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STATE-OF-ART REVIEW OF SHRINKAGE EFFECT ON CRACKING AND DEFORMATIONS OF CONCRETE BRIDGE ELEMENTS

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Abstract. Present state-of-art review deals with concrete shrinkage influence on cracking resistance and deformations of structural elements of concrete bridges. It has been shown that shrinkage deformations are one of major causes of defects in bridge structures in over the world. Various factors that influence the behaviour of the shrunk members have been discussed. The paper illustrates behaviour of a restrained member due to shrinkage and accompanying creep. For increasing crack resistance of concrete bridge structures the research recommends using lower cement contents and shrinkage reducing admixtures. Other measures are performing mixtures with slightly higher water/cement ratios, reducing the amount of reinforcing steel in the bridge elements and eliminating structural restraints.

Keywords. Shrinkage, cracking, deformation, bridge, reinforced concrete, creep.

1. Introduction

Civil engineering works, especially bridges, are omnipresent in every society, regardless of culture, religion, geographical location and economical development. They affect human, social, ecological, economical, cultural and aesthetic aspects of societies. Therefore not only a good design and quality construction, but also a durable and safe exploitation of such structures are imperative goals of structural engineering.

Europe has a large capital investment in the road network including bridges, which are the most vulnerable element. Project *BRIME* has been performed in 1998–99 [1]. This project was undertaken by the national highway research laboratories in the United Kingdom, France, Germany, Norway, Slovenia and Spain. It has been reported that in these countries from almost 500,000 highway bridges more than 30 % need to be repaired [1].

In recent years awareness of cracking in bridge decks has been on the increase in the United States. Bridge deck cracking has been recognised as a major and costly problem for highway structures in that it often accelerates corrosion, increases maintenance costs, and shortens the service life of the deck. According to a study conducted by Federal Highway Administration (USA) in 2005, the amount of the nation's 590,750 bridges rated structurally deficient or functionally obsolete was 27,5 % [2]. Following the *ASCE* infrastructure report, it will cost $9,4 billion a year for 20 years to eliminate all bridge deficiencies in the USA [3].

Several factors are known to affect deck cracking including bridge design, concrete mixture design, mixture materials, and placing, finishing and curing practices. It has been shown that the primary source of deck cracking is attributed to a combination of shrinkage and thermal stresses, which are influenced by the mentioned factors [4].

Effects of shrinkage and accompanying creep of concrete along with cracking provide the major concern to the structural designer because of the inaccuracies and unknowns that surround them. In general, these effects are taken into account of long-term deformation and prestress loss analysis of reinforced concrete (RC) structures (for instance, [5–7]). Though considered as long-term effects, shrinkage and creep also have influence on crack resistance and deformations of RC members subjected to short-term loading. Although development and verification of shrinkage models is an important issue, reviewing of such models is out of scope of present paper. Comprehensive investigations on shrinkage models have been reported in [8–11].

Present state-of-art report deals with concrete shrinkage and accompanying creep influence on cracking resistance and deformations of structural elements of concrete bridges. Factors that influence the behaviour of the shrunk members and ways to increase durability of bridge structures are discussed.

2. Basic causes of cracking in traffic RC structures

Mechanical loading, deleterious reactions, and environment loading can result in the development of tensile stresses in concrete. Furthermore, concrete shrink as it dries under ambient conditions. Tensile stresses occur when free shrinkage is restrained. The combination of high tensile stresses with low fracture resistance of concrete often results in cracking.

All concrete structures have micro-cracks in the concrete cover due to shrinkage. Proper curing will limit the extent of these cracks, and the time to corrosion initiation is therefore dependent on the effectiveness of the curing system used. The additional cracking caused by the corrosion reduces the concrete resistance to further contamination and the rate of corrosion can increase significantly [12]. The stresses induced in the concrete by the expansive products arising from the corrosion of reinforcement will ultimately lead to cracking of the cover concrete. This cracking reduces the durability of a structure and it will ultimately lead to the spalling of cover concrete. For bridges, this poses particular problems due to the safety risks resulting from lumps concrete falling onto a live carriageway [1].

In fresh concrete, cracks may be caused by a rapid loss of moisture or by settlement around reinforcing bars [13, 14]. In hardened concrete, cracks form whenever the tensile stress in the concrete exceeds the tensile strength of the concrete. Cracking is a major problem with newly placed concrete decks in the USA [15]. This cracking is caused by several factors. High heat of hydration causes the plastic concrete to expand. When the concrete sets and cools, tensile stresses develop and increase due to drying shrinkage. Restraining the deck against normal thermal movements contributes to additional tensile stress. The bridge decks tend to develop full depth transverse cracks and partial depth longitudinal cracks within a few months of the concrete being placed [16].

A survey of 72 bridges for transverse deck cracking in the Minneapolis/St. Paul was reported by French *et al.* [17]. For steel-concrete composite bridges, end restraint and shrinkage were the most significant factors contributing to deck cracking. Such bridges exhibited more cracking on interior spans than the end ones. It has been observed more cracking in curved bridges compared with straight ones and with increased restraint owing to steel configuration, girder depth, or close girder spacing. Cracking also increases when larger diameter bars are used as transverse reinforcement [17]. Nawy has demonstrated that as spacing is decreased through the use of a larger number of bars, a larger number of narrower cracks are formed [18].

