Unexpectedly low tensile strength in concrete structures

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During an extensive investigation of some 25 concrete bridges and other structures suffering from alkali-silica reaction it has been found that the uniaxial tensile strength of the concrete was extremely low in relation to both the compressive strength and the splitting tensile strength. It is known that concrete with damage due to ASR has reduced mechanical properties. The literature indicates that with an expansion of 1 ‰ a reduction of 30 % may occur. The reduction found in some of the bridges was, however, up to 82 % with an expansion between 0.5 and 1.0 ‰. There was no clear reduction of the tensile splitting strength and the compressive strength.

Previous research on older concrete structures without ASR showed that low tensile strength is not exclusively connected to the presence of ASR. Although not conclusive, Petrographic Fluorescence Microscopy (PFM) research and visual inspection of the structural damage of the concrete structures with ASR indicate that at least part of the damage must be due to ASR. The structural damage due to ASR and due to other causes cannot be distinguished.

Tests on reinforced beams taken from two of the ASR affected structures and tested in shear proved that the concrete had a reduced tensile strength, though the reduction was less than indicated by the uniaxial tensile tests. The orientation dependency of the tensile strength as found for these two structures can partly account for this difference. On the other hand, positive structural effects of ASR such as prestressing of the concrete due to the swelling within the reinforcement net can also explain this difference.

Key words: ASR, PFM, tensile strength

1. Introduction

For many years it was believed that an unambiguous relationship exists between the compressive strength and the tensile strength of concrete. The solid confidence on this relationship leads to the direct derivation of the tensile strength from the compressive strength in many national or international concrete codes. It was therefore a big surprise when research on concrete structures, that were damaged by alkali-silica reaction (ASR), showed that the uniaxial tensile strength can be significantly lower than could be expected on the basis of the present compressive strength or on basis of the measured splitting tensile strength [Siemes and Bakker (1997)]. The uniaxial tensile strength in those structures proved to be so low that radical safety measures had to be taken, like demolition, payload reduction (Figure 1), strengthening or monitoring.

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Figure 1. Load limitation to 20 tonsting on a viaduct due to a reduction of the load-bearing capacity from ASR

It is obvious to assume that the observed phenomenon of the unexpectedly low uniaxial tensile strength is directly related to ASR. However, it was found that concrete structures without ASR could also have a low uniaxial tensile strength [Siemes and Visser (2000)]. This phenomenon was only observed in old concrete structures, leading to the assumption that ageing may play a role. In general little attention is paid to the tensile strength in concrete of existing structures. Sometimes the low tensile strength obtained by measuring in an existing structure is reported in literature, however, an explanation is never given [Quitmann and Hallauer (1997)]. Perhaps this is because the general starting point for the structural design of concrete structures is that the tensile strength may be neglected for structures loaded in bending. However, knowledge of the tensile strength of concrete becomes especially important when the following aspects are taken into account during the design of new structures or the assessment of existing structures:

- Bond and anchorage of rebars
- Shear and punching without shear reinforcement
- Splitting caused by dowel action
- Anchorage of bolts
- Plane concrete pipes, footings etc.

The tensile strength of concrete is important for the design of roads, the analysis of concrete dams or large structures to prevent thermal cracking and sometimes for the design of prestressed elements. The tensile strength of concrete is also of interest in determining the initiation of cracking in plain and reinforced concrete members in relation to durability aspects.

The backgrounds of the low uniaxial tensile strength are still not completely understood. There is in the meantime however enough information collected to give a state-of-the-art overview of the problem.

2. Remarks on the material properties in ASR-affected concrete structures

ASR-affected concrete can be considered as a type of concrete with special properties, of which the expansion is clearly recognised. Therefore the changes in mechanical properties for an ASR-affected concrete are mostly related to the degree of the expansion.
An example of the dependency of the cube compressive and the tensile strength in relation to the expansion is given in table 1.

