Concrete Strength in Old Swedish Concrete Bridges

Håkan Thun
Ph. D., Research Engineer
Division of Structural Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden
E-mail: Hakan.Thun@ltu.se

Ulf Ohlsson
Ph. D., Assistant Professor
Division of Structural Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden
E-mail: Ulf.Ohlson@ltu.se

Lennart Elfgren
Ph.D., Professor
Division of Structural Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden
E-mail: Lennart.Elfgren@ltu.se

ABSTRACT

In this paper the development and variation of compressive and tensile strength of concrete are presented for old reinforced concrete bridges in Sweden.

The mean increase in concrete compressive strength was about 70% for twenty bridges built during 1931-1962 (a rather high dispersion must be taken into consideration). The increase is related to the original 28-day concrete compressive strength which varied between 18 and 51 MPa.

The compressive strength within a typical reinforced railway concrete trough bridge was approximately 15% higher in the longitudinal beams than in the bottom slab (measured on drilled cores). The tensile strength showed a similar variation as the compressive strength, but the difference could not be statistically verified.

Different equations to convert compressive strength into tensile strength have also been studied. The investigation shows that it is important which conversion equation that is used in an assessment situation.

Keywords: strength variation; strength development; drilled cores; concrete; bridges

1 INTRODUCTION

When a bridge is evaluated regarding its load carrying capacity there are several influencing factors that have to be considered. Some of these factors are: in-place concrete strength, concrete cover of the reinforcement, amount and quality of the reinforcement, degree of degradation etc. Of the factors mentioned, the main focus in this paper has been on studying the in-place concrete strength, since e.g. an increase of the concrete strength with time can be a valuable asset when assessing a bridge several years after it was constructed. The subject has in turn been divided into the following areas:

- Development of concrete strength with time: Is the concrete compressive strength of old bridges increasing with time? Efforts have been made to establish the phenomenon for old Swedish road bridges.
- The variation of concrete strength within a structure: Can a concrete strength variation be expected between different structural members in a reinforced railway trough bridge (i.e. the slab versus the longitudinal beams)?
- How to determine the tensile strength when only the compressive strength of concrete is examined?

The origin of the results presented in this paper is a project that was initiated when an increase of the axle load from 25 tons to 30 tons was planned on the railway line between Luleå in Sweden and Narvik in Norway. The railway line, with a total length of 473 km, was built between 1884 and 1902 for the transportation of iron ore and is now used for both iron ore and passenger transport.

2 METHODS

Drilled cores have been used in this investigation to determine the in-place concrete strength of old reinforced concrete railway trough bridges.

To drill out and test cores is a common method to estimate the in-place strength of a structure. Most countries have adopted standard procedures for how a core should be prepared, stored, etc. before testing. In this study the preparation, the storage etc. have been made according to the Swedish concrete recommendations, BBK94[1]. A water-cooled drill with diamond edges has been used. The cores have been air-cured for at least three days before testing. The ratio between the length and the diameter has been 1.0 (a diameter of approximately 100 mm). The cores have been marked with a drill hole number and a serial number. The cores have been used for uniaxial tensile tests, splitting tensile tests and compressive tests.

The uniaxial tensile tests have been performed with a closed-loop servo-hydraulic test machine (Dartec) under displacement control. Prior to testing, a notch has been milled on each specimen and after cleaning the specimen has been glued to the steel plates and then attached to the test machine. The data have been collected using four Crack Opening Displacement gauges (COD-gauges) with 90 degrees between the gauges.

3 STRENGTH DEVELOPMENT WITH TIME FOR OLD BRIDGES

3.1 Test results from 20 bridges built during 1931-1962

Data from Vägverket, the Swedish Road Administration, have been examined and evaluated for nineteen bridges built during 1931-1946 and one bridge built in 1962. This investigation is a further study of the work presented in Rådman[2]. The focus has been on comparing the concrete cube compressive strength at 28 days with the concrete compressive strength from drilled cores that have been tested during the years 1990-1994 (i.e comparison between cast Swedish standard 150 mm cubes and drilled cores with the diameter and length of 100 mm. This choice of comparison is based on the established relationship between the compressive strength of a horizontally drilled core with the height and diameter of 100 mm and the compressive strength of a cast 150 mm cube, see Möller et al. [3] or prEN 13791[4] ("Testing cores with equal length and nominal diameter from 100 mm up to 150 mm gives a strength value equivalent to the strength value of a 150 mm cube manufactured and cured under the same conditions", Section 6.1). These two different concrete compressive strengths have been compared and the result is presented in Figure 1.

