especially between the superplasticiser and cement.

Table 2 Concrete mix compositions used in the preparation of RPC

Mix designation	M1	M2	M3	M4	M5
Steel fibers (kg/m3) SF1 (40/0.5) SF2 (13/0.2)	 76 190	 228	 228	 228	 234
Cement (kg/m3)	720	720	955	720	980
Silica fume (kg/m3)	230	230	239	230	303
Quartz sand 0,125-0,25 0,25-0,5 (kg/m3)	 123 1112	 123 1112	 105 945	 123 1111	 105 965
Superplasticiser (kg/m3)	30	25	35	31	40
water (l/m3)	190	170	215	190	209
Fresh concrete properties Temperature Pores Density Consistency	 24˚C 5% 2,41 kg/m^3 140 mm	 24˚C 5% 2,91 kg/m^3 150 mm	 25˚C 5% 2,35 kg/m^3 250 mm	 24,5˚C 5% 2,36 kg/m^3 190 mm	 26˚C 5% 2,306kg/m^3 220 mm

(The composition is presented by cubic meter of concrete)

Concrete mixes were prepared in laboratory mixers, with the capacity of 10 and 100 liters, depending on the quantity. Steel fibers were added manually throughout the time of concrete preparation because the quantity of fibers was significant, and as "hedges" would have formed if the adding rate were excessive. The order in which components were added, and the mixing time, was defined in accordance with previous research, all in order to obtain good distribution of fibers within the concrete matrix.

Concrete mixes were placed in molds in two layers and vibrated on vibrating table during 40 seconds. After vibration, mixes were wrapped in nylon foil and kept for 5 to 6 hours under laboratory conditions. After 6 hours, samples were taken out of the molds and then exposed to steam heating during 36 hours under next conditions: normal atmospheric pressure and steam temperature around 90°C. After the steam heating, samples were submerged into water for further cure until the age of 28 days was attained.

COMPRESSIVE AND BENDING STRENGTH RESULTS

All five RPC samples were submitted to compressive and bending strength testing (prisms measuring 40 x 40 x 160 mm were used). The measurement was conducted in expert's laboratory in Zagreb, 28 days after concrete preparation. The bending strength was measured first, and then compressive strength, on each half of the sample. Results obtained on four mixes are presented in the following table. Mix M2 obtained unsuccessful results due to incompatible between the superplasticiser and cement.

Table 3 Compressive and bending strength results determined after 28 days on prisms

Mix / Sample	Failure force (kN)	Bending strength (MPa)	Failure force (kN)	Compressive strength (MPa)
M1/1 (623 g)	23,1	54,1	222,0 231,0	138,7 144,4
M1/2 (612 g)	15,8	36,9	282,6 206,0	114,1 128,7
M1/3 (666 g)	21,3	49,8	217,0 209,3	135,6 130,8
M2/1 (627 g)	n/a	n/a	n/a	n/a
M2/2 (628 g)	n/a	n/a	n/a	n/a
M2/3 (626 g)	n/a	n/a	n/a	n/a
M3/1 (619 g)	17,47	40,87	256,4 252,3	160,3 157,7
M3/2 (636 g)	17,63	41,25	248,1 259,6	155,1 162,3
M3/3 (643 g)	19,76	46,23	241,7 235,8	151,1 147,4
M4/1 (631 g)	17,36	40,62	242,5 247,7	151,6 154,8
M4/2 (655 g)	17,38	40,66	254,8 221,7	159,3 138,6
M4/3 (644 g)	20,16	47,17	259,5 245,1	162,2 153,2
M5/1 (627 g)	23,24	54,38	274,7 285,3	171,7 178,3
M5/2 (628 g)	18,75	43,87	279,4 267,5	174,6 167,2
M5/3 (626 g)	20,56	48,11	279,5 291,5	174,6 182,2

Fig. 16 and Fig. 17 View of prisms submitted to testing and prism cross section after failure

GAS PERMEABILITY TEST RESULTS

The gas permeability was tested according to EN 993-4 [12]. The testing was conducted on cylinders 50 mm in height and diameter, which were drilled from the prism measuring 100 x 100 x 500 mm, taken from the mix M1. Drilled cylinders were then cleaned under water jet, and dried in oven at 110°C ± 5°C until the constant weight. After that, cylinders were cooled to room temperature in desiccator and finally polished and coated with epoxy resin.

Fig. 18 Sample coating with epoxy resin

The measurement was performed after accuracy of the gas permeability measuring device was checked and after proper insertion of sample into the sample holder. For each of three tested samples the flow of gas through sample had to be determined at no less than three different changes in pressure (here: 1.0, 1.5 and 2.0 bars). Then the gas permeability coefficient was calculated for each measurement and, at that, 5 percent was the maximum allowable deviation of this coefficient for three different changes in pressure. The mean value of the specific gas permeability coefficient (K) was determined as an arithmetic mean of three samples.