Table 1. Lower bound Residual strength mechanical properties as percentage of values for unaffected concrete at 28 days for various amounts of free expansion [ISE (1992)]

Property	Residual strength as compared with unaffected concrete for various amounts of free expansion			
Expansion	0.5 ‰	1.0 ‰	2.5 ‰	5.0 ‰
Compression	100 %	85 %	80 %	75 %
Tension	85 %	75 %	55 %	40 %

It is important to be aware of the fact that the relative homogeneity of the normal concrete can disappear due to the ASR expansion. The extent of the ASR damage strongly varies from place to place, which results in cracks in concrete. In the early age the microcracks increase. Later on these microcracks will develop into macrocracks. The way of development of such cracks in concrete strongly depends on the geometry of the concrete structure, the rebar configuration (to what extent and in which direction the expansion is restrained through the reinforcement) and the exposure conditions. These parameters determine not only the local changes of the material properties, but also the degree of the local expansion. Thus, the inhomogeneity is to a large extent dependent on the considered structure.
The concrete structures described in this paper (bridge decks and walls of a lock) have reinforcement only in two directions. The existence of rebars restrains the ASR expansion in the direction of the rebars. This delays the damage process. In the unreinforced direction no hindrance to expansion will exist due to the absence of the rebars, and cracking will occur parallel to the reinforcement. Bored cores from these concrete structures indeed show that a lot of cracks are present in the concrete. These cracks are predominantly parallel to the reinforcement, which is a well-known ASR phenomenon (Figure 2).

Figure 2. Horizontal cracks due to ASR damage in a core taken form a bridge deck

The cores taken from the structures were often considerably fractured, which could be seen especially well in the cores taken perpendicular to the dominant crack directions. For mechanical testing, parts of the cores were selected as specimens which were not completely fractured. Also core parts with very large cracks were omitted because practice showed that the specimen preparations (especially sawing the specimens from the cores) resulted in broken specimens before they could be tested. Hence, the worse fractured parts of the bored cores, where the loss of cohesion was (almost) complete, were avoided. From a statistical point of view, the low mean uniaxial tensile strength thus would be even lower if parts with uniaxial tensile strengths of (near) zero would have been included.

3. ASR and its related research in the Netherlands

Until about ten years ago it was believed in The Netherlands that Alkali Silica Reaction (ASR) did not occur at all in Dutch concrete structures. With increased knowledge on ASR and better diagnosis techniques, it became clear that this degradation could also be a problem in Dutch concrete structures. Since that period some dozens of concrete structures with damage due to ASR have been found [Heijnen et al. (1996)]. The damage in these structures is, in general, not recent.

The first concrete structures that have been assessed for ASR damage were considered to be isolated cases. However in 1996 about 20 bridges in highway A 59 in the southern part of the Netherlands were found to have damage due to ASR. The age of these structures varied between 20 and 40 years. There are some hundreds of similar structures, all built within a period of some twenty years and with the same kind of concrete composition. Therefore, it is expected that many of these structures are potentially sensitive to ASR as well. Considering the fact that critical damage due to ASR can develop within a few years, it was decided to do the assessment of the structures in the A 59 quickly and in a systematic way. The basis for the assessment was the British ISE-procedure [ISE (1992)] that had to be tuned to the specific Dutch circumstances [Siemes and Bakker (2000)].
Whilst the compressive behaviour of ASR-affected concrete causes little dispute, the question of the effect of ASR on the tensile strength remains open. Up to now, the consensus seems to be that the tensile strength is reduced by ASR. However, the reduction of the tensile strength according to the different researchers varies from about 5 % [Ahmed et al. (1999)] to 82 % [Siemes et al. (2000)].

After evaluation of the ISE-procedure, it was decided to extensively test the mechanical properties on cores drilled from the structures subjected to ASR. Among others, uniaxial compressive tests, splitting tensile tests and uniaxial tensile tests were performed.

