A NEW TEST TO ASSESS THE CONCRETE SUSCEPTIBILITY TO "THE DECAY" OF THE BRIDGE DECK SLABS

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Keywords: concrete deck slab decay, complex pathology, alkali-silica reaction, ageing test, GCG-DUG test

Abstract

Since 1995, a new type of concrete deterioration has been observed, developing on bridges in Belgium. Named "the decay of bridge deck slabs", it ultimately leads to the perforation of the slabs. This phenomenon is due to several deleterious processes occurring concurrently: alkali-aggregate reaction, chloride attack and freeze-thaw action.

In order to assess the durability of the old concretes, several classical tests have been performed. However, the resulting data does not fit with the field observations. Therefore a new test, named "GCG test" has been developed, combining three different ageing test types: expansion, freeze-thaw and chloride exposure.

The modified expansion methods used, Duggan, NBRI or Danish TI-B51, respectively led to three versions of the test: GCG-DUG, GCG-NBRI, GCG-DAN.

The study showed that the GCG-DUG test, correlated well with the field observations made on several concrete decks.

In addition, relevant test parameters have been highlighted and some thresholds are proposed.

1. INTRODUCTION

Since 1995, the Belgian Public Works Administration has been coping with concrete degradation on girder bridge decks [1]. The process, referred to as "decay of bridge deck slabs", can over time leads to the slabs perforation and is characterized by different forms of degradations. Planar cracking of the upper concrete is observed without correlation to the position of the reinforcement steel layers. Concrete is crumbled on the upper surface. In those areas, white spots of ettringite and sometimes silica gel are often observed.

These alterations are also underlined by the presence of typically darker patches on the lower deck surface (Figure 1) which remain visible regardless of external weather conditions, meaning that these latter are not simple humidity patches.

The deck slab structure is composed, from top to bottom, of a wearing course made of bituminous macadam, a protective layer, a waterproofing layer, and a reinforced concrete slab of about 18cm thickness[*].

By January 2007, 75 cases of bridge deck decay had been identified, out of a total of about , 3,700 bridges supervised by the Administration. A study, involving universities and research institutes, showed that the pathology is complex and results from a combination of several phenomena, which are: alkali-silica reactions (ASR), secondary sulfate precipitations, chloroaluminate formation, and freeze-thaw [2].

After the study of pathology and diagnosis, the essential concern is the durability prediction. To assess the susceptibility to decay of the old concrete of those bridge decks, it is necessary to perform some ageing tests. First of all, standards tests with regard to ASR and freeze-thaw were carried out. Because these standard tests are not suitable, a new test, GCG, with three versions, is proposed.

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2. CONCRETE SAMPLES

Several different concretes, drilled outside the visual degradation areas, have been tested. They are classified according to the degree of degradation in the bridge after a visual inspection and examination of cores (column 1 in Table 1). All of the bridge decks were covered by an old and deficient waterproofing:

- "Bad" - bridge decks showing serious visual deterioration: For example bridge 10 (built in 1981), bridge FH (built in 1971), bridge 28 (built in 1971);
- "Medium" - bridge decks showing more or less deterioration: For example bridge WB (built in 1969, with two concrete mixes based on CEM I and CEM III cement types), bridge SB (built in 1971), bridge 18 (built in 1963);
- "Good" - bridge decks in a good state, despite a poor deck waterproofing: For example bridge H (built in 1966), bridge K (built in 1960).

Concrete from other structures, two concrete cubes of prestressed beams (built in 1994 and in 1997) and a quay slab (built in 1963) were also tested.

3. CLASSICAL STANDARD TESTS

3.1 Methods

The two following tests are usually made in Belgium to evaluate the susceptibility of a concrete composition with regard to the alkali-silica reaction [3]. If the results of a modified NBRI expansion test are positive (swelling > 0.1 %), the composition is considered as certainly sensitive against ASR. If not, the concrete might be nevertheless sensitive against ASR, but with a slower kinetics. Therefore, a modified Duggan expansion test is carried out. If the results are positive (swelling > 0.1 %), a petrographic observation is performed on the tested sample, to determine the secondary reactions: either alkali-silica and/or sulphate.

Both tests, *modified NBRI and modified Duggan,* have been carried out on cores of 50mm diameter and ± 130mm length.