To be able to compare the two concrete compressive strengths the original concrete cube compressive strength at 28 days, $f_{c,200}$, has been increased with a factor of 1.053 (= 1/0.95, according to Swedish standard, Betongprovning[5]) to correspond to standard cubes, $f_{c,150}$, with the dimension of 150 mm (the original cube size was 200 mm), $f_{c,150} = 1.053 f_{c,200}$.

The drilled core dimensions had an approximate length/diameter-ratio of 1.0 (the diameter was approximately 100 mm). In Figure 1 the x-axis shows the year of construction for each bridge with the oldest to the left. On the y-axis the concrete compressive strength at 28 days is given together with the concrete compressive strength from drilled cores, $f_{c,100}^{\text{core}}$. The 28 days' compressive strength values represent the strength in the bridge deck or the main girders, from where it is assumed that the drilled cores are obtained.

The bridge records that have been used in this investigation are not complete. This leads to the fact that e.g. the cement content and the water to cement ratio have not been found for all bridges. For the bridges where this information has been found the water-cement-ratio varies between 0.49-0.65 and the cement content varies between 300-400 kg/m^3. Regarding the cement type that has been used, the investigation shows that it varies between the bridges - at least seven different brands have been used. Unfortunately no information regarding the properties of the cement types used has been obtained. A reasonable assumption is that these cement types had similar properties as cement types used in other countries during the same period.

In Figure 1 all bridges show an increase in concrete compressive strength. Of the 20 bridges, 5 bridges show a moderate increase: 0-10 MPa, 10 bridges: 10-30 MPa and 5 bridges more than 30 MPa (up to 52 MPa). For the bridge that shows the highest increase, i.e. 52 MPa, the high increase is probably due to the fact that the cubes were not stored according to the regulations the first few days - the temperature was lower, which can be seen from the bridge records. This gives a misleading concrete compressive strength at 28 days and if it had been stored according to the concrete recommendations it would probably have been higher.

If this bridge is excluded, the average increase in concrete compressive strength for the remaining 19 bridges is approximately 20.7 MPa, corresponds roughly to an increase of 70%, compared to the 28-day strength. The standard deviation is 13.7 MPa (if the bridge mentioned above is included the average increase is 22.2 MPa with a standard deviation of 15 MPa). One way to confirm the time-dependent differences statistically is to perform a paired sample comparison between the mean value of the cube compressive strength at 28 days and the mean value of the compressive strength from drilled cores for each bridge. A so-called statistical hypothesis test, using a method called *t*-test where the means are compared (see Montgomery[6] or Coladarci[7]), confirms the difference. This kind of analysis presumes that the observations are independent random variables, both samples are drawn from independent populations that can be described by a normal distribution and that the standard deviation or variances of both populations are equal. Since there are not so many tests it is not certain that all three conditions are satisfied. However, if it is assumed that the conditions above are fulfilled, the null-hypothesis (H_0) would be that the mean values are equal (i.e. there is no statistical difference between the cube compressive strength at 28 days and the compressive strength from drilled cores) and the alternative hypothesis (H_1) that the mean values are not equal. If the level of significance is chosen to 0.05 (α) an analysis with the software Statgraphics (by Statistical Graphics Corp.) leads to rejection of the null-hypothesis at the 95% confidence level since the *p*-value is less than 0.05, i.e. 0.000003. Thus, the growth of concrete strength is confirmed.

3.2 Discussion and comparison with other tests

Bungey & Millard[8] state that measured in-situ values expressed as equivalent cube strengths, are usually lower than the strengths of cubes made of concrete from the same mix compacted and cured in a “standard” way. This is probably due to the fact that in-situ compaction and curing vary widely. This variation is confirmed in Möller et al.[3] where work by Bellander[9] is presented which shows that this difference between concrete compressive strength of cores and cubes increases with increased concrete compressive strength. With this in mind, the core compressive strengths, $f_{c,100}^{core}$, ought to be lower than the cube compressive strengths, $f_{c,150}$.