The uniaxial tensile tests have been performed according to Rilem CPC 7 on cylinders with a length of two times the diameter (which is slightly more than the prescribed 1.8). For making it possible to take cores without damaging the reinforcement the diameter has been set on 75 mm.

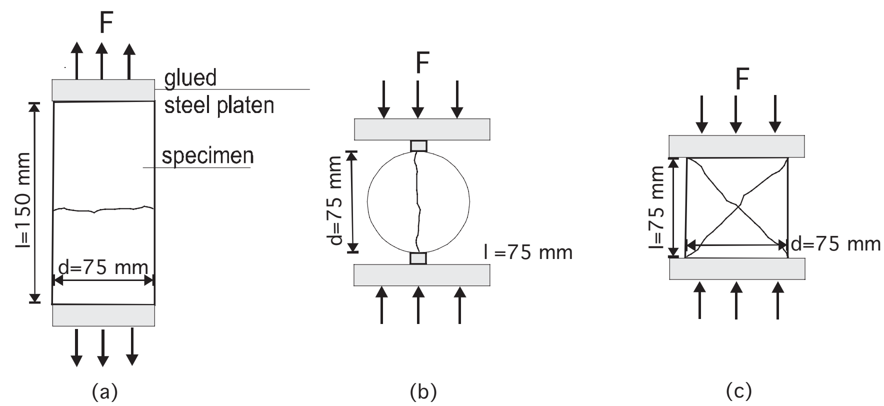

Figure 3. Uniaxial tensile test (a), splitting tensile test (b) and uniaxial compressive test (c): specimen sizes, applied forces and fracture planes.

The splitting tensileon tests tests and the uniaxial compressive tests have been performed according to standard Dutch codes (NEN 6720) except for adopting smaller size of specimens (with a diameter of 75 mm and a length of 75 mm). In Figure 3 the load direction in the various tests is indicated. In part of the investigation this loading direction and the orientation of the cylinders were varied to verify the influence. The specimens in the uniaxial tension test and in the splitting tension test were loaded in such a way that the fracture plane was always perpendicular to the axis of the cylinders. A schematic view of the specimen and the applied loads is given in Figure 3.

The specimens for the mechanical tests were obtained by drilling long cores from the structure. After the cores were inspected visually, the places for sampling were marked. Reinforcement and very large cracks where the cores nearly loss their cohesion were avoided. Next the specimens were sawn from the long cores. The sampling of the specimens for the mechanical tests was performed on a random basis.

In Table 2 an overview is given of 25 concrete structures where the uniaxial tensile strength has recently been tested in combination with the compressive strength and/or the splitting tensile strength. Only mean values are given. In all structures mentioned in Table 2 structural damage due to ASR has been found. In these structures typical expansions of 0.5 to 1.0 ‰ have been measured [Heijnen et al. (1996)] with local outliers. The ages of the structures were about 20 to 40 years with an exception for the Noordersluis with an age of about 70 year. The structures are of various types, constructed in different periods by various contractors.

In cases where the splitting tensile strength was not tested a prediction of it is given on basis of the compressive strength. The splitting tensile strength $f_{t,spl}$ in the Dutch concrete codes is directly related to the compression strength f_c' by:

$$f_{t,spl} = 1 + 0.005\, f_c' \qquad (1)$$

This relationship is known to fit well for most concrete. For those structures in Table 2 where also the splitting tensile strength was measured, it can be seen that this relationship applies reasonably well.

The splitting tensile strength is often in the Dutch concrete code related to the uniaxial tensile strength $f_{t,\,uniax}$ by:

$$f_{t,uniax} = 0.9\, f_{t,spl} \qquad (2)$$

However, it can be calculated from Table 2 that for the investigated structures the ratio between the mean uniaxial tensile strength and the (predicted) mean splitting tensile strength is about 0.5 with a very large scatter. In fact this indicates that for these structures there is no constant ratio. The relationship between the uniaxial tensile strength and the splitting tensile strength varies for each individual structure as well as within one structure.