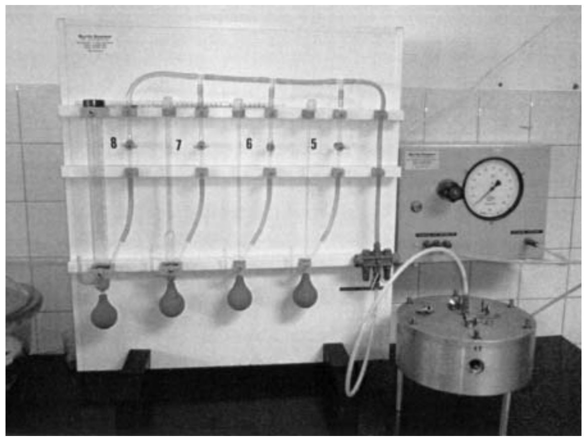

Fig. 19 Gas permeability testing equipment

Gas permeability tests provide a more reliable insight to the opened and connected concrete porosity. For the regular concrete specific gas permeability coefficient (K), depending on the concrete structure, hydration degree and the quality of concrete curing, can vary within limits of 10^{14} do 10^{19} per m^2. Influence of a cement type, water/cement ratio, and, above all, concrete curing on the gas permeability coefficient is indisputable. Badly cured concrete could have up to a 100 times larger gas permeability coefficient, which could result in a reduced construction durability by half [14], [15].

The testing of RPC showed that the bubble on the measuring device does not move at the pressure difference of 3 bars, and so it may be concluded that the sample is gas-impermeable.

CAPILLARY WATER ABSORPTION TEST RESULTS

The water absorption by capillarity was tested at 28 days according to HRN.U.M8.300:1985 [13] at the Faculty of Civil Engineering in Zagreb. Tested samples were 150 mm in diameter and 100 mm in height. Prior to testing, samples were heated in oven at 105°C and were they conditioned for 2 days under laboratory conditions. After that, sample sides were sealed with silicone putty to the height of several centimeters so that only one surface was left exposed to capillary water absorption testing. Once the silicone putty was dry, the initial weight of all samples was registered and samples were submerged in water to the depth of several centimeters only. Samples were then placed into an inclined position to prevent formation of air bubbles.

The water absorption by capillarity was measured in 1, 3, 5, 10, 15 and 30 minute intervals following immersion in water, and then after 1, 2, 3, 4, 5, 6 and 24 hours. After processing of results it was established that all samples show linear dependence between the water absorption by capillarity and the square root of time. The height of water elevation in samples during capillary absorption could not be determined as this height did not exceed the area sealed with silicone putty. Results obtained by determining the coefficient of water absorption by capillarity are presented in Table 4.

Fig. 20 Determination of water absorption by capillarity on concrete samples

Table 4 Results of water absorption by capillarity for RPC

Time	Sample A (kg/m2/s)	Sample B (kg/m2/s)	Sample C (kg/m2/s)
Md	0	0	0
1 min	0,000613	0,000754	0,00066
3 min	0,00029	0,000306	0,000291
5 min	0,00022	0,000212	0,000198
10 min	0,000122	0,000122	0,000117
15 min	0,000089	0,0000896	0,0000864
30 min	0,0000526	0,0000518	0,0000511
1 h	0,0000314	0,0000310	0,0000302
2 h	0,0000182	0,0000181	0,0000176
3 h	0,0000133	0,0000133	0,0000131

4 h	0,0000105	0,0000107	0,0000103
5 h	0,00000888	0,00000888	0,00000864
6 h	0,00000451	0,00000451	0,00000439
24 h	0,00000242	0,00000251	0,00000241

CONCLUSION

Despite its superior mechanical and physical characteristics, RPC has still not established itself as material for the realization of large-span structures. The first reason for this is that engineers are currently neither ready nor properly trained to make use of exceptional performance of the new material. The second reason is that an appropriate "know-how" is needed to actually obtain exceptional results with RPC. Thirdly, there are no national regulations about the use of RPC and, finally, RPC behavior as related to the durability of structures has not as yet been fully investigated.

The research work currently conducted at the Faculty of Civil Engineering in Zagreb offers hope that RPC might soon impose itself as material for the construction of large-span bridges situated in aggressive environments. Results obtained by the study of gas permeability and water absorption by capillarity show that RPC can be ranked among materials ultra-resistant to sea salt action.

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