Why the increase then? It is well-known that the 28-day strength is not the final strength, but this surprisingly high increase in later years can be due to several reasons. According to Johansson[10], the most likely has to do with the properties of the Portland cements used during the 1930s and 1940s. During this period the Portland cements had a different ratio of dicalcium silicate (C_2S) to tricalcium silicate (C_3S) and were more coarsely ground (i.e. the fineness was lower) compared to the Portland cements of today, see e.g. Lea[11], Taylor[12] or Neville[13]. The two silicates are primarily responsible for the strength of the hydrated cement paste: where the tricalcium silicate (C_3S) influences the early strength and the dicalcium silicate (C_2S) the later increase in strength. The trend during the last few decades has been that, due to improved manufacturing methods, the amount of tricalcium silicate has increased which results in higher early compressive strength (in combination with a higher fineness) and a lower increase in long-term strength. If the content of C_3S and C_2S is compared for an “old” cement and a “modern” cement, one can in an example presented by Lea[11] find that the average content of C_2S was 45% and for C_3S 25% (the cements in this example were from 1900-1910). For a “modern” cement the average content of C_2S is between 15-20% and for C_3S between 50-70%.

In tests performed by Washa & Wendt[14], in which concrete cylinders from 1910 and 1923 were tested, cylinders *stored indoors* exhibit a little change in compressive strength from 2 to 10 years but thereafter showed large strength increases, in the order of 30 to 70% at 50 years. For concrete cylinders *stored outdoors* the increase was in the order of 10 to 40% during the 10 to

50 year period. The 50 year strength was on average 2.35 times the average 1 month strength for the cylinders from 1910 and 1.5 for the cylinders from 1923.

The specimens used in the study from 1910 were made with relatively coarse cement with the highest C_2S content (i.e. 44%, a C_3S content of 28.9% and with a specific surface of 104.5 m^2/kg, average value) and the concrete cylinders from 1923 were made with cements having intermediate specific surface and C_2S content (i.e. 33.7%, a C_3S content of 38.3% and with a specific surface of 123 m^2/kg, average values). A coarse cement has a lower value of the specific surface than a fine-grained cement. As an example, the cement used mainly for housing structures in Sweden today (CEM II/A-LL 42.5 R) has a specific surface of about 460 m^2/kg and a cement used for civil engineering structures (CEM I 42.5 N BV/SR/LA) has a specific surface of about 310 m^2/kg.

Later on, in Washa et al. [15], results from concrete cylinders made in 1937 and stored outdoor for 50 years were presented (from the same test programme as in Washa & Wendt[14]). For these concrete cylinders it was shown that the increase in compressive strength was on average 65% from 1 month to 10 years, but after 10 years the compressive strength decreased or remained essentially the same up to 50 years. The cylinders were made with cement with relatively low C_2S content (i.e. 23.2% and with a C_3S content of 50%, average values) and a higher specific surface (on average 179.5 m^2/kg) compared to the cylinders made in 1910 and 1923.

In a German study by Walz[16] it is reported that concrete specimens stored outside and made with German Portland cement after 30 years had a compressive strength 2.3 times the 28-day compressive strength tested on drilled cores. The average content of C_2S was 13% and for C_3S 62%, the water-to-cement ratio varied between 0.5-1.29 and the cement had a specific surface of 230 m^2/kg.

How can this phenomenon with strength development with time be used in practice? In the Danish Road Report 291[17], a guideline for reliability-based classification of existing bridges, a conservative increase in the compressive strength of concrete is proposed when evaluating the load carrying capacity of existing bridges. A deterministic increase in the compressive strength can be assumed for intact concrete structures in the absence of contradictory information. For bridges built in 1945 or earlier a compressive strength 50% higher than the original 28-day strength may be assumed (with references to Walz[16] and Washa & Wendt[14]). However, for concretes containing silica fume or accelerators no increase above the 28-day strength should be assumed.

The mean increase in compressive strength in our tests, 70% during 30 to 60 years, is thus somewhat lower than the corresponding American and German results.

As mentioned earlier all but one bridge in this study are built during the 1930s and 1940s and the phenomenon with increased concrete compressive strength could in other words be expected for bridges built during the same period. If this increase can also be expected for bridges built during the 1950s and 1960s has not been verified in this study, but the bridge built in 1962 that is included, indicates that an increase could be expected but probably not as high as for the older bridges. The reason for this is most likely the above-mentioned change in composition of the cements that has taken place over the years.