Table 2. Overview of the mean compressive strength, splitting tensile strength and uniaxial tensile strength of various structures

structure code	mean compressive strength (MPa)	mean uniaxial tensile strength (Mpa)	mean splitting tensile strength (MPa)	Ratio uniaxial/ splitting tensile strength	Predicted splitting tensile strength (MPa)
Noordersluis	50.4	1.8	3.4	0.51	3.5
A59/1	69.1	1.7	not tested	0.38	4.5
A59/2	72.3	2.0	not tested	0.43	4.6
A59/3	57.5	2.6	not tested	0.67	3.9
A59/4	72.8	2.5	not tested	0.54	4.6
A59/5	62.7	1.9	not tested	0.41	4.6
A59/6	55.0	0.7	4.2	0.18	3.8
A59/7	64.5	1.6	4.2	0.38	4.2
A59/8	50.2	1.7	4.5	0.49	3.5
A59/9	69.2	2.4	not tested	0.53	4.5
A59/10	56.9	2.0	not tested	0.53	3.8
A59/11	60.5	1.0	3.8	0.25	4.0
A59/12	64.3	2.3	not tested	0.55	4.2
A59/13	66.7	2.5	not tested	0.58	4.3
A59/14	58.9	2.7	not tested	0.69	3.9
A59/15	62.4	1.5	4.3	0.37	4.1
A59/16	62.0	1.6	not tested	0.39	4.1
A59/17	71.2	2.8	not tested	0.62	4.6
A59/18	69.1	3.2	not tested	0.71	4.5
A59/19	58.0	3.0	not tested	0.77	3.9
A59/20	63.3	2.6	not tested	0.62	4.2
Zaltbommel	57.9	1.7	2.8	0.44	3.9
Druten	55.0	1.3	4.1	0.34	3.8
Stadion	67.7	1.6	4.2	0.36	4.4
Kolhorn	55.7	1.2	2.9	0.31	3.9

4. Reflections on the measured strengths

ASR-affected concrete may be considered as a particular form of concrete with special properties, of which expansion is the dominant one. Therefore, the volume change due to the expansion was logically related to the change of the mechanical properties of ASR-affected concrete. However, it is the differential expansion that may cause cracks between the expanding and non-expanding parts. As a result, the change of properties due to the expansion has a characteristic of the structural effect rather than a material effect. That is to say, the property variation depends on the size of the related

structure, the boundary condition and the environmental factors, which have influences not only on the changes of properties but also on the expansion itself.
From Table 2 it follows that:

- the measured splitting tensile strength is of the same magnitude as the splitting tensile strength that was predicted on basis of the compressive strength of the concrete; this means that relationship 1 is still applicable for the investigated concretes
- the uniaxial tensile strength can be substantially lower than predicted with relationship 2; the largest deviation was found for the structure with code A59/6; in stead of the correction factor 0.9 a correction factor of 0.18 was found; as an average the correction factor has a mean value of 0.5 and a standard deviation of 0.15.

Two effects are likely to have influenced the strength level. Firstly, due to the effect of ASR, the compressive and the tensile strength were reduced. Secondly, due to ongoing hydration, the strength has increased. It can be estimated that the compressive strength has increased by a factor 2 during the service life. According to table 1 the compressive strength is reduced to about 85 % and the tensile strength to about 75 % as compared to the 28 day strength, since the typical expansion of the investigated structures was about 1 $^{0}/_{00}$. Because the compressive strength has likely increased due to ongoing hydration by about a factor 2, it thus follows from table 1 that the effect of ASR is 215 % on the compressive strength and 225% on the tensile strength as compared with the 28 day strength. This is however extremely unlikely. It is more likely that the reductions of the strength as given in table 1 are relative to the unaffected concrete at that age. Notice that both effects did not affect relationship 1, but relationship 2 for the uniaxial tensile strength was affected. It thus follows that the strength reductions as a function of the expansions as given in table 1 applies for the splitting tensile strength but likely not for the uniaxial tensile strength.