For the *modified NBRI expansion test*, the sample is firstly prepared by being stored 1 day in distilled water at 82°C. During the test, the sample is immerged in a NaOH 1N solution at 82°C. The length of the sample is measured daily ,with an accuracy of 0.001mm, for 20 days.

For the *modified Duggan expansion test,* the sample is firstly exposed to the following procedure: 3 days in distilled water at 21°C; 1 day in air at 82°C; 1 day in distilled water at 21°C; 1 day in air at 82°C; 1 day in distilled water at 21°C; 3 days in air at 82°C. Afterwards, the sample is immersed in distilled water at 21°C. The length of the sample is measured daily for 20 days, with an accuracy of 0.001mm.

The *freeze-thaw test* is carried out on cores of 50mm diameter and ± 100mm length according to the following procedure (NBN B15-231): after immersion in water to a constant weight, the sample is submitted to freeze-thaw (14 cycles for 24 hours). The sample is directly placed in air at -18°C, without any control of the cooling speed. The degradation of concrete is estimated by the measurement of the decrease in *ultrasonic* (*US*) *velocity*.. This measurement is carried out daily by direct transmission through the cores with pointed transducers along the longitudinal axis of the core.

Petrography is carried out on thin sections of 25 microns thickness, cut from the samples before and after ageing tests. The observations have been focused on the cracking system and the ASR frequency: The crack density is defined by the number of cracks counted in all the fields by scanning the whole thin section by the surface unit. This way, the method takes into account the crack lengths, or in other terms the propagation of the cracks. Under normal light and a 40x magnification conditions, the width of the visible cracks is at least about 10 microns. The ASR frequency is estimated by counting the number of signs or sites of reaction, such as: alkali-silica gel in pores and cracks or visibly reacted aggregate particles.

3.2 Results

Standard ageing tests results are given in Table 1, while petrographic analysis results are given in Table 2.

3.3 Discussion

The swelling of the samples after the modified NBRI test is higher than the limit of reactivity of 0.1 % in all the cases reviewed except for the bridge K.

The modified Duggan test gives a swelling lower than the limit of reactivity of 0.1 %.

After freeze-thaw testing, the velocities are very variable, without any relation to the initial velocity. This intial velocity gives an indication of the concrete quality.

For each bridge concerned, the petrographic results don't show any clear differences between the measured parameters values ("crack density" and "ASR activity") before testing (initial state) and after testing (modified NBRI and modified Duggan).

The examination of the results of these classical ageing tests (Tables 1 and 2) does not allow making a distinction between the bridges classified "bad", "medium" or "good" with regard to the concrete decay.

4. NEW GCG TEST

4.1 Introduction

In order to understand this complex pathology, standard ageing tests, combined with a complementary "exposure to chlorides", have also been consecutively performed on the same sample of young concretes (28 days). The results of these tests didn't allow an understanding of the mechanism of the deterioration probably due to the great influence of the concrete maturation. Nevertheless, there seems to be a real interaction between the three different mechanisms of alkali-silica reactions, chloride reactions and freeze-thaw.

The new original ageing test is based on this observation and combines these three mechanisms. The test was named "GCG" after the French terms "Gonflement, Chlorures, Gel" which mean "swelling, chloride and freezing". It is a mix of standards test procedures following a given order. These three mechanisms are also present in the field in a combined way.

The "GCG" test was performed, on concretes of several years old, by comparing and combining three alternative techniques related to ASR expansion trials:

- GCG-DUG, where the swelling mechanism is based on the modified Duggan test method (see hereafter);
- GCG-DAN, where the first "G" test step is based on the modified Danish test method (Appendix 1);
- GCG-NBRI, where the first "G" test step is based on the modified NBRI test method (Appendix 2).

These three techniques were applied on samples extracted from Bridge 18 and Bridge K. Results are given in Appendix 3.

The petrographic analysis results, after the different ageing tests, illustrate the efficiency of the "GCG-DUG" test compared to the others (Table 3): indeed, it clearly differentiates between the "medium" and "good" classes: the "crack density" and "crack mean width" measured is much higher within the "medium-class" bridge (bridge 18) than within the "good-class" bridge (bridge K).

It is well-known that the modified Duggan expansion test increases concrete micro-cracking [4] and facilitates ettringite formation [5]. These two observations probably explain why the "GCG-DUG" test seems to simulate very well the concrete decay where ettringite deposits are often observed.