In this context it must also be mentioned that the concrete compressive strength of course can decrease with time due to e.g. environmental degradation. This could lead to an interesting fact in the future. The old bridges in this study possess in many cases, due to the strength increase, an extra safety. A hypothesis is that this will not be the case for, let say a bridge, that is built today and evaluated in 50 years, since the cement composition in the cements of today's will give a fast increase in strength up to 28 days but a lower increase in the years thereafter, resulting in a lower extra safety.

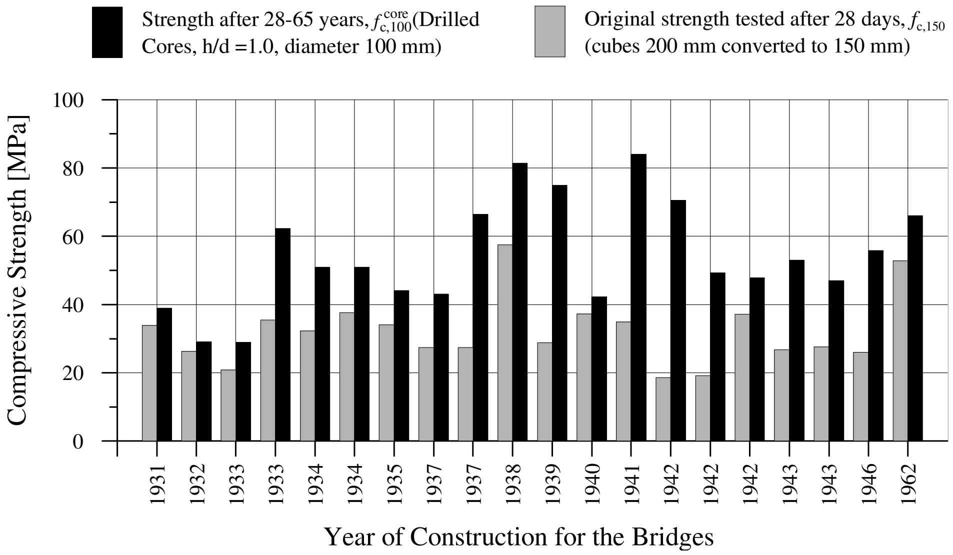


Figure 1 Concrete compressive strength for 20 Swedish road bridges built during 1931-1962. The concrete cube compressive strength at 28-days at the time the bridges were built has been converted into concrete compressive strength of 150 mm standard cubes (from 200 mm standard cubes), $f_{c,150} = 1.053\ f_{c,200}$. The cores have been obtained and tested during the period 1990-1994 with the approximate length/diameter-ratio of 1.0, (diameter about 100 mm). Based on work by Rådman[2].

3.3 Test results for eight bridges built between 1965-1990

An increase in the compressive strength can also be seen for another series of bridges built between 1965 and 1980, see Table 1, where the results from compressive and tensile strength tests are presented from an investigation of eight railway bridges (road underpasses), Thun et al. [25]. The concrete compressive strength was examined during the late 1990s. Unfortunately there is no possibility to compare these mean values in Table 1 with the 28-day compressive strength from the time the bridges were built, since no information regarding this has been available. However, since the bridges are built with the old Swedish concrete classes K400 and K45 (from BBK79[1]), the concrete delivered to the construction sites should probably have a mean concrete compressive strength of approximately 45-47 MPa tested on 150 mm cubes after 28 days (maximum aggregate size of 32 mm). This should at least be a qualified guess.

The mean concrete core compressive strength varies between 61.3 and 85.3 MPa which is an increase with some 30 to 90%. Table 1 also shows the tensile strength. The mean uniaxial tensile strength varies between 2.6 and 3.8 MPa. To some extent the concrete compressive strength "follows" the tensile strength, i.e. a bridge with high tensile strength has also a high compressive strength.

Table 1 - Concrete compressive and tensile strengths for eight concrete bridges determined with drilled cores with the diameter and height of 100 mm. The cores are obtained from the longitudinal beams if nothing else is said.