Possible explanations for the low uniaxial tensile strength are as follows:

- During an uniaxial tensile test it is very difficult to maintain a centric load. As a result, eccentricity exits, which causes bending moments in the specimen. These moments can create additional tensile stresses. In addition to the load eccentricity, the inhomogeneity due to ASR in the concrete may also causes an eccentric stress distribution. These kind of eccentricities cause a measured tensile strength which can be much lower than the actual uniaxial tensile strength.
- In the uniaxial tensile test the whole specimen is under high tensile stress, whereas in the splitting and flexural tests only part of the specimen is under high tensile stress. Therefore, the probability that in an uniaxial tensile test a defect is present in a region with high tensile stresses is larger than that in a splitting and a flexural test. The correction factor 0.9 in relationship 2 considers this phenomenon. On the basis of the literature research on both the effect of ASR and the test method on the tensile strength of concrete, [Han (2001)] suggested that the correct factor in relationship 2 could be larger.
- There are other material defects which can lead to an apparent reduction of the tensile strength, which is mainly due to the decrease of effective cross section of the specimen. These defects can situate in the places where only the unaxial tensile strength is influenced.

The last point mentioned can be further clarified by means of the results of a Polarisation and

Fluorescence Microscopy (PFM) study. The specimens from the ASR damaged parts of the Noordersluis and the 20 bridges in highway A 59 have been investigated for signs of ASR viz. reaction gel and attenuated aggregates. Additionally the investigation was used to find data on the concrete composition, the hardening process and possible other types of damage. Much attention has been paid to find clues of the latter, as they may indicate if ASR alone can cause the high reduction of the uniaxial tensile strength.

The microscopic study made clear that there were in addition to the ASR more possible explanations (Fig. 4) for the low uniaxial tensile strength of the concrete:

- the bond between the cement stone and the aggregate was poor; normally 75 % percent of the surface of the aggregate is bonded; in this case this is less, sometimes only 25 %. The places with no bonding will be called bond cracks although the low bonding is a result of possibly insufficient mixing rather than cracking;
- the (apparent) water/cement ratio in the cement stone varies on a microscopic scale from 0.45 to 0.65; this means that locally the amount of pores can be high
- there is a high amount of microcracks through the cement stone; the crack width could amount to 0.1 to 0.2 mm, formally they are not longer considered as microcracks; part of them will be caused by ASR but another part is caused by the hydration process, (lack of) curing, shrinkage or fatigue.

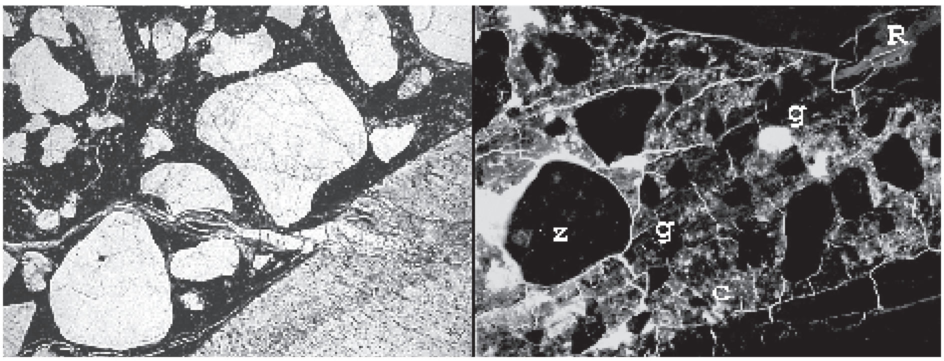

Figure 4. PFM-micrographs of two different thin sections of ASR-affected concrete showing an ASR-gel filled crack from an attenuated aggregate particle into adjoining cement paste. left transmitted light; right fluorescent light. R = reacted particle; g = ASR-gel; z = sand; c = cement. The size of micrograph is 2.7 mm x 1.8 mm.