4.2 GCG-DUG test method

The "GCG-DUG" test is performed on cores of 135mm length and 50mm diameter. Beforehand, the samples are exposed to the following preparation step, as in the modified Duggan procedure (3 days in distilled water at 21°C, 1 day in air at 82°C, 1 day in distilled water at 21°C, 1 day in air at 82°C, 1 day in distilled water at 21°C, 3 days in air at 82°C).

Afterwards, "GCG-DUG" cycles are performed during 35 days (sometimes more), as follows:

Test starts on Monday morning, and the procedure of each day of the week is:

- 8 am -9 am: measurement of the ultrasonic velocity V_8, swelling l and mass m
- 9 am - 2 pm: exposure to freezing at – 18°C for 5 hours
- 2 pm - 4 pm: reheating at 20 ± 2 °C for 2 hours
- 4 pm - 4 pm 30: ultrasonic velocity V_{16} measurement
- 4 pm 30 - 8 am: exposure to swelling and chlorides by immersion of the sample in an individual NaCl solution (0.5N or 30g/L) at 21°C during 15 hours and 30 minutes

During the week-end (from Friday 4 pm 30 to Monday 8 am), the sample is only exposed to swelling and chlorides.

4.3 Results

The results are given in graphic form showing the evolution of the parameters V_8, V_{16}, l and m versus time. Mass is sometimes not useable due to the loss of stones during the test.

The analysis of all curves show three phases during the "GCG-DUG" test (Figures 2 and 3):

- phase 1 = initial phase (from 0 to T_1), without variation of sample length. V_8 is very close to V_{16} and both are growing up to the V_{16} maximum value.
- phase 2 = reaction phase (from T_1 to T_2) with uniform expansion. V_{16} decreases. V_8 increases a little bit up to a maximum and then decreases. V_8 is always higher than V_{16}.
- phase 3 = degradation phase (after T_2). Expansion and ultrasonic velocity variation increase highly. Depending on the concrete sensitivity to decay, phases 2 and/or 3 may not be observed during the test.

During the second phase (reaction development), a "week-end effect" is often observed (Figure 2). After a week-end period with only chloride and swelling exposures, the core expansion increases highly, it then decreases during the following week, when freeze-thaw exposure occurs. Moreover, V_{16}, measured after the freeze-thaw cycle, is always lower than V_8, measured after chloride and swelling exposures. It seems, therefore, that low temperature alters ASR gel and results in a decrease of swelling. If the ASR gel, which fills in the cement past voids, is less compact due to the freezing of the water ultrasound propagation through the sample will be less easy and the velocity will decrease. This "week-end effect" is a proof of the interaction between swelling and freeze-thaw mechanisms.

Among all the results (Table 4), the following parameters were chosen to qualify the degradation evolution on the graph:

- Time of the end of the phases: T_1 , T_2
- Length variation during phase 2: Δl_2
- Mass variation during phases 1 and 2 : Δm_1, Δm_2
- Ultrasonic velocity variation during phases 1 and 2 : $\Delta V_{8,1}$,$\Delta V_{8,2}$ and $\Delta V_{16,1}$,$\Delta V_{16,2}$
- Length variation between 1st and 35th day: Δl_{35}
- Mass variation between 1st and 35th day : Δm_{35}
- Ultrasonic velocity variation between 1st and 35th day: $\Delta V_{16,35}$.

The $\Delta m_{35}/\Delta l_{35}$ ratio appears also very interesting to underline the residual concrete quality. It is representative of the mass to be absorbed by the unit length increasing.

At the end of the test, some samples are totally destroyed; the Bridge 10 sample was even destroyed after 5 days (Figure 4), while others are still in good condition (Figure 5).

After ageing, some samples were analysed by petrography. This analysis is compared with the petrographic analysis performed on other samples extracted from the same bridge deck slab area (Table 5). The GCG-DUG test greatly increases the crack density, without changing the ASR activity. These observations could be related to the freeze-thaw mechanism and sulphate mobilization during the GCG-DUG test.

The crack index (ci) is equal to [crack density (cd) x maximum crack width]/100. While the crack density takes into account the crack propagation, the crack index includes in addition the crack width. That way, it should better represent the concrete degradation and should improve the discrimination between the different quality classes of concretes : the value is lower than 20 for class of "good" concretes, while it is greater than 30 for concretes of lower quality (Table 5).