Bridge No. [a]	**Type of Strength/Force**		**Individual Values**								***m***	***s***	***CoV***
1	Compressive strength drilled cores, [MPa]	f'_c =	--	--	--	--	--	68.4	78.7	71.9	**73.0**	**4.3**	**0.06**
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	--	--	--	2.3	3.2	2.3	**2.6**	**0.4**	**0.16**
2	Compressive strength drilled cores, [MPa]	f'_c =	--	--	--	--	--	88.3	77.3	84.5	**83.4**	**4.6**	**0.05**
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	--	--	--	4.1	3.6	3.8	**3.8**	**0.2**	**0.05**
3	Compressive strength drilled cores, [MPa]	f'_c =	--	--	--	--	--	74.0	77.0	69.7	**73.6**	**3.0**	**0.04**
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	--	--	--	2.77	3.76	3.30	**3.3**	**0.4**	**0.01**
4	Compressive strength drilled cores, [MPa]	f'_c =	--	65.7	71.1	64.2	58.7	54.7	65.0	60.4	**62.8**	**5.0**	**0.08**
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	--	--	--	--	2.33	2.98	**2.7**	**0.3**	**0.12**
5	Compressive strength drilled cores, [MPa]	f'_c =	--	--	--	--	--	77.0	86.0	75.4	**79.5**	**4.7**	**0.06**
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	--	--	--	3.89	3.49	3.09	**3.5**	**0.3**	**0.09**
6	Compressive strength drilled cores, [MPa]	f'_c =	--	--	--	71.7	61.5	63.8	53.9	55.6	**61.3**	**6.4**	**0.10**
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	--	--	--	2.72	3.26	2.97	**3.0**	**0.2**	**0.07**
7	Compressive strength drilled cores, [MPa]	f'_c =	--	--	--	--	--	71.2	65.5	59.1	**65.3**	**4.9**	**0.08**
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	--	--	--	2.72	2.53	4.07	**3.1**	**0.7**	**0.22**
8	1 Specimen No.:		S1:2	S3:2	S5:2	S6:2	S2:1	S2:2	S4:1	S4:2			
	Compressive strength drilled cores, [MPa]	f'_c =	69.9	70.8	78.2	66.5	69.3	74.1	74.0	77.8	**72.6**	**4.2**	**0.06**
	1 Specimen No.:		--	--	S13 [b]	S14 [b]	S10	S8:2	S11:2	S12:2			
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	2.90	2.91	3.12	3.17	2.49	2.71	**2.9**	**0.3**	**0.09**
	1 Specimen No.:		--	--	S1:1	S3:1	S5:1	S6:1	S8:1	S9:1			
	Splitting strength, [MPa] [c]	$f'_{t,sp}$ =	--	--	3.7	4.4	4.8	3.6	6.4	6.5	**4.9**	**1.3**	**0.26**
	2 Specimen No.:		--	--	B1:2	B1:1	B7-1:3	B8-2:2	B9:2	B10:2			
	Compressive strength drilled cores, [MPa]	f'_c =	--	--	80.3	83.4	86.4	83.9	88.3	89.2	**85.3**	**3.4**	**0.04**
	2 Specimen No.:		--	--	B2:2	B4:2	B5:2	B7-1:2	B8-1:2	B9-3:2			
	Uniaxial tensile strength, [MPa]	$f'_{t,uni}$ =	--	--	3.64	2.25	2.62	3.63	3.25	3.47	**3.2**	**0.6**	**0.21**
	2 Specimen No.:		--	--	B5:1	B6:1	B6-2:1	B7-1:1	B8-1:1	B9:1			
	Splitting strength, [MPa] [c]	$f'_{t,sp}$ =	--	--	5.5	6	6.3	6.1	6	6.4	**6.2**	**0.3**	**0.05**

m = mean value, *s* = standard deviation, *CoV* = coefficient of variation.

[a] Bridge No. 1 = Boden C (year of construction 1971), 2 = Garnisonsgatan (1970), 3 = Gammelstad (1970), 4 = Luossajokk (1965), 5 = Haparandavägen (1980), 6 = Kallkällevägen (1966), 7= Bensbyvägen (1965) and 8= Lautajokki (1967, 2= long. beam and 1 = slab).

[b] No record left of exact location in the longitudinal beams for the core.

[c] The splitting strength is reduced with 7% due to the smaller dimensions (height and diameter about 100mm) instead of the standard dimensions 150×300mm since a smaller core gives higher values, Möller et al.[3].

4 STRENGTH VARIATION WITHIN A TROUGH BRIDGE

An extensive study was carried out on a typical reinforced concrete railway trough bridge in order to check the concrete strength variation within this type of structure, see Figure 2. The bridge was situated at Lautajokki close to the Artic Circle and had a span length of 6.1 m and a width of 4.1 m and was built in 1967. It was exposed to railway traffic until 1988 when it was taken out of traffic when a part of the railway line was rebuilt. The reinforced concrete trough bridge consists of a slab, filled with ballast, connected to and carried by two longitudinal beams. This type of concrete trough bridge was very common between 1950 and 1980.