Any of the three above mentioned inhomogeneities will cause the uniaxial tensile strength to be much lower than would be expected on the basis of the splitting tensile strength. The high percentage of cracks, pores and low bonding will result in a very low effective cross sectional area of the specimens. Moreover, at the crack ends, high local tensile stresses may arise due to the singular character of the stress at these points. Due to the high local stresses, low uniaxial tensile strengths are found.

The stress transfer in the concrete in the splitting tensile tests is more like the stress transfer in the compression test than in the uniaxial tensile test. The crack will in principle not follow the weakest spots, but it will follow the plane between the two small loading platens. Moreover, part of the bond cracks and the micro-cracks will be closed due to the compressive stress caused by the external load because the specimen is in vertical direction in fact loaded in compression. The fracture plane in the splitting tensile strength is not necessary or not likely the weakest spot in the specimen. The splitting tensile test is therefore not appropriate for finding the effects of inhomogeneities.

5. Other influences on the tensile strength of concrete

Additional tests have been carried out in order to study the influence of the size and orientation of the cores taken from structures on the tensile strength.

Sampling

The cores taken from the structures were often considerably fractured, which could be seen especially well in the cores taken perpendicular to the dominant crack directions (Figure 2). The specimens for the mechanical testing parts were selected from parts of the cores which were not completely fractured. Also core parts with very large cracks were omitted because practice showed that the specimen preparations (especially sawing the specimens from the cores) resulted then often in broken specimens before they could be tested. Hence, the worse fractured parts of the drilled cores where the loss of cohesion was (almost) complete were avoided. From a statistical viewpoint, the low mean uniaxial tensile strength thus would be even lower had parts with uniaxial tensile strengths of (near) zero be included.

Specimen Dimensions

The influence of the specimen dimensions has been tested by varying the specimen length and diameter. In addition to the specimens with a diameter of 75 mm, also specimens with diameters of 100 mm and 150 mm have been tested. The specimen length was varied in accordance with the diameter: lengths of twice the diameter were used for the uniaxial tensile tests and equal to the diameter for the splitting tensile tests. The test specimens with a diameter of 150 mm had in general a length of slightly less than 2 times the diameter, because of the availability of test material. In Table 3 an overview is given of the mean test results.

Table 3. Test results on specimens with diameters 75, 100 and 150 mm

Location	Severe damage			Moderate damage		
Diameter	75 mm	100 mm	150 mm	75 mm	100 mm	150 mm
Uniaxial tensile strength (MPa)	0.6	0.6	0.6	1.4	1.1	1.4
Splitting tensile strength (MPa)	-	3.1	2.5	-	4.2	3.5
Ratio uniaxial/splitting	-	0.19	0.24	-	0.26	0.40

There is no evidence that the diameter (and corresponding length) has a significant influence on the uniaxial tensile strength. The splitting tensile strength reduces with increasing diameter. The reduction of the splitting tensile strength can be understood from the fact that with increasing diameter, the probability on a crack within the loading plane increases, thus reducing the (apparent) splitting tensile strength. The indifference of the uniaxial tensile strength to the specimen diameter (and corresponding length of the specimen) is more surprising. The indifference suggests that the microcracks are fairly homogeneous throughout the concrete. For the uniaxial tensile test, the homogeneity is such that for the smallest specimen dimensions the microcrack distribution is already homogeneous, increasing the specimen dimensions then has no influence. For the splitting tensile strength, this is not the case, apparently the vertical distribution of the cracks is still wider than the load area in the splitting tensile strength test. This is also true if the scatter in the test results is taken into account (variation coefficients were in general about 0.25 or more).

