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Bridge structures cracks – What made that phenomena so common?

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Abstract

The common phenomena – cracks appearance on newly built reinforced concrete bridge structures - is being detected in Poland for several years now. That phenomena is regarded as threatening in case of bridge structures, despite the fact that reinforced concrete theory considers cracks as a standard concrete performance. Cracks are very likely to appear on concrete surface. Cracks are usually detected during concrete surface treatment before protective coating laying. Cracks appear on monolith structures, mainly at the slab spans and foreheads as well as, at support columns in a minor range. Concrete surface cracks openings reach up to 2 mm size. The experience gained throughout consulting works on cracked structures are discussed in that paper. The influence of concrete surface mechanical cleaning prior the protective coatings laying on the crack "visual" intensification was also discussed herein. Crack openings measurement rules, as well as the most common mistakes made during the crack measurements and their real value assessment were described in the paper. The maximal crack opening allowances fluctuations in Polish and European concrete Codes were also discussed here. It was proved that the spotted crack opening increase is caused by the codes changes and by bold reinforcing cover. The bold cover is regarded as the corrosion protection of reinforcing bars. The cover bold and crack opening allowance dependency was discussed in the paper. The effect of Euro codes and the Minister of Transport and Maritime Economy Ordnance from May 30th 2000 titled “Technical requirements for highway engineering structures and their locations” simultaneous obligation on reinforced concrete structures cracks assessment was deliberated.
At the conclusion the necessary modifications in crack assessment practice were claimed. The cracks should be assessed on the basis of homogenous code system. Their openings are dependent straight forward from the reinforcement cover thickness. One should avoid crack measurement at the sections, at which the crack edges are mechanically shattered. The crack opening assessment should be dependent on cover thickness. The rod anti shrinkage activity reaches the cover depth approximately to the depth equal to the rod diameter only. That fact should be taken under consideration during crack assessment.
Keywords: Concrete structures; bridges; cracks

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1. Introduction

More and more problems with reinforced concrete structures are noted in Poland recently. Cracks appear on brand new structures, very often before putting them into service. They appear on all elements made of reinforced concrete, like retaining walls, foreheads and supports as well as on bridge superstructure. These problems are more serious in case of plate girders structures then the beam ones. The cracks are less likely to appear on pre-stressed bridge spans, thus this article will refrain from discussing them.

2. The cause of reinforced concrete cracking

The cracks on reinforced concrete structures appeared from the very beginning of this structure type existence. In general there are two reasons for this phenomena: concrete shrinkage and exceeding the concrete tension strength.

2.1. Shrinkage

Shrinkage is an essential feature of the concrete and it is always present. Its cause is the change in volume of concrete mix, which occur in the processes of hydration of cement and concrete hardening. The hardened concrete has a slightly smaller volume than the freshly laid concrete. Volume changes are not uniform in the chunk of hardening concrete and lead to the formation of internal stresses therein.

There are two ways of shrinkage attitude adopted in the literature. They differ in recognizing reasons and duration of shrinkage phenomena. These are:

- autogenic shrinkage (or chemical one), which is the outcome of volume changes appearing due to chemical reactions occurring during concrete hardening;
- shrinkage caused by concrete drying, which is made by water evaporating from the concrete.

According to the PN-B-0364 code, almost 93% of autogenic shrinkage appears during 180 days of concrete maturing, and shrinkage caused by concrete drying during 360 days (in case of sample section equal to h_0 = 50 mm).

There is a need for introducing supplementary, the third type of shrinkage: that would be early stage concrete shrinkage. As for as now the shrinkage measurement used to be begun after 24 hours from concrete lying. In that case an early stage shrinkage in phenomena assessment was neglected. However even in that stage of hardening some volume changes are present, which cause tension stresses. And in case of the fresh concrete its tension strength is close zero. Even in that stage some cracks, not visible with naked eye, may appear.

The shrinkage is not a phenomenon extending always in the identical and uniformed way. The following factors have a significant impact on its development in time and the size of boundary shrinkage deformation:

- air humidity and the environmental temperature during concrete hardening;
- the concrete mix composition;
  - the type of cement and cement class;
  - cement/water ratio;
  - clastic stock of sand and coarse aggregate;
  - workability and consistency of the concrete mix;
- concrete maintenance;
- concrete exposition class – to design concrete against the aggressive environment influence;
- anti-shrinkage reinforcement.