4.4 Discussion

The analysis of results (Table 4) clearly shows that:

- The new GCG test has a good repeatability
- The most relevant parameters able to describe together the sensitivity of the sample to concrete decay, are: Δl_{35}, $\Delta V_{16,35}$, $\Delta m_{35}/\Delta l_{35}$.

With regards to the deterioration degree of the bridges (bad, medium, good), limits values can be proposed (Table 6), to evaluate the sensitivity to concrete decay.

The GCG test has been defined in such a way that it doesn't excessively promote the ASR; the results obtained confirmed this issue (table 5 – see "ASR activity" column). Indeed, the experience showed that if the swelling mechanism of the test had promoted too much the ASR as with the GCG-DAN and GCG-NBRI tests (table 3), the distinction between "good", "medium" and "bad" concretes is not possible (table 7).

5. CONCLUSIONS

With regards to the new degradation locally named “concrete decay” observed in more than 75 bridges in Belgium, it was necessary to find a sensitivity test to predict the durability of the structure. Classical standard ageing tests in relation with alkali-silica reaction, freeze-thaw and chloride exposure applied separately were not satisfactory.

A new test named “GCG-DUG” was then developed, based on the combination of those three mechanisms, with a preparation similar to the modified Duggan procedure.

Three physical parameters were defined in order to assess the concrete sensitivity to decay:

- length variation at 35 days
- ultrasonic velocity variation at 35 days
- mass and length variations ratio at 35 days.

By testing 12 different concretes, limit values were found to distinguish three classes depending on a low, medium or high sensitivity to the decay.

Concurrently, petrographic analysis has been carried out on the tested samples to observe the variations of the cracking and of the alkali-silica reactivity frequency; a crack index has been defined to discriminate the concretes between the sensitivity classes by taking into account the cracks propagation (length) and the cracks width; that way, it should better represent the concrete degradation after the “GCG-DUG” test.

The Duggan test is well known to cause microcracking and to mobilize ettringite. The GCG-DUG test, partly based on the Duggan test, represents a real interaction between the different degradation processes involved in the “concrete decay”, such as alkali-silica reaction, ettringite mobilization and freeze-thaw action. This interaction is also proven by the “week-end effect”.

The estimation of the decay sensitivity by the “GCG-DUG” test is very important in order to determine the waterproofing effectiveness to be achieved on site. It is also a way to plan waterproofing renewal of a bridges stock**.**

6. REFERENCES

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Table 1: Classical standard ageing test results.

		Modified NBRI test	**Modified Duggan test**	**Freeze-thaw**		
Class	***Bridge name***	*Length variation* %	*Length variation* %	*Initial US velocity* m/s	*Final US velocity* m/s	*US velocity variation* %
Bad	*Bridge 10*	-	0.062	3664	2519	-31.0
	Bridge FH	0.375	0.085	3978	2645	-33.5
	Bridge 28	0.123	0.032	4071	2968	-27.1
Medium	*Bridge WB-CEM I*	0.100	0.039	-	-	-
	Bridge SB	-	-	4153	3453	-16.9
	Bridge 18	0.141	0.072	4406	2033	-53.9
Good	*Bridge H*	0.106	0.034	4153	3849	-7.3
	Bridge K	0.011	0.011	4425	2331	-47.3
	Bridge WB-CEM III	-	-	-	-	-
-	*Cubes 1994*	0.250	0.034	4570	4655	+1.9
	Cubes 1997	-	0.011	4548	4548	0
	Quay slab	-	0.095	4305	2063	-52.1

Table 2: Petrographic observations before and after classical standard ageing tests.

	Bridge 18			Bridge K		
	Crack density (cracks/cm²)	Crack mean width (µm)	ASR activity	Crack density (cracks/cm²)	Crack mean width (µm)	ASR activity
Initial State	3.2	10-20	3	1	25	1
After Modified NBRI	3.1	100	3	< 1	25	2
After Modified Duggan	3.7	25-50	3	< 1	25	1
ASR frequency estimation: 1 = poor (1 to 2 reactive sites); 2 = medium (3 to 4); 3 = high (≥5)						

Table 3: Petrographic observations before and after GCG ageing tests.