Before the concrete strength was examined, the bridge was exposed to a full-scale fatigue test performed in the laboratory at Luleå University of Technology during 1996, Paulsson et al. [18,19]. The Swedish Concrete Recommendations, BBK94[1] indicated that it would only last for 500 load cycles (with respect to the shear fatigue capacity) with an axle load of 360 kN, but the bridge managed 6 million load cycles and it showed no signs of being close to failure.

In the strength investigation after the fatigue test a total of 12 cores were taken from the slab and 10 from the longitudinal beams. For every strength test, see Table 1, efforts have been made to test cores from the same level, but in some cases this has not been possible to achieve due to heavy reinforcement. The purpose has also been to receive 3 test specimens from each drilled core, but for drill holes B6, B7, B8 and B9 it has not been possible, which has led to the need of drilling a new hole very close to the first one, see Figure 2. The cement used in the bridge has been Swedish Standard Portland Cement with a fineness of approximately 360 m^2/kg (Blaine). The results from the tensile and compressive strength tests are presented as bridge no. 8 in Table 1. The mean concrete core compressive strength is 72.6 MPa for the slab and 85.3 MPa for the beam. For the slab the mean uniaxial tensile strength is 2.9 MPa and the splitting strength is 4.9 MPa. For the beam the mean uniaxial tensile strength is 3.2 MPa and the mean splitting strength is 6.2 MPa.

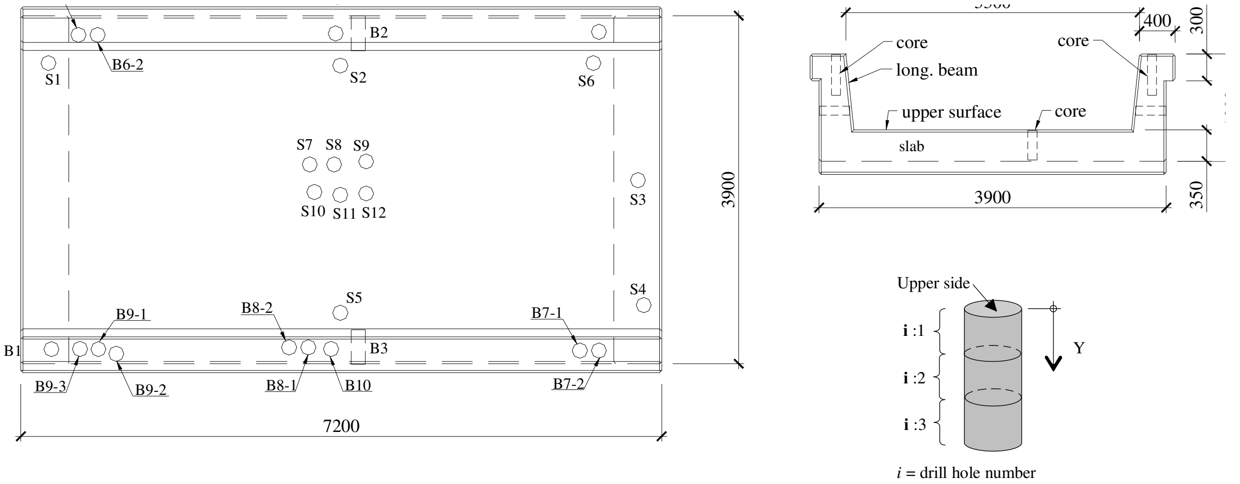


Figure 2 Dimensions and cross-section of the Lautajokki Bridge – a typical Swedish railway reinforced concrete trough bridge. The illustration also shows, in principle, where the cores have been obtained.

It is a well-known fact that there is a variation of concrete properties within a member of a structure. This variation may be due to differences in concrete compaction and curing and/or differences in the quality of the concrete delivered. The bottom parts are usually better compacted with higher density than the top parts, where the percentage of ballast may be smaller. This is due to the influence of the gravity force and the stability of the concrete mixture. If the concrete strength property is considered, the strength variations that can be found in a member of a structure are different depending on if it is eg. a wall or a slab. According to Bungey & Millard[8] the variation between the top and the bottom for a beam can be up to 40% and for a slab 20% (here the loss in strength is concentrated to the top 50 mm). This variation of strength in a member, i.e. higher in the bottom than in the top, has also been found by e.g. Bartlett & MacGregor[20].