A similar low influence of the specimen lengths (while keeping the diameter of the cores constant) was found. The low influence of the specimen dimensions on the tensile strength is likely a consequence of the high intensity of cracks in the specimens.

Specimen Orientation

The tensile strength of ASR damaged concrete was expected to be orientation dependent due to a strong preferential crack direction in most structures. To check this, cores with a diameter of 75 mm have been drilled in three directions out of a bridge deck (Zaltbommel) suffering from ASR. Moreover, cores have been drilled from two areas, which were classified as 'severely damaged' and 'moderately damaged' on the basis of a pre-investigation (consisting of visual inspection and mechanical tests on vertically drilled cores). The horizontally drilled cores furthermore have been drilled in horizontal direction on depths of 200 mm and 400 mm (thickness of the deck varying from 600 mm to 950 mm). In Table 4 the results of the tensile testing have been summarised.

Table 4. Mean tensile test results on ASR concrete with various orientations

Location	severely damage		moderately damage	
Orientation	vertical	horizontal	vertical	horizontal
Uniaxial tensile strength (MPa)	0.6	1.1	1.2	1.6
Splitting tensile strength (MPa)	3.1	2.9	3.9	3.9
Ratio uniaxial/splitting	0.19	0.37	0.30	0.40

The uniaxial tensile strength determined from the vertically bored cylinders is significantly lower than those determined from the horizontally bored cylinders. The splitting tensile strength is not dependent of the orientation. The depths of sampling for the horizontal drilled specimens had no noticeable influence on the strength, only the severity of the damage seemed to be of importance. Also the orientation in the horizontal plane had no significant influence within the variation of the data.

The lower uniaxial tensile strength for the vertically drilled specimens were expected since for the vertically drilled specimens, the cracks in the cores were predominantly perpendicular to the axis of the cylindrical specimens. Hence, in the uniaxial tensile tests, a low effective cross sectional area can be expected which resulted in relatively low uniaxial tensile strengths. For the horizontally drilled cores, however, the cracks run predominantly parallel to the axis of the cylindrical specimens. Therefore, they have a much lower effect on the uniaxial tensile strength. The indifference of the splitting tensile strength for the orientation of the specimens is likely a consequence of the small change in any direction to load the specimens at a place which is already severely cracked (viz. at a fracture plane orientated horizontally in the bidge decks). Although it seems from table 1 that also the splitting tensile strength is affected by cracking due to ASR, it is likely that the effect measured is due to minor, randomly oriented cracks which are not parallel to the free expansion direction.

6. Low uniaxial tensile strength in concrete without ASR

Recently it is pointed out that the phenomenon of the low uniaxial strength is not exclusively connected with the presence of ASR [Siemes and Visser (2000)]. Research on the old concrete structures showed that a considerable reduction of the uniaxial tensile strength (Table 5) was found. The studied concrete structures showed no ASR damage at all. This might mean that the low value in Table 2 for the uniaxial tensile strength can not only be related to ASR. However, the damage in the structures suffering from ASR indicates that it is likely that at least part of the damage is due to ASR.

Table 5. Test results on structures without ASR

Structure code	Mean compressive strength (MPa)	Mean uniaxial tensile strength (MPa)	Mean splitting strength (MPa)	Ratio uniaxial/splitting	Predicted mean splitting tensile strength (MPa)
Berkum	68	2.6	4.2	0.62	4.4
Asperen	56	1.3	not tested	-	3.8
Amstelveen	61	2.5	4.6	0.54	4.1
Utrecht	43	0.7	2.7	0.26	3.2

In the assessment of two existing small storm surge barriers on the German Baltic coast, tensile strength was measured in addition to the compressive strength [Quittmann and Hallauer (1997)]. With further analysis of the results it was found that the tensile strength is clearly lower than that derived on the basis of the present compressive strength. The authors did pay no further attention on this phenomenon in their publication.