	Bridge 18			Bridge K		
	Crack density (cracks/cm²)	Crack mean width (µm)	ASR activity	Crack density (cracks/cm²)	Crack mean width (µm)	ASR activity
Initial State	3.2	10-20	3	1	25	1
After ageing:						
GCG-DUG	30.0	100	2	5.7	25-100	1
GCG-DAN	7.5	10-50	4	1	5-50	1
GCG-NBRI	3.9	25	3	1.4	10-50	2
ASR frequency estimation: 1 = poor (1 to 2 reactive sites); 2 = medium (3 to 4); 3 = high (≥5)						

Table 4: **GCG-DUG** test results.

Class	**Bridge name**	**Sample #**	T_1	T_2	Δl_2	Δm_1	Δm_2	$\Delta V_{8,1}$	$\Delta V_{16,1}$	$\Delta V_{16,2}$	Δl_{35}	Δm_{35}	$\Delta V_{16,35}$	$\Delta m_{35}/\Delta l_{35}$
			Day	Day	%	%	%	%	%	%	%	%	%	-
Bad	*Bridge 10*	2	2 3	6 6	0.2 0.1	0.3 0.2	0.3 0	1.0 -	11.9 -	-24 -	- -	- -	- -	- -
	Bridge FH	4	8 8 8 8	>48 >55 >43 >55	2.2 2.6 2.3 1.8	0.4 0.4 0.4 0.4	2.4 3.0 1.0 2.2	9.1 11.5 9.7 10.7	9.7 8.8 8.1 10.5	<-68 <- 67 <-70 <-65	1.2 1.2 1.4 1.0	1.8 2.1 - 1.5	-64 -63 -66 -60	1.5 1.8 - 1.5
	Bridge 28	1	6	22	0.3	0.4	0.4	4	0	-35	1.1	1.4	-60	1.2
Medium	*Bridge WB-CEM I*	1	7	22	0.2	0.5	0.4	7	-9	-26	1.0	-	-59	-
	Bridge SB	1	3	>44	0.4	0.6	0.5	-1	-6	-37	0.5	1.0	-36	2.1
	Bridge 18	1	3	55	1.1	0.3	1.4	5	5	-43	0.8	1.2	-26	1.5
Good	*Bridge H*	4	15 14 15 15	>55 >55 >55 >55	0.6 1.1 0.5 0.5	0.5 0.5 0.5 0.4	-0.3 1.3 0.8 0.8	8.7 12.6 7.9 10.5	7.3 8.9 6.6 9.7	- - - -	0.3 0.5 0.2 0.3	- 1.2 0.9 0.9	-7 -19 -4 -4	- 2.4 4.5 3.0
	Bridge K	1	13	>66	0.7	0.4	1.1	8	8	-44	0.2	0.7	-8	3.5
	Bridge WB-CEM III	1	>45	-	-	0.5	-	5	3	-	0.1	0.54	3	6.5
Other structures	*Cubes 1994*	4	7 7 7 7	>55 >55 >55 >55	1.0 1.4 1.3 1.2	0.3 0.3 0.3 0.3	0.4 - - -	5.4 4.2 4.9 3.9	2.4 -2.1 -0.6 0.6	<-35 <-47 <-41 <-37	0.6 0.8 0.7 0.7	0.9 1.2 1.1 1.1	-32 -48 -40 -37	1.5 1.5 1.6 1.6
	Cubes 1997	3	6 7 7	>45 >45 >45	0.5 0.4 0.5	0.3 0.3 0.2	0.5 - -	1.9 2.4 1.9	-2.8 -3.5 -3.3	-26 -27 -30	0.3 0.3 0.4	0.7 - -	-24 -26 -28	2.3 - -
	Quay slab	2	3 3	>45 >45	0.5 0.5	0.1 0.1	- -	5.4 0.3	2.0 -1.4	-16 -31	0.7 0.7	- -	-14 -25	- -

Table 5: Petrographic observations before and after **GCG-DUG** ageing tests.