If the result presented in Table 1 is compared for the structural parts, i.e. the slab and the longitudinal beams, it appears that the mean compressive strength is 12.7 MPa (approximately 15%) higher in the longitudinal beam than in the slab for the Lautajokki Bridge. This indicates that there is a difference in concrete compressive strength between the side beams and the slab (this difference can be introduced as a partial coefficient for strength, see Nilsson et al. [21]).

The tensile strength for the Lautajokki Bridge shows a similar variation as the compressive strength, but the difference is lower. The mean uniaxial tensile strength is 0.3 MPa (8.5%) higher in the beam than in the slab and for the splitting strength the same relationship is 1.3 MPa (20%). If the two test methods and the result they give are compared the difference is a bit high. The mean uniaxial tensile strength for the slab is 2.9 MPa and the mean splitting strength is 4.9 MPa. In e.g. Eurocode[22] and CEB-FIP[23] an approximate value of the axial tensile strength is set to 90% of the splitting strength and in the Swedish concrete recommendations, BBK94[1], it is set to 80% of the splitting strength. In this study the uniaxial strength for the slab is approximately 60% of the splitting strength. For the beam this percentage is even lower than for the slab, i.e. 50%.

In order to clarify if there is a statistical difference between the structural parts regarding the compressive strength and the tensile strength, a similar hypothesis test that was mentioned earlier can be performed. However, if it is assumed that the conditions mentioned earlier are satisfied, the null-hypothesis (H_0) would be that the mean values are equal (i.e. there is no statistical difference between the two structural parts) and the alternative hypothesis (H_1) that the mean values are not equal. If the level of significance is chosen to 0.05 (α) an analysis with the software Statgraphics (by Statistical Graphics Corp.) for the case of compressive strength leads to rejection of the null-hypothesis at the 95% confidence level since the p-value is less than 0.05, i.e. 0.00005. The confidence interval for the difference between the means extends from 8.1 to 17.2. Since the interval does not contain the value 0.0, there is a statistically significant difference between the means of the two samples at the 95% confidence level.

If the same analysis is performed for the mean value of the uniaxial tensile strength and the splitting strength, it is shown, contrary to the case for compressive strength, that there is no statistically significant difference between the means of the two structural parts at the 95% confidence level for neither the uniaxial tensile strength nor the splitting strength.

5 TENSILE STRENGTH AS A FUNCTION OF THE COMPRESSIVE STRENGTH

In this paper the concrete tensile strength has been presented along with the compressive strength for the tested bridges presented in chapter 3.3. The reason for this is that the tensile strength is a fundamental property. However, as the tensile strength is difficult to test, it has become common to use equations where the tensile strength is expressed as a function of the compressive strength. There are mainly two approaches: (a) $f_t \sim f_c^{1/3}$ and (b) $f_t \sim f_c^{2/3}$ and we will look at these two possibilities.

(a) $f_t \sim f_c^{1/3}$: This seems to be used in e.g. Eurocode[22] when calculating the concrete shear force capacity. Here, the tensile/shear strength is set to a function of the cubic root of the compressive strength.

$$f_{\mathrm{t}} = A \cdot f_{\mathrm{c}}^{1/3} \tag{1}$$

However, in the Eurocode equation also effects of friction in cracks, dowel action and compressive strengths are included, Westerberg[24]. Eq. (1) can therefore not be seen only as a physical relation between the compressive strength and the tensile strength.

For high strength concrete the following relationship between the compressive strength and uniaxial tensile strength is given, HPCS[25] (This is similar to Eq. (1), since it is raised to approximately 1/3):

$$f_\mathrm{t} = 0.87 \cdot f_\mathrm{c}^{0.37} \tag{2}$$

(b) $f_\mathrm{t} \sim f_\mathrm{c}^{2/3}$: In Möller et al.[3] the following equation is proposed:

$$f_\mathrm{t} = B \cdot f_\mathrm{c}^{2/3} \tag{3}$$

where the coefficient $B = 0.21$ or 0.24 (in HPCS[25] a similar relation as Eq. (3) is suggested between the compressive strength and the tensile splitting strength, i.e. $f_\mathrm{t,sp} = 0.25