7. Concluding remarks

The fact that the uniaxial tensile strength can sometimes be dramatically lower than the splitting tensile strength or the expected strength on basis of the compressive one has been found more or less by chance. For the basic investigation of concrete structures that showed signs of ASR it has been decided on the basis of an expert's opinion to do the tensile testing according to the uniaxial test described in Rilem recommendation CPC 7. The extremely low uniaxial tensile strength that has been found in most of the investigations was however not expected. From literature study on the tensile test it was found that the uniaxial tensile test method was rarely used in practice. This could partly explain why the extremely low uniaxial tensile strength was not reported before.

Although in this paper the uniaxial tensile strength is reported as a material property of the concrete, this is in fact not true. The specimens that were used for the testing were selected from the concrete between cracks in relatively sound concrete (this causes a measured value that is higher than the real uniaxial tensile strength). Further the effects of the excentricities in the uniaxial test are omitted (this causes a measured value that is lower than the real uniaxial strength). Nevertheless the uniaxial tensile test results are very indicative for the defects in the concrete. The compressive and splitting tensile results are considerably less indicative.

A relatively low tensile strength in older concrete is not unique for Dutch concrete. In various publications this phenomenon is mentioned, but no special attention has been paid to it. Perhaps this is because the general starting point for the structural design of concrete structures is, that the tensile strength is not taken into account. This statement is however less general than often is believed. The tensile strength plays an important role in carrying shear and torsion forces and in the bond between concrete and reinforcement. Moreover the tensile strength plays an important role in the overall integrity of a concrete structure. The structural consequences of the low uniaxial tensile strength should therefore be considered.

On the basis of the observed low uniaxial tensile strength for the Dutch concrete structures, a research programme was started to study the possible influence of the low uniaxial tensile strength on the shear capacity of a bridge deck. For this purpose beams have been cut from the existing bridges Heemraadsingel and Zaltbommel both from severely ASR damaged parts and moderately damaged parts of the bridges. These beams showed a reduced shear capacity. This reduction would not have been predicted on the basis of the compression strength or the tensile splitting strength [Den Uijl et al. (2000)]. The reduction of the tensile strength as calculated from the beam tests was however less than indicated by the uniaxial tensile strength. Possibly, the orientation dependency of the tensile strength can partly account for this difference. On the other hand, positive structural effects of ASR such as prestressing of the concrete due to the swelling within the reinforcement cave may underlie this difference.

In this research, it was found that the splitting tensile strength was changing similarly as the compressive strength. However, in literature on other types of low tensile strength it was found that under some circumstances also this relation may change. In a research project on concretes which were produced with Portland cement or blast furnace slag cement and with various water/cement ratios, it was observed that the splitting tensile strength was reduced to about 60 to 70 % of its original value [Polder (1996)]. This reduction was obtained by testing the concrete after an exposure period from 3 to 16 years in the North Sea at a depth of 30 m. The splitting tensile strength was not measured at the beginning of the exposure. In the same period the compressive strength hardly changed. An explanation for the reduction was not found. In a long-term investigation where concrete was exposed to fresh water and high pressures it was found [Clayton (1986)], that the bending strength was lower than for concrete that was exposed to the atmosphere. This phenomenon will be caused by the high water pressure in the pores of the concrete. Consequently this reduction is due to internal mechanical loading for which the applied load was not corrected.

The series of investigations, on which this paper is based, makes clear that in the assessment of existing concrete structures it is not enough to measure the compressive strength of the concrete. Especially if unusual cracking is present, it is necessary to measure also the splitting and the uniaxial tensile strength. Even when the different strengths have been determined, analysis of the structural safety of the structure of the measured strengths should be done with care. For 'standard' concrete we can rely for the structural analysis on the rules given in concrete codes. If concrete has a deviant behaviour, such as an unexpectedly low uniaxial tensile strength, all these rules must be reconsidered and a decision must be made on the type of test that is needed to quantify the material properties.

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