Krauss & Rogalla pointed out that the general chemistry and fineness of cements have changed over time [16]. The end result is that today's concretes made with to modern cements, gain strength more rapidly than the previous ones. As a result, modern concretes with a high early compressive strength and modulus of elasticity have an increased risk of cracking because of the higher stresses that develop as a result of early shrinkage and thermal strains. So, in 1974, bridge deck cracking in Virginia reportedly increased when the strength requirement was raised from 20,7 to 27,6 MPa. Similarly, a 1995 report on the condition of 29 bridges in Kansas stated that there was twice as much cracking with 44 MPa concrete than with 31 MPa concrete [16]. In 1997, the high performance concrete (HPC) deck in the Louetta Overpass (Texas) cracked more than the ordinary concrete deck in the adjoining lane. The high-strength concrete (HSC) viaduct in Denver cracked before construction was finished [19]. In 2001, after the construction of the Big-I (segmental multi-bridge structure in the state of New Mexico) a large number of shrinkage cracks were observed in 18 of the 56 newly constructed bridge decks. This unexpected problem cost approx $250,000 per bridge to mediate [20].

Investigation into causes of cracking in transport structures (namely bridge structures, pavements, and footings) has been presented in the circular performed by Transportation Research Board [21]. Table 1 provides a classification of cracks due to environmental conditions, and discusses when they are most likely to occur.

3. Factors affecting shrinkage of concrete

Four main types of shrinkage associated with concrete are plastic shrinkage, autogenous shrinkage, carbonation shrinkage, and drying shrinkage. Plastic shrinkage is associated with moisture loss from freshly poured concrete into the environment. Autogenous shrinkage is the early shrinkage of concrete caused by loss of water from capillary pores due to the hydration of cementitious materials, without loss of water into the surrounding environment. This type of shrinkage tends to increase at lower water to cementitious materials ratio and at a higher cement content of a concrete mixture. Autogenous shrinkage occurs primarily as a result of chemical shrinkage (ie volume reduction due to the hydration reaction) and self-desiccation (ie the internal consumption of water by the hydration reaction) in concretes made with significant lower water demands ($0{,}2 < W/C < 0{,}42$). Carbonation shrinkage is caused by the chemical reactions of various cement hydration products with carbon dioxide present in the air. Drying shrinkage can be defined as the volumetric change due to the hardened concrete drying. This type of shrinkage is caused by the diffusion of water from hardened concrete into the environment. Drying shrinkage is a volumetric change caused by the movement and the loss of water squeezing out from the capillary pores resulting in the development of tensile stresses since the internal humidity attempts to make uniform with a lower environmental humidity. The above shrinkage is the most significant in thinner structures (with a large surface area to volume ratio) due to the more rapid loss of water. Pavements, bridge decks, and slabs are examples of thin structures that may be susceptible to cracking induced by drying [4].

In general case shrinkage consists of two major components: drying and autogenous shrinkage. Although autogeneous shrinkage was described as early as 1930's [22], it did not pose significant problems in construction until recently since a high W/C was typically required to maintain sufficient workability.

The ratio of autogeneous and drying shrinkage in total shrinkage of concrete is schematically illustrated in Fig 1. In the case of ordinary concrete, it is not a problem if shrinkage is treated without distinguishing between autogeneous and drying shrinkage because the ratio of autogeneous shrinkage to total shrinkage is not large in such concrete. On the other hand, in the case of HSC, autogeneous and drying shrinkage should be distinguished because the ratio of these shrinkages to total shrinkage varies with respect to age when concrete is exposed to drying conditions [23].

One of most substantial factors influencing free shrinkage is the water-to-cement ratio (W/C). The W/C required for complete hydration is typically assumed to be approx 0,42 depending on the amount of gel porosity that is assumed. For high W/C ratios resulted in autogenous shrinkage strains between 20 and 110 micro-strains. This is only 10 to 20 % of the long-term shrinkage [20]. Consequently, autogenous shrinkage was neglected for many years.

Weather plays a major role in concrete shrinkage. Environmental conditions such as extreme (high or low) ambient temperatures, low relative humidity, high wind speed and solar radiation can induce shrinkage unless the concrete is protected from these factors. It has been reported [24] that the shrinkage of investigated bridge structures decreases over winter months and then rises to a maximum during summer months, the concrete actually gains back a portion of the initial shrinkage when rain water or melted snow permeates into the structure.

The magnitude of shrinkage deformations depends on concrete mixture proportions and material properties, method of curing, ambient temperature, humidity condi-

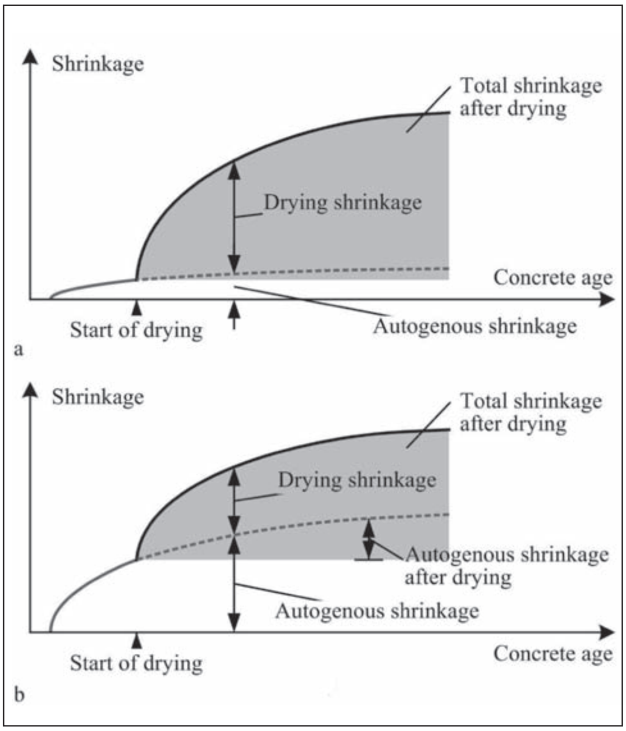

Fig 1. Shrinkage strain components in normal (a) and high-strength (b) concrete [23]

Table 1. Classification of cracks [21]

Type of cracking	Form of cracks	Primary cause	Time of appearance
Plastic settlement	Over and aligned with reinforcement	Poor mixture design leading to excessive blending, excessive vibrations	10 min to 3 h
Plastic shrinkage	Diagonal or random	Excessive early evaporation	30 min to 6 h
Thermal expansion and contraction	Transverse	Excessive heart generation, excessive temperature gradients	1 day to 2–3 week
Drying shrinkage	Transverse, pattern or map cracking	Excessive mixture water, inefficient joint, large joint spacing	A week to months
Freezing and thawing	Parallel to the surface of concrete	Lack of proper air-void system, non durable coarse aggregate	After one or more winters
Corrosion of reinforcement	Over reinforcement	Inadequate cover, ingress of sufficient chloride	More than after 2 years
Alkali-aggregate reaction	Pattern and longitudinal cracks parallel to the least restrained side	Reactive aggregate plus alkali hydroxides plus moisture	Typically more than 5 years, but weeks with a highly reactive material
Sulphate attack	Pattern	Internal or external sulphates promoting the formation of ettringite	1 to 5 years

tions, and geometry of the concrete element. Tremper has pointed next factors of the overall shrinkage of concrete [25]:

- Characteristics of the cement. The proportion of gypsum added to the clinker during grinding has a large effect on shrinkage.
- Clay-like particles and coating of aggregates increase the drying shrinkage.
- Aggregates, even though clean, vary in their contribution to drying shrinkage. Aggregates of high absorption tend to produce a greater shrinkage.
- There is a general relationship between drying shrinkage and unit water content. This statement is compatible with that restraint to shrinkage is proportional to the absolute volume of aggregate. Aggregates of smaller maximum size require more mixing water and hence produce more shrinkage.
- Higher slump requires more water and produces a greater shrinkage.
- The higher the temperature of concrete at the time of mixing, the greater the quantity of water required to produce a given slump.
- Concrete that is held in a transit mixer with the drum rotating beyond 70 revolutions, the minimum required to produce thorough mixing, requires more mixing water because of the formation of dust of abrasion and the absorption of heat of work.
- Admixtures have effects on shrinkage varying from none to a substantial amount. Water-reducing retarders that have been compounded to destroy the retarding effect, as a class, appear to produce the greatest increase in drying shrinkage.

If concrete made with the best materials, proportioned for best results, mixed and placed under optimum conditions is assigned a rating of 100, departures from such conditions can have a cumulative effect as illustrated by Table 2 [25].

Table 3 presents the dependence of the composition of volume changes that occur in hardening cement paste on W/C ratio. Table 3 shows that the final volume of C-S-H gel does not depend so much on the initial water-cement ratio. With the same amount of viscous components, the remarkable difference in creep and shrinkage behaviour between UHPC and ordinary concrete is certainly a key point for understanding the origin of creep and shrinkage [26].

Modulus of elasticity of aggregate directly influences drying shrinkage of concrete. Troxell *et al.* [27] reported that the drying shrinkage of concrete increased 2,5 times when an aggregate with a high elastic modulus was substituted by an aggregate with a low elastic modulus. Lura *et al.* [28] reported that concrete with lightweight aggregates (LWA) showed low drying shrinkage at the initial age, but at later ages the rate of shrinkage was higher compared with normal weight aggregate concrete due to lower modulus of elasticity of LWA offering a less resistance to the shrinkage of the cement paste. Matsushita & Tsuruta [29] reported effects of the type of coarse aggregate on autogeneous shrinkage of concrete. It was concluded that if the volume of coarse aggregate was maintained constant, the type of coarse aggregate negligibly affected the autogeneous shrinkage of HSC.

4. Influence of shrinkage on deformations of concrete structures

Strains and deflections in concrete bridges usually increase with time over the entire life span of the bridge, although in a decreasing rate. The physical mechanisms responsible for the time dependent deformation increase in concrete are creep and shrinkage, where the former is stress dependent and the latter is stress independent. In prestressed bridges, this trend is accelerated due to stress relaxation in tendons. If the bearing structure is statically indeterminate, this phenomenon is accompanied by redistribution in internal forces along the bridge in order to match restrained boundary conditions at the supports.

The term free shrinkage is commonly used for the contraction of hardened concrete exposed to air, with a relative humidity less than 100 %. Free shrinkage develops gradually with time; the word free refers to the case of a member that can shorten without restraint, thus producing no stresses.

Table 2. Main factors causing drying shrinkage of concrete [25]

Cumulative multipliers	Cause for increasing of shrinkage
100 × 1,25 = 125	Due to choice of cement
125 × 1,25 = 157	Due to excessive clay in aggregates
157 × 1,25 = 235	Due to use of aggregates of poor inherent quality with respect to shrinkage
235 × 1,25 = 306	Due to use of 19 mm max aggregate where 38 mm could have been used
306 × 1,25 = 336	Due to use of 150–180 mm slump where 75–100 mm slump could have been use
336 × 1,25 = 350	Due to allowing temperature of concrete to reach 27 °C during mixing, whereas with reasonable precautions, a temperature of 16 °C could have been maintained
350 × 1,25 = 385	Due to too long a haul in a transit mixer, or too long a waiting period at the job-side before discharge, or to too many revolutions at mixing speed
385 × 1,25 = 500	Due to poor choice of an admixture

Table 3. Approx estimation of the relative volume changes in cement paste with different values of initial W/C ratio [26]

Index	Parameter	Operation	UHPC	VHPC	HSC			Ordinary concrete		
A	Water-to-cement (W/C) ratio	A	0,20	0,25	0,30	0,35	0,40	0,45	0,50	0,60
B	Fraction of unreacted cement	B	0,53	0,42	0,31	0,20	0,10	0,10	0,10	0,10
C	Water-to-cement volume ratio	A×3,15	0,63	0,79	0,95	1,10	1,26	1,42	1,58	1,89
D	Initial cement volume ratio	$(C+1)^{-1}$	0,61	0,56	0,51	0,48	0,44	0,41	0,39	0,35
E	Initial water content	C×D	0,39	0,44	0,49	0,52	0,56	0,59	0,61	0,65
F	Solid increment to percolation	0,65–D	0,04	0,09	0,14	0,17	0,21	0,24	0,26	0,30
G	Consumed cement at percolation	F/1,16	0,03	0,08	0,12	0,15	0,18	0,20	0,23	0,26
H	Le Chatelier's (free) contraction	G×0,18	0,01	0,01	0,02	0,03	0,03	0,04	0,04	0,05
J	Final volume of unreacted cement	B×D	0,33	0,23	0,16	0,10	0,04	0,04	0,04	0,03
K	Total consumed cement	D–J	0,29	0,32	0,35	0,38	0,40	0,37	0,35	0,31
L	Consumed water	K×1,34	0,39	0,43	0,48	0,51	0,53	0,50	0,47	0,42
M	Final volume of C-S-H	K×2,16	0,62	0,70	0,77	0,82	0,86	0,80	0,75	0,67
N	Final solid volume	J+M	0,95	0,94	0,93	0,92	0,90	0,85	0,79	0,71
P	Final free water volume	E – L	0,00	0,01	0,01	0,01	0,02	0,09	0,14	0,24
R	Final gas volume	I–N–P–H	0,05	0,04	0,04	0,04	0,04	0,03	0,02	0,01
S	Final capillary volume	R+P	0,05	0,05	0,05	0,06	0,06	0,12	0,17	0,25
T	Final C-S-H pore volume	M×0,28	0,17	0,20	0,21	0,23	0,24	0,23	0,21	0,19
U	Final porosity	T+S	0,22	0,25	0,27	0,29	0,30	0,34	0,38	0,43
V	Saturation ratio of capillary pores	P/S	0,00	0,11	0,20	0,26	0,38	0,74	0,87	0,96

Typically, for ordinary concrete about 40 and 90 % of the ultimate shrinkage will have occurred after 1 and 12 months, respectively. For better understand how volumetric changes of hardened concrete can result in cracking, Fig 2a compares the time dependent strength (cracking resistance) development with the time dependent residual stresses that develop. If strength and residual stress development are plotted as shown in Fig 2a, it is likely that the specimen will crack when these two lines intersect. Similarly, it follows that if strength of the concrete is always greater than the developed stresses, no cracking will occur.

The residual stress that develops in concrete as a result of restraint may sometimes be difficult to quantify. This residual stress cannot be computed directly by multiplying the free shrinkage strain by the elastic modulus (ie *Hooke's law*), since stress relaxation occurs. Stress relaxation is similar to creep, however, while creep can be thought of as the time dependent deformation due to sustained load, stress relaxation is a term used to describe the reduction in stress under a constant deformation. This reduction of stress is illustrated in Fig 2b in which a specimen of original length (I) is exposed to drying and a uniform shrinkage strain develops across the section. If the specimen is unrestrained, the applied shrinkage would cause the specimen to undergo a change in length (shrinkage) of ΔL^+ (II). To maintain the condition of perfect restraint (i.e., no length change) a fic-

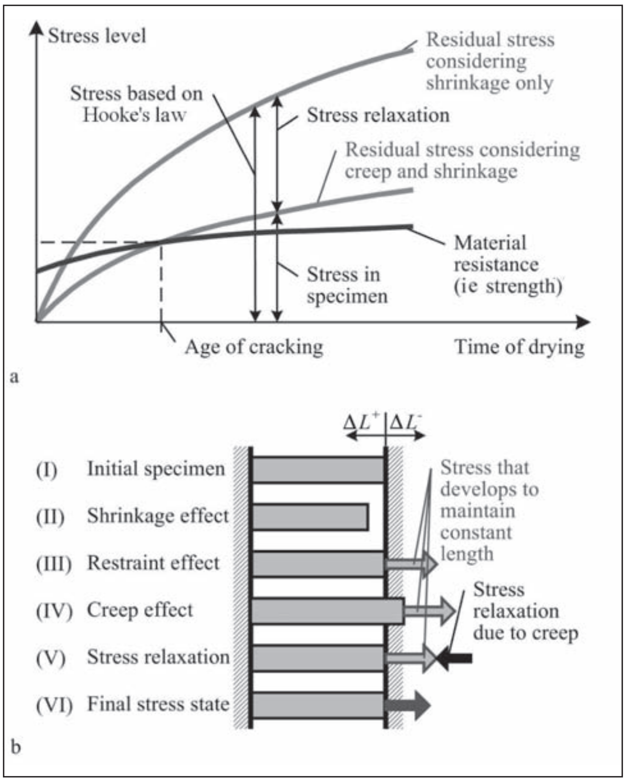

Fig 2. Stresses in a restrained concrete member due to shrinkage and accompanying creep [30]: a) stress development and b) conceptual description of relaxation

titious load can be envisioned to be applied (III). However, it should be noted that if the specimen was free to displace under this fictitious loading the length of the specimen would increase (due to creep) by an amount ΔL^{-} (IV). Again, to maintain perfect restraint (ie no length change) an opposing fictitious stress is applied (V) resulting in an overall reduction in shrinkage stress (VI). This illustrates that creep can play a very significant role in determining the magnitude of stresses that develop at early ages and has been estimated to relax the stresses by 30 to 70 % [30].

Deformational behaviour of plain and RC members due to shrinkage has been analysed under the assumption of uniform distribution of shrinkage strain across the section. As shown in Figs 3a and 3c, shrinkage of an isolated plain concrete member would merely shorten it without causing camber. Reinforcement embedded in a concrete member provides a restraint to shrinkage leading to compressive stresses in reinforcement and tensile stresses in concrete (Figs 3b and 3d). If the reinforcement is not symmetrically placed in a section, shrinkage causes non-uniform stress and strain distribution within the section height (Fig 4). The maximal tensile stresses appear on the extreme concrete fibre, close to larger concentration of reinforcement.

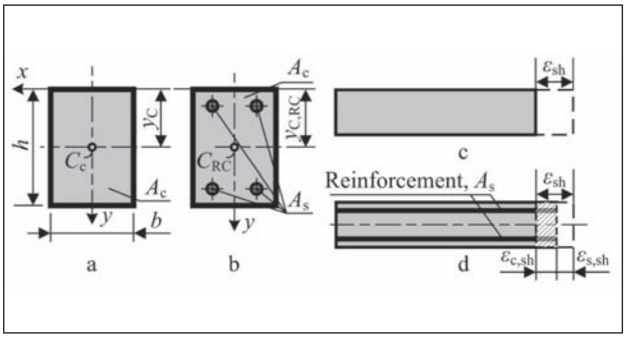

Fig 3. Deformations of concrete and RC member due to shrinkage: a) plain concrete member; b) symmetrically reinforced section; c) free shrinkage deformation; d) deformations in a symmetrically reinforced element due to restrained shrinkage

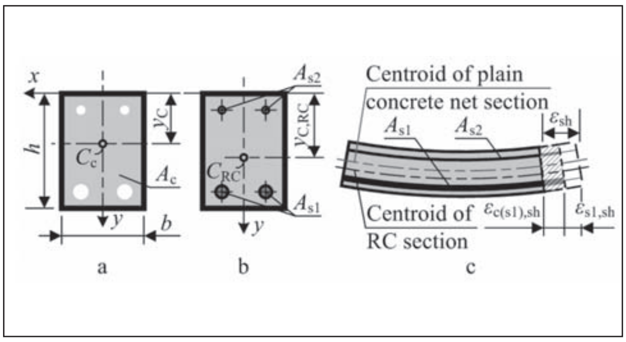

Fig 4. Deformations of asymmetrically RC member due to shrinkage: a) plain concrete net section; b) asymmetrically reinforced section; c) deformations in asymmetrically reinforced element due to restrained shrinkage

5. Experimental and theoretical research of shrinkage effect on behaviour of RC bridge members

Europe. During 1980–90, the Institute of Reinforced and Prestressed Concrete of the Swiss Federal Institute of Technology has performed more than 200 full-scale load tests of bridges. Creep and shrinkage normally occur during the first 5 years of the structure life. However, it has been observed on several occasions that the deformations of post-tensioned concrete bridges have greatly exceeded the calculated values, with increasing deformations during more than 10 years after construction [31]. Comprehensive analysis of deteriorations in roadway members in Vilnius (Lithuania) has been performed by Kamaitis [32, 33]. The variability in creep and shrinkage properties was studied by Santos *et al.* [34] in 4 concrete bridges in Portugal. Creep and shrinkage measurements in the specimens resulted in coefficient of variation as 10–20 % for creep and 10–20 % for shrinkage inside the box-girder and 20–30 % for shrinkage outside the box-girder. Paeglitis & Sahmenko investigated the peculiarities of use of LWA for bridge structures in Latvia [35].

Bosnjak & Kanstad [36] demonstrated the use of advanced numerical techniques for the deformation problem. They calculated the deflections in Mjøsund Bridge in Norway, which has a main span length of 185 m. Deflections in the early part of the construction were observed within ±10 % of the computed values when the MC 90 creep and shrinkage model was used. Lee *et al.* studied the stresses created due to autogeneous shrinkage of HPC [37]. During this research the Finite Element method was used to determine the stresses. It was found that the autogeneous shrinkage of concrete developed at a much higher rate than the tensile strength of concrete. Dias studied the effect of mix constituents, retarding and air entraining admixtures and additives, and environmental factors on plastic shrinkage of concrete [38]. Branch et al conducted research on the factors affecting plastic shrinkage for HPC [39].

According to report [1], cracks due to restrained shrinkage cause 12 % and 10–14 % of deteriorations in bridges structures in France and Germany, respectively; in UK and Norway the shrinkage cracking is one of major causes of the deterioration. In Norway, most defects due to shrinkage occur in bridges having a concrete wearing surface on top of the structural deck [40]. The control of such cracking is the goal of the Norwegian NOR-IPACS project. The project involves determination of the required material properties, temperature and stress calculation programs and field testing on construction sites [41]. Fig 5 shows a principal sketch of the interaction between different project parts.

It has been showed that the autogenous shrinkage contribution may be substantial. This fact is illustrated in Fig 6. It shows that for a given initial temperature the subsequent autogenous shrinkage development at different temperatures may be described using the maturity concept [41].

North America. Cusson & Repette developed a model of early-age performance of reconstructed concrete bridge structures [42]. This model was applied in the numerical investigation [43] of the roles and magnitude of the factors responsible for the observed cracking in HSC barrier walls of the Vachon Bridge (Québec). The computer simulation indicated that 3 series of cracking occurred in the first 3 hours after setting concrete. Stress due to traffic vibration most likely played a role in the initial cracking at this early age. The last series of cracks was estimated to occur at 1,1 days. At this time, thermal stress was found to be the most important cause of cracking, followed by autogenous shrinkage. Drying shrinkage was found to be negligible [43].

Griffin *et al.* [44] tested by deck contraction induced deflection in a HPC bridge. The purpose of the study was to calculate HPC highway bridge deflections due to shrinkage and temperature changes in the deck and to compare with the analytical results obtained from the finite element model of the bridge. The strain measurements in the bridge deck showed significantly larger curvatures and approx 100 micro-strains less compression at the mid-span than predicted by the analytical model. The experimental data suggested that thermal contraction was the primary cause of the additional displacement. Additional displacements were also caused by shrinkage contractions in the deck and the shrinkage deflections were relatively small compared to effects of thermal contractions.

Babaei investigated the method to mitigate transverse cracking in concrete bridge decks [13]. The reasons for the cracking were observed to be the following:

- Plastic settlement cracking. This type of cracking occurs because concrete attempts to settle, but it is restricted from settlement by the reinforcing bars. The factors that affect settlement cracking are slump, bar size and cover depth;
- Thermal shrinkage cracking. The peak temperature of curing concrete is usually reached in about 12 to 18 hours after pouring the deck. At this time concrete starts to harden and cools down and shrinks. The longitudinal steel girders restrain this shrinkage and tensile stresses develop and result in cracking;
- Drying shrinkage. The drying shrinkage cracking occurs after curing. These strains are superimposed on the thermal contraction strains;
- Cracking due to flexure. Cracking of this nature is transverse and it occurs over the internal supports.

Linford & Reaveley provided recommendations to minimise transverse cracking of bridge decks in Utah [45]. It was found that the deck cracking was influenced by the size of concrete placement. The research also discussed the effect of restraint on deck cracking: rigid attachment between the concrete deck and the steel girders leads to transverse and diagonal crack as the concrete shrinks. More recent investigations on various aspects of shrinkage are given in [15].

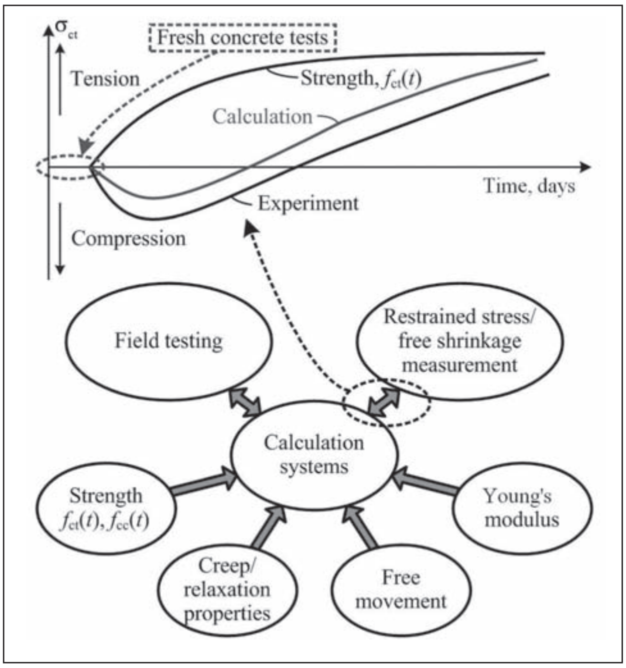

Fig 5. The interaction between the parts of the research on investigating cracking behaviour of bridge structures made from HSC [41]

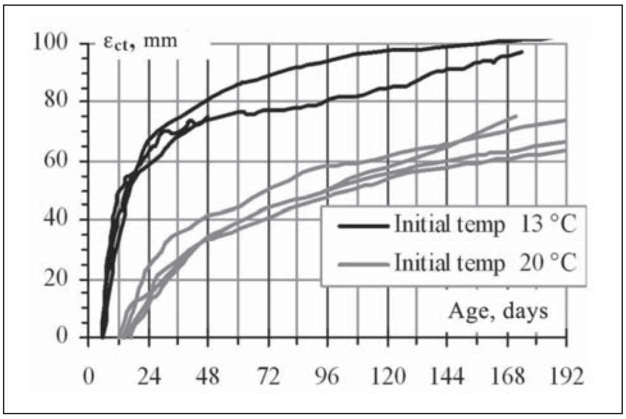

Fig 6. Experimental results reported by Bjøntegaard *et al.* [41]: autogenous shrinkage with two different initial temperatures

Asia. It was reported that bridges in Japan are subjected to illegal overloads that are much greater than design loads [46]. The failure mechanism starts with the formation of transverse cracks from shrinkage and overloads. Similar problem was also found in South Korea. The Korea Institute of Technology reports that cracks in concrete decks occur as a result of drying shrinkage [46]. These cracks further increase as a result of traffic loads and penetrate through the deck thickness. Leaching of the concrete and corrosion of the reinforcement then occur, leading to a punching shear failure. Some decks have failed in this manner.

A comprehensive experimental and theoretical inves-

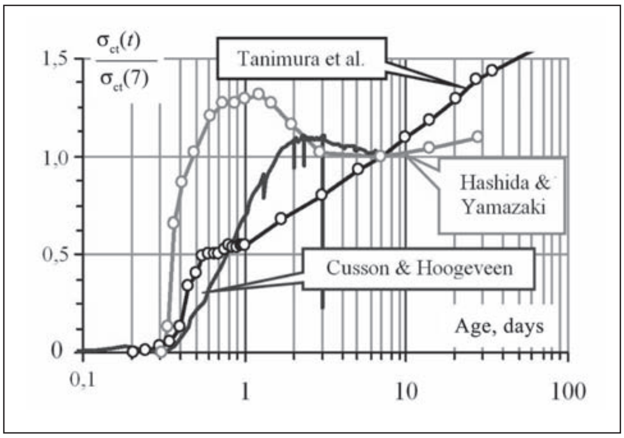

Fig 7. Comparison of autogenous shrinkage induced stresses (normalised to value given at 7th day) in RC given by Tanimura *et al.* [49], Hashida & Yamazaki [50] and Cusson & Hoogeveen [51]

tigation on different types of RC members typical for bridge structures has been carried out by a Japanese research group [47–50]. Tanimura *et al.* [49], Hashida & Yamazaki [50] and Cusson & Hoogeveen [51] measured the stress caused by restraining autogenous shrinkage of concrete. Fig 7 shows the comparison of the restrained stress produced with age after the initial setting of concrete given during these researches. According to Fig 7, the restrained stress begins obviously to be produced at final setting time of about 7 hours. Although the macroscopic volume change of unrestrained concrete begins by the initial setting time, the restrained stress is not generated, which is explained by the stress relaxation due to lower Young's modulus and larger creep deformation of concrete at early age. The difference in stress variation character shown in Fig 7 might be due to different ratio of perimeter and reinforcement percentage of bars p. For the specimens of Tanimura *et al.* [49] this factor was 0,18 (1×∅22,5 mm; $p \approx 4,0$ %), for Hashida & Yamazaki [50] this ratio was 4,56 (12×∅29 mm; $p \approx 2,4$ %) and for the tests of Cusson & Hoogeveen [51] it was 1,57 (4×∅10 mm; $p \approx 0,8$ %).

Investigations by the authors. Similar to the above results were obtained by the authors [52]. The experimental programme consisted of testing 8 lightly reinforced concrete beams having constant reinforcement ratio $p \approx 4,0$ %. The beams 3,0 m in span were tested by short-term loading under a four-point system. The experimental programme comprised two series. In the beams of the first series, the tensile reinforcement consisted of four ∅10 mm bars, whereas the beams of the second series had two ∅14 mm bars. Prior to the beam tests, measurements of concrete shrinkage and creep were performed. In order to exclude shrinkage influence on cracking resistance of the beams, large amounts of top reinforcement were assumed in half of the specimens (second numbers of twins).

Tension stiffening was far more pronounced for the beams of the first series having smaller diameters of tensile reinforcement. These beams at the load corresponding to 50 % of the ultimate bending moment on average had 33 % smaller curvatures than the beams of the second series. The beams having heavy top reinforcement possessed a slightly higher cracking resistance. Two factors may serve as an explanation of this phenomenon: 1) increase of section modulus; 2) difference in tensile stress in the extreme bottom fibre induced by shrinkage.

6. Methods to reduce shrinkage influence on durability of RC structures

Krauss & Rogalla suggested that aggregates with a low modulus of elasticity, low coefficient of thermal expansion, and high thermal conductivity result in reduced shrinkage and thermal stresses. Aggregates with a higher modulus of elasticity increase the modulus of elasticity of the concrete resulting in greater restraint to drying shrinkage and thermal shortening [16]. The following recommendations on incensement of the cracking resistance of bridge structures reported in [15]:

- Reduce cement contents;
- Add retarders (eg fly-ash or slag), which reduce peak temperatures due to heat of hydration;
- Use larger aggregates. Large aggregates decrease cement demand and mitigate drying shrinkage;
- Pay close attention to placement and curing;
- Keep water/cementitious material ratios as high as possible while retaining the required conditions;
- Consider the use of shrinkage reducing admixtures to limit drying shrinkage;
- Consider reducing the amount of reinforcing steel in the bridge deck.

Shrinkage cracks can also be reduced or prevented at the design level by minimising the degree of restraint in the concrete structure and thus reducing tensile stresses in concrete. Examples of mitigation measures include:

- Enhanced curing;
- Smaller spacing of construction joints, smaller spacing of construction joints;
- Saturated LWA, as a partial sand replacement, in order to reduce internal drying by releasing additional water to unhydrated cement particles;
- Reduced exposure to temperature extremes.

Russell provides recommendations on the improvement of bridge deck performance [53]. Practices that can reduce cracking in bridge decks are as follows:

- Minimise potential shrinkage by decreasing the volume of water-cement paste in the concrete mix consistent with achieving other required properties;
- Use the largest practical maximum size aggregate to reduce water content;
- Use minimum transverse bar size and spacing that are practical;

- Avoid high concrete compressive strengths;
- Use windbreaks and fogging equipment, when necessary, to minimise surface evaporation from fresh concrete;
- Apply wet curing immediately after finishing the surface and cure for at least 7 days;
- Apply a curing compound after the wet curing period to slow down the shrinkage and enhance the concrete properties.

Concrete material factors important in reducing early cracking included low shrinkage, low modulus of elasticity, high creep, low heat of hydration, and selection of aggregates and concrete that provided a low cracking tendency. Other material factors helpful in reducing cracking included reducing the cement content, increasing the water-cement ratio, using shrinkage-compensating cement, and avoiding materials that produced very high early compressive strengths and modulus of elasticity values.

The advantages of using a longer curing period include a lower permeability, increased hydration of the cement so that less free water is available to produce shrinkage and higher tensile strength when the concrete begins to shrink [53, 54]. One of the ways to protect concrete bridge structures from deteriorations is to use protective coatings [55, 56]. All these factors and methods contribute to a more durable bridge structures.

7. Conclusions

This paper presents a state-of-art report of shrinkage influence on cracking and deformations of concrete bridge structural elements. Shrinkage and creep influence on behaviour of such structures was investigated using theoretical assumptions and experimental data reported in the literature. This report discusses causes of cracking and ways of minimising strains and stresses induced by restrained shrinkage that can cause deteriorations in transportation structures: namely bridge structures, pavements, and footings.

The paper illustrates behaviour of a restrained member due to shrinkage and accompanying creep. It has been reported that modern high-strength concrete tends to crack more easily due to lower creep and higher thermal shrinkage, drying shrinkage, and elastic modulus, compared to traditional concrete mixtures. The difference between deformations of symmetrically and asymmetrically reinforced shrunk member is also discussed.

It has been shown that shrinkage deformations are one of major causes of defects in bridge structures all over the world. Various factors that influence the behaviour of the shrunk members (such as concrete mixture proportions and material properties, method of curing, ambient temperature and humidity conditions, and geometry of the concrete element) need to be taken into account during the construction of concrete structure. Furthermore, the structural effect, which tends prestressing loss in prestressed bridges or redistribution in internal forces along the bridge having statically indeterminate structure, must be taken into consideration.

In order to assess the effect of uncertainties during the constructions of early-age concrete properties (in repaired structures or bridge barrier wall over the existing slab) or restraining action in bridge structures on the total stress state, future work on high-strength concrete should focus on growing tensile strength and the modulus of elasticity of concrete in bridge structures shortly after pouring.

The research recommends for mitigating cracking in newly constructed or repaired concrete bridge elements to use lower cement contents and larger aggregates with higher elastic modulus, to add the shrinkage reducing admixtures to limit drying shrinkage and to perform mixtures with slightly higher water/cement ratios. Further steps would include reducing the amount of reinforcing steel in the bridge deck (minimised bar size and spacing) and eliminating structural restraints.

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