		Initial state		After ageing			
Class	*Bridge*	ASR activity	Crack density (cracks/cm²)	Crack density (cracks/cm²)	ASR activity	Crack mean width (μm)	Crack index (-)
Bad	*Bridge FH*	2	2.2	54	2	250	135
Medium	*Bridge 18*	3	3.2	30	2	100	30
Good	*Bridge H*	0	0.8	18	0	100	18
	Bridge K	1	1.0	6	1	100	6
-	*Cube 1994*	0	0.5	25	0	125	31
ASR frequency estimation: 1 = poor (1 to 2 reactive sites); 2 = medium (3 to 4); 3 = high (≥5)							

Table 6: **GCG-DUG** test - limit values of sensitivity to decay.

sensitivity	**ΔL_{35}** %	**$\Delta V_{16,35}$** %	**$\Delta m_{35}/\Delta l_{35}$** -
Low	< 0.3	> -10	> 3
Medium	0.3 to 1	-10 to -40	1.5 to 3
High	> 1	< -40	< 1.5

APPENDIX 1: GCG-DAN TEST METHOD

The “GCG-DAN” test is performed on cores of 135mm length and 50mm diameter.
Beforehand, the samples are placed into distilled water at room temperature till a constant weight.
Afterwards, “GCG-DAN” cycles are performed during at least 35 days:

Test starts on Monday morning, and the procedure of each day of the week is:

- 8 am - 9 am : measurement of ultrasonic velocity, length and mass
- 9 am – 2 pm : exposure to freezing at – 18°C for 5 hours
- 2 pm – 4 pm : reheating at (20 ± 2)°C for 2 hours
- 4 pm – 4 pm 30 : measurement of ultrasonic velocity
- 4 pm 30 – 8 am : exposure to swelling and chlorides: immersion of the sample in an individual NaCl (0.5N or 30g/L) and NaOH (0.5N or 30g/L) solution at 50°C. for 15 hours and 30 minutes.

During the week-end (from Friday 4 pm 30 to Monday 8 am), the sample is only exposed to swelling and chlorides.

APPENDIX 2: GCG-NBRI TEST METHOD

The “GCG-NBRI” test is performed on cores of 135mm length and 50mm diameter.
Beforehand, the samples are placed into distilled water at 82°C for 1 day.
Afterwards, “GCG-NBRI” cycles are performed during at least 35 days:

Test starts on Monday morning, and the procedure of each day of the week is:

- 8 am - 9 am : measurement of ultrasonic velocity, length and mass
- 9 am – 2 pm : exposure to freezing at – 18°C for 5 hours
- 2 pm – 4 pm : reheating at (20 ± 2)°C for 2 hours
- 4 pm – 4 pm 30 : measurement of ultrasonic velocity
- 4 pm 30 - 8 am: exposure to swelling and chlorides: immersion of the sample in an individual NaCl (0.5N or 30g/L) and NaOH (0.5N or 30g/L) solution at 50°C. for 15 hours and 30 minutes.

During the week-end (from Friday 4 pm 30 to Monday 8 am), the sample is only exposed to swelling and chlorides.

APPENDIX 3: GCG-DAN AND GCG-NBRI RESULTS

The results are given in the same graphic forms as for the GCG-DUG test. The shape of the curves is different for each kind of GCG tests and the results are not obvious to be analyzed. Within the scope of this paper, only the values at 35 days are given in table 7. The use of NaOH solution in both tests, may lead to the dissolution of some aggregates with, as consequence, an impact on the mass measurement. In that case, the mass variation is not indicated.

Table 7: **GCG-NBRI** and **GCG-DAN** test results.

Test	***Bridge name***	**Sample #**	Δl_{35}	Δm_{35}	$\Delta V_{16,35}$	$\Delta m_{35}/\Delta l_{35}$
			%	%	%	-
GCG-NBRI	*Bridge 18*	1	0.1	-	-3.4	-
	Bridge K	1	0.2	-	-3.0	-
GCG-DAN	*Bridge 18*	1	0.1	-	6.7	-
	Bridge K	1	0.0	-	-3.7	-

Figure 1: Dark patches on the lower deck surface.