2.1.1. Air humidity and the environmental temperature during concrete hardening

Low air humidity (below 50%) ease, and high one (over 80%) hampers water evaporating from the concrete. The temperature acts just the other way round. High temperature ease water evaporating, while the low one lowers it. The shrinkage arises, while the temperature and humidity conditions favour water evaporation. According to the PN-B-0364 code shrinkage volume is 80% bigger in presence of 50% air humidity then in 80% one.

2.1.2. Concrete mix composition

Concrete mix composition is a very general concept and covers many factors, for example the type of cement and cement class applied, water/cement ratio, aggregate grade, clastic stock screen curve for fine (sand) and coarse aggregates, admixtures and additives for concrete applied, concrete aeration, the consistency of the concrete mix. The most important factors will be discussed below.

2.1.2.1. The type of cement and cement class

According to the Polish regulations, which were issued by General Directorate of National Road and Motorways, bridge concrete should be prepared with the use of Portland cement. Portland cement has a high heat of hydration. High heat of hydration in case of concrete elements, imposes high temperature gradients between element surface and the inside part, and consequently high internal stresses. And these internal stresses enforce creation of cracks. The cements with low heat of hydration could be a remedy for this undesirable phenomena. The requirement that the cement strength class was not lower than the designed class of concrete leads to increased concentrations of fine particles of cement in concrete and increase its water greediness, which is an issue backing to shrinkage increase of the concrete.

Concrete of the preferred class can be made with the use of cement strength class lower than the class of the designed concrete. To ensure the workability of the concrete mixture fly ash in an amount up to 15% by weight of cement can be used as the addition to the fines fractions. Such a mixture would reach the required strength later, but it will have reduced tendency to shrinkage.

2.1.2.2. Clastic stock of sand and coarse aggregate

The clastic stock of aggregates should be continuous and it should cover all the fractions. There are aggregates boundary screen curves in codes concerning concrete. However some country's shortage of sand fraction 1/2 mm in excavated sands are observed in practice. These sands are approved in recipes and used for concrete fabrication. The sand fraction shortage must be replaced with any other material to achieve concrete mix workability. Usually this shortage is covered with enlarged portion of cement (roughly 20 kg for concrete cubic meter) and extra water. The concrete mix prepared that way will reveal strong tendency for excessive shrinkage.

2.1.2.3. Workability and consistency of the concrete mix

Concrete mix meant for lying in the formwork should have sufficient workability and consistency. In case of bridge structural elements it should be the thick-plastic consistency K-2 according to PN-B-06250 (corresponding to the S1 class according to PN-EN 206). There is concrete transporting with the use of pump with a 125 mm diameter tube monoculture practice in Poland. This method of concrete lying is suitable for concrete of liquid consistency K-5 according to PN-B-06250 (corresponding to the S3 class according to PN-EN 206).. And that means further increase the content of cement and water in the mixture. The administrative rules limit the value of the water/cement ratio to 0.45, but due to the addition of superplasticizers mixture becomes fluid. Growing content of cement and water in the concrete mix leads to shrinkage intensification.

2.1.3 Fresh concrete curing

Fresh concrete curing is to prevent freshly laid and hardening concrete from excessive water loss caused by evaporating. The excessive water loss increases concrete shrinkage and allows for numerous pores creation.

2.1.4 Concrete exposition class

The PN-EN 206 code demands that corrosive influence of the environment, in which the concrete structure will be placed, should be considered. This code defines such called classes of expositions, based on the environment conditions in which the concrete structure will be presented. The XF4 class, which is the highly moisture environment with de-icing salts or sea water present, is the most suitable case for bridge structures. Some examples of XF4 class are:

- Road and bridge pavements are exposed for de-icing agents during winter period.
- Concrete surfaces directly exposed to aerosols containing de-icing agents and freezing.

According to the Polish regulations the concrete intended for use in class XF4 environment should meet the following requirements:

- Water/concrete ratio not bigger then;
- Cement content in the concrete mix should be not less than 340 kg/m^3 [5];
- Concrete class not lower then C 30/37;
- Cement class not lower than the concrete class.

The supportive achievement of these rules leads to the necessity of designing concrete mix having a cement content of more than 340 kg / m^3 to assure providing material with the use of pump armed with a ø 125 mm tube. Such concrete mixes are susceptible to shrinkage increase.

2.1.5 Anti-shrinkage reinforcement

There is an anti-shrinkage reinforcement built into the structure in order to reduce shrinkage. The minimal anti-shrinkage reinforcement section in case of stressed elements is 0,15% at $\lambda \leq 25$, 0,20 % for $25 < \lambda \leq 50$ and 0,25% for $\lambda > 50$, where λ is a n element slenderness, according to PN-91/S-10042 code. It is assumed that shrinkage stresses are carried by the reinforcement in case of stressed elements. However the tension stresses in concrete are verified to avoid cracking.

3. Crack width measurement

The crack width measurement is a difficult task, as on majority of bridge structures the anticorrosion covers are performed. These coatings are to protect concrete against the access of water and carbon dioxide. This is to avoid damp concrete and its carbonation. The concrete surface should be cleaned of laitance and other contaminants before the anticorrosion coating is applied. That could be done mechanically by grinding, sanding or blast-friction; high pressure water or water with sand. During mechanical cleaning of the concrete surface quite often the crack edges are broken, thus the optically visible crack width, measured at the concrete surface, reaches the value p to 2.5 mm. At first glance it seems that this rift is a threat to the strength and capacity of the structure. Crack width measurements should always be done in locations where cracks have no edges damaged. Measurements could be done with the use of width crack template only. Samples crack widths have black stripes printed on, starting from 0,1 mm up to millimeters.

Table. 1 Results of the crack measurements at the structure # 1.

No	Element	Crack width, [mm] measured					Mean value, [mm]
		1	2	3	4	5	
1	7-8 span	0,3	0,5	0,4	0,4	0,4	0,37
		0,4	0,4	0,3	0,4	0,3	
		0,2	0,4	0,4	0,4	0,4	
2	6-7 span	0,4	0,5	0,5	0,4	0,4	0,44
		0,5	0,3	0,4	0,4	0,5	
		0,5	0,5	0,4	0,4	-	
3	5-6 span	0,4	0,3	0,3	0,3	0,4	0,29
		0,5	0,3	0,4	0,2	0,2	
		0,4	0,4	0,3	0,3	0,2	
		0,3	0,1	0,1	-	-	
4	Cantilever at support 5 (bottom)	0,2	0,2	-	-	-	0,20
5	slab at support 7	0,3	0,4	0,4	-	-	0,37

	(upper)						
6	1-2 span	0,1	0,1	0,3	0,3	-	0,20

The crack width measured at 7-8, 6-7 spans and over the 7th support exceed allowed values, which are equal to:

- 0,2 mm according to the PN-91/S-10042 code ;
- 0,3 mm according to the PN-EN 1992-1-1 code.

Crack measurements can be performed on cores drilled from a bridge structure with diameters of Ø 100 mm or Ø 150 mm also. Example crack measurements results are summarized in Table 2.

Table 2. Core crack measurements results.

No.	Core number	Core diameter [mm]	Crack width, [mm]			remarks
				Side surface		
			Head surface	in reinforcement cover	at the core depths under the reinforcement	
1	1	150	0,1	-	-	The crack visible in reinforcement cover
2	3	150	0,1	0,1	0,1	The crack visible along the core
3	6	100	0,2	0,2	0,1	The crack visible along the core
4	7	150	0,2	0,1	capillary crack < 0,05	The crack visible along the core
5	9	150	0,3	0,1	0,1	The crack visible along the core
6	11	150	0,2	0,1	0,1	The crack visible along the core
7	13	150	0,2	0,2	0,2	The crack visible along the core
	Mean value		**0,19**	**0,13**	**0,12**	

The crack width measured at cores drilled at laboratory are lower then allowed values, which are equal to:

- 0,2 mm according to the PN-91/S-10042 code ;
- 0,3 mm according to the PN-EN 1992-1-1 code.

There were 13 concrete cores made on site No # 1. The samples were used for testing: compressive strength, and static elastic modulus.

The drills were made in a perpendicular direction to the side surface of the plate, at the half of slab thickness. Cracks were observed at 7 cores, wherein at 6 wells cracks were visible at the full length of the core (about 45 cm). Cracks observed at cores reached a depth of approx. 40 cm from the bottom slab surface. That means, that the slab concrete was cracked across the whole tension zone, probably till the cross section neutral axis.

4. Concrete mix shrinkage investigation

IBDiM Concrete Laboratory has performed an experiment in which the concrete plastic shrinkage from the moment of lying was determined. These investigation was regarded as inventive in contrary to the standard method in which:

Standard – the method using AMSLER appliance the zero reading is made after 24 hours on the 100x100x500 mm beam,

The plastics shrinkage from drying during first 24 hours is neglected.

The concrete mix was placed in 4 gutters, 100 mm wide and 1000 mm long each, on a polyethylene film layer. The locks with sensors recording the displacement with 0,001 mm accuracy were provided then. Two samples were protected from drying with concrete curing surface agent, and two other were left untreated. The samples were not conditioned before the experiment. The investigation was begun just after the sample was laid in a formwork.

From the zero time up to 168 hours linear changes of samples were recoded. Shrinkage test results are shown in Figure 1.

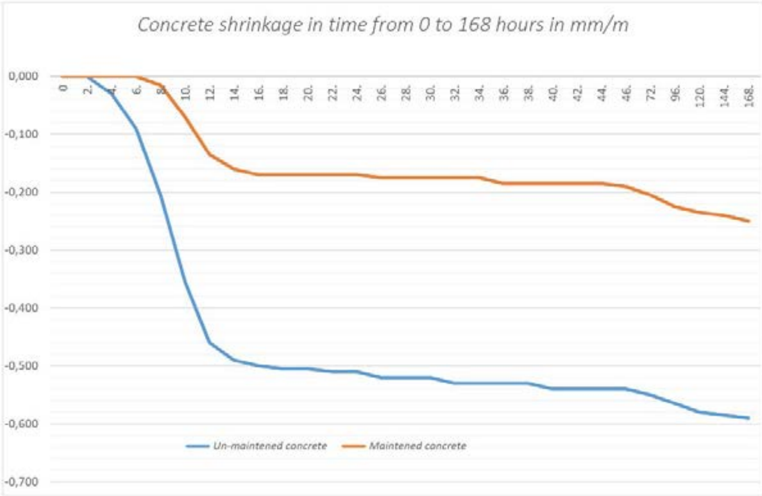

Fig. 1. Cured and not cured concrete shrinkage comparison.

The first change in length of the samples were observed after 3 hours in case of unprotected concrete and after 7 hours in the case of cured one. The biggest dynamic in linear changes was observed within a period of 7 to 14 hours from sample forming. The uncovered concrete has shown linear changes within this period up to 0.500 mm/m, while the protected one up to 0.165 mm/m. After 24 hours the unprotected concrete shrinkage value reached 0.510 mm/m, and the protected one - 0.170 mm/m. After 168 hours of maturing the protected concrete shrinkage gained 0.250 mm/m and unprotected one has reached the maximum allowable limit 0.590 mm/m. Immediate treatment of the fresh concrete, which means cutting off the possibility of water evaporation from concrete, is of the primary importance for concrete linear change. It must be stresses that in this initial phase concrete has negligible strength, what deprives it from the possibility to interact with anti-shrinkage reinforcement. Uncured concrete in the first 12 hours from forming has over 3 times greater plastic shrinkage than concrete which experienced maintenance. Standard concrete shrinkage tested at AMSLER appliance reaches approx. 0.35 - 0.40 mm after 90 days of hardening, which meets the requirement for a bridge concrete (0.6 mm/m). However, if the value of 0.4 mm gained after 24 hours will be enriched with the value received during the experiment, the total shrinkage value will be 0.57 mm/m in case of concrete cured in the first 24 hours, and 0.91 mm/m in case of uncured one.

The experiment has confirmed the importance of concrete curing, which consists in protecting concrete from early evaporation of water, on concrete shrinkage and shrinkage cracks. Minor faults in concrete maintenance during the initial period of hardening must result in an prompt concrete cracking.

5. The analysis of code regulations changes in the field of concrete cover thickness and allowed crack width

Together with the concrete structure applying the rules concerning minimal reinforcement cover were introduced. The reinforcement cover has to protect steel reinforcement against destroying influence of the environment. The protection is provided by a combination of two cover operating functions:

- protection coating: concrete cover has a certain thickness and forms protective layer preventing reinforcement from direct exposure to environmental factors;
- passivation protection: concrete is an alkaline, and in the pH ≥ 9 environment the steel does not corrode.

Table 3, as well as figures 2 and 3, summarize the results of the code changes analysis in terms of required concrete cover thickness of and the allowable crack width, given in mentioned codes.

Table 3. Results of the code changes analysis

No	Code number	Minimal cover thickness, [mm]	Cover measurement	Allowable crack

		Beam case		Slab case	reference point	width [mm]	Year of the code issue
		Beam side	Beam bottom				
1	PN-58/B-03261	25	30	15 (25 slabs exposed to the smoke treatment)	Main reinforcement edge	Not specified	1958
2	PN-91/S-10042	30	30	30	Main reinforcement edge	0,2	1991
		25	25	25	Stirrup or secondary reinforcement edge		
3	PN-B-03264:2002	40	40	40	Stirrup or secondary reinforcement edge	0,2	2002
4	PN-EN 1992-1-1: 2008	40	40	40	Stirrup or secondary reinforcement edge	0,3	2008

Fig. 2 shows recommendations for setting concrete cover and reinforcing rods spacing in bridge beams in accordance to the PN-58/B-03261 code, and Fig. 3 - according to the PN-91/S-10042 code. General guidelines for the preparation of your text.

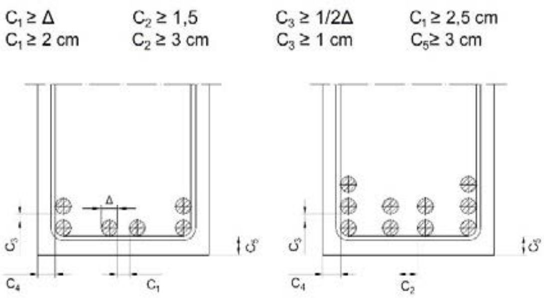

Fig. 2. Recommendations for setting concrete cover and reinforcing rods spacing in bridge beams in accordance to the PN-58/B-03261 code.

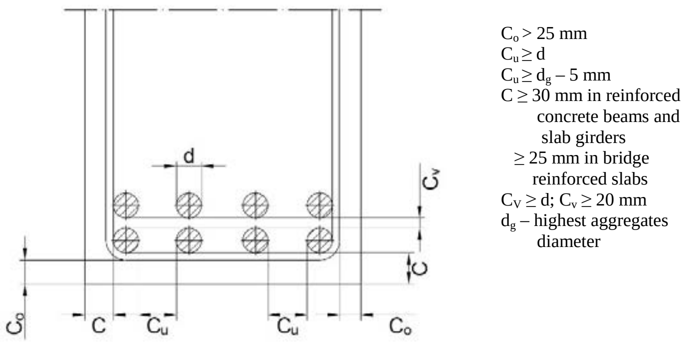

Fig. 3. Recommendations for setting concrete cover and reinforcing rods spacing in bridge beams in accordance to the PN-91/S-10042 code.

The analysis of the code rule changes proves that the advised cover thickness increases. The allowable crack width growths as well.

6. Slab reinforcement rules changes

Up to the 70s of the 20th century, there was a rule, that slab reinforcement should be arranged in such a way as to employ the maximum possible internal forces arm during designing reinforced concrete bended sections. The main slab reinforcement was placed as close as possible to the concrete edge and secondary reinforcement was laid over the main one. Recommended then slab reinforcing rule is shown at Fig. 4.

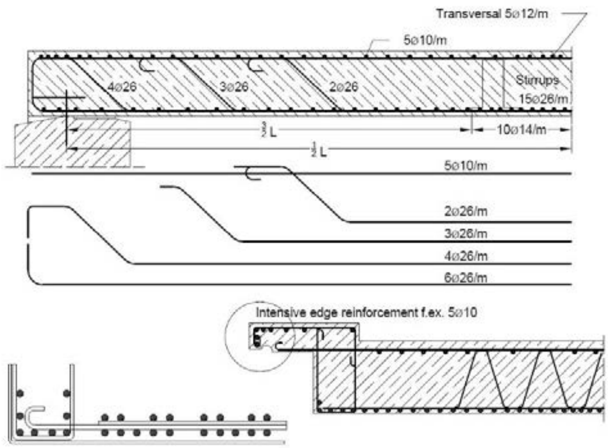

Fig. 4. Recommended slab reinforcing rule according to Szczygieł (1978) [Szczygieł].

At the end of the 70s (20th century) transformed slab reinforcing rules were introduced. Secondary reinforcement was treated as the equivalent to beam stirrups and the main reinforcement was placed on the secondary reinforcement. A new mode of slab reinforcing rule is shown at Fig 5.

The below described change in slab reinforcement rules meant that the actual main reinforcement concrete cover thickness, measured between the concrete surface and the main reinforcement rod edge increased by the thickness of secondary reinforcement rod. As the secondary reinforcing bars diameter are usually much smaller than the diameter of the main reinforcement rods, a new way of slab reinforcement led to the situation that actual cover thickness was increased with approx. 20 mm. That is about the half the cover thickness recommended by the standards. Problems related to cracks in bridge structures made of reinforced concrete have increased exponentially.

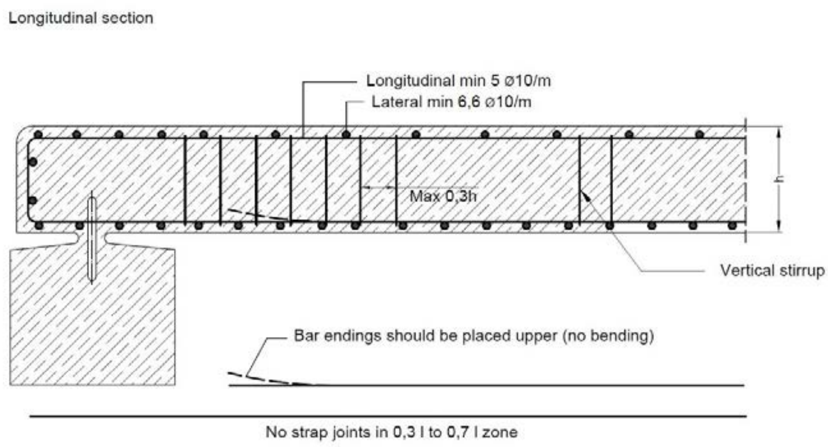

Fig. 5. Recommended slab reinforcing rule according Leonhardt (1982) [Leonhard]

7. Cracks appearance in relation to the structural requirements in reinforced concrete bridge structures

The above analysis shows that the problems related to the reinforced concrete bridge cracks result directly from changes in legislation and design rules, as they lead to excessive thickening of the concrete cover. The rod anti-shrinkage influence extending into the concrete to a depth approximately equal to the diameter of the rod. The cover laying farther away may be cracked. The code (Eurocodes) authors sanctioned this fact by introducing rules on allowable maximum opening of cracks.

At a time when the first standards were established, the reinforced concrete cover thickness was set in case of the beams as 25 or 30 mm (approx. 1 inch), and in case of slabs as 15 mm (approx. ½ inch). It was established in connection with the diameters of the slabs and beams main reinforcement, which were taken approx. 25 ÷ 40 mm in beams and 16 ÷ 32 mm in slabs. The main reinforcement bars acted as anti-shrinkage reinforcement and cracks appearance was not a major problem.

Problems with producing properly sealed concrete and problems with proper concrete compaction in a heavily-armed bridge cross sections led to the slab and beams edges corrosion damage. The tendency for concrete cover expanding in codes and structural designing rules were observed. It was unfortunately forgotten that bridge reinforced concrete structures are large in dimensions and that concrete is the material, which shrink during the process of hardening. Extending of cover meant that at the reinforced concrete structure surface a relatively thick layer of concrete appeared. In case of beams it reaches approx. 45 mm thickness, and in case of slabs - up to 55 to 60 mm. This extra layer is not anti-shrinkage reinforced. There are recommendations, in some publications, to additionally reinforce the cover with anti-shrinkage thin rods. Extra rods of anti-shrinkage reinforcement should be built in at middle of the cover depth. Nobody gave clues however which way construct such reinforcement, and how to ensure the stability of the spatial grid of heavy main reinforcement inserted into a light mesh of anti-shrinkage reinforcement. There are significant forces acting on reinforcement during the pouring of concrete and its compaction (vibration). The authors have never met practical solution of additional anti-shrinkage reinforcement of the cover.

The only solution is to return to the cover thickness that applied up to the 70s. There should be also the recommendation introduced that the cover thickness should not exceed 150% of the diameter of the main reinforcement bars. Only proper concrete with proven good freeze resistance and properly aerated one should be applied for bridge structures. Tight, but not aerated concrete shows sample damage during freeze resistance investigation. That damage do not transfer straight forward onto concrete damage in structures. The problem needs further detailed research.

The recommendations of the General Directorate for National Roads and Motorways (GDDKiA) in Poland decide that bridge structures should be made of concrete that meets the following requirements:

- concrete class C25/30 according to the PN-EN 206,
- absorbability according to the PN-88/B-06250,
- freeze resistance F150 according to the PN-88/B-06250,
- water tightness W8 according to the PN-88/B-06250,

which cause that class C25/30 concrete can hardly meet the above given requirements as they are incoherent:

- the concrete with 4% absorbability and freeze resistance F150 has C45/55 class;
- C25/30 class concrete and 4% absorbability does not meet the freeze resistance criteria;
- C25/30 class concrete and freeze resistance F150 has about 6,5% absorbability .

In practice the reinforced concrete structures are designed as exactly C25/30 concrete structures. C40/50 or C45/55 class concretes are produced in built in to meet above mentioned criteria in regard of absorbability and freeze resistance.

Introduction the recommendations to the GDDKiA provisions, that bridge structures should be designed with C45/55 class concrete would restore the consistency of the technological requirements in relation to the concrete and would ease structure designing process and reinforcement assembly. Employment of minimum C40/50 class concrete would increase corrosion resistance and durability of concrete structures.

8. Summary and Conclusions

The cracks in reinforced concrete bridge structures are the common phenomena. The main reason for the cracks presence are the new standard requirements concerning the concrete cover introduced recently. The cover thickness recommended in the standards exceed the reinforcement anti-shrinkage possibilities.

The return to the thickness of concrete cover advised until the 70s is essential. The recommended slab cover thickness was 25 mm and 30 m for beams. The 70s’ reinforcing rules should be reinstated, as well as the rule that slab main reinforcement is placed under the secondary one should be compulsory.

There is no choice otherwise, but to refrain from the building small and medium-sized span reinforced concrete bridges as “in situ” in favour to pre-stressed structures only. Pre-stressing effectively prevents structure cracking.

References

Klemczak Barbara, Knoppik-Wróbel Agnieszka, Specification and causes of early thermal-shrinkage cracks appearance in concrete structures, Building Review n^{o} 2/2012, pages 28-36

Leonhard Fritz, Basis of Concrete Bridges Building, Transport and Communication, Warsaw 1982

Szczygieł Juliusz, Reinforced and pre-stressed concrete bridge structures, Transport and Communication Publishers, Warsaw 1978

Bajorek Grzegorz et all, Concrete – Specification, performance, production and conformity. Improved PN-EN 206:2014-04 Code Handbook , SPTB, Polish Association of Ready Mixed Concrete Producers, Cracow 2014

The concrete according to PN-EN 206:2014 Code, The information from Research and Product Development of the Management Board Proxy. Górażdże Group, Heideleberg Cement Group

PN-58/B-03261 Concrete and reinforced concrete bridge structures. Static calculations and designing

PN-88/B-06250 Normal concrete

PN-B-03264:2002 Concrete, Reinforced concrete and pre-stressed structures. Static calculations and designing

PN-EN 206:2014-04 Concrete – Specification, performance, production and conformity

PN-91/S-10042 – Bridges. Concrete, Reinforced concrete and pre-stressed structures. Designing.

PN-EN 1992-1-1:2008 Eurocode 2 Design of concrete structures - Part 1-1: General rules and rules for buildings, Fachinger, J., 2006.

Requirements and guidelines on fabricating concrete for bridge structures, General Directorate of National Road and Motorways, Warsaw 1990