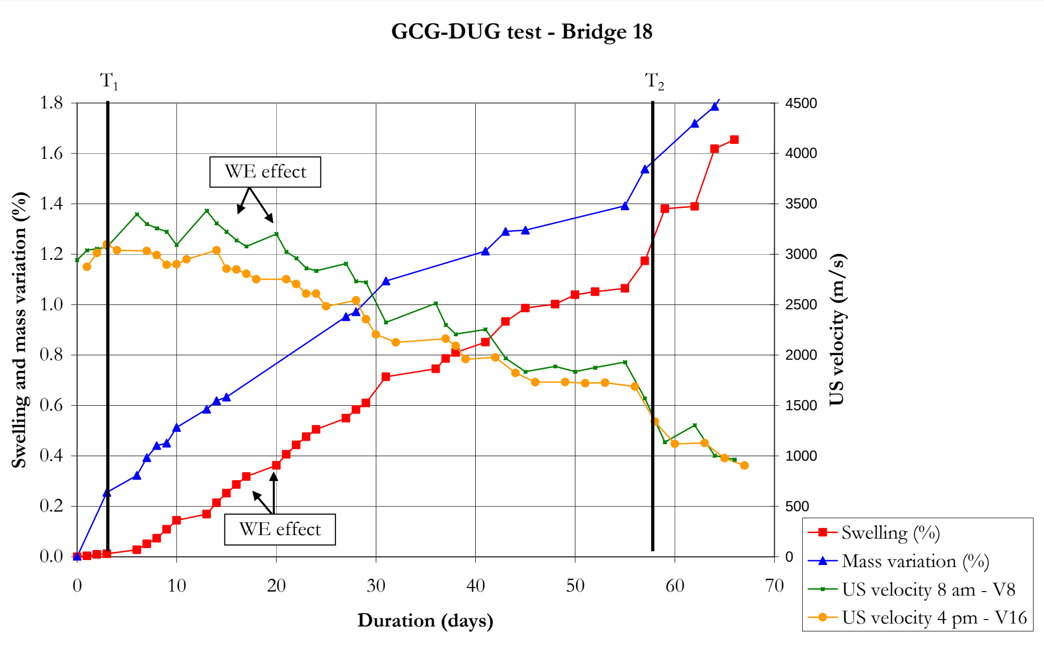

Figure 2: **GCG-DUG** test results – case of Bridge 18.

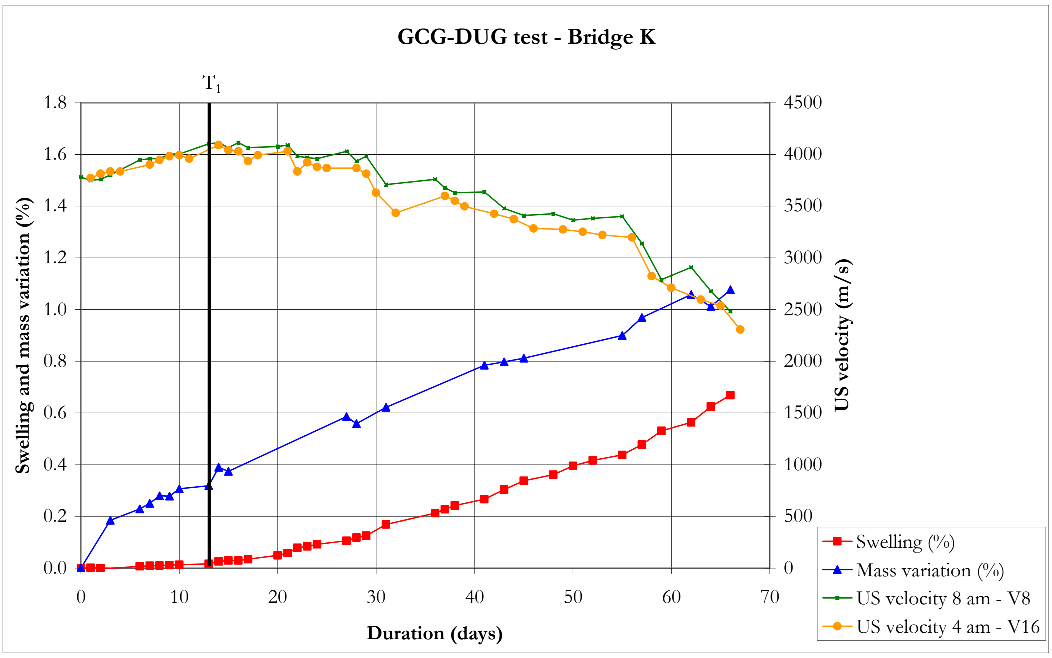

Figure 3: **GCG-DUG** test results – case of Bridge K.

Figure 4: Bridge FH after the "GCG-DUG" test. Concrete is completely cracked (ø 50 mm).

Figure 5: Bridge H after the "GCG-DUG" test. Concrete is still in good condition (ø 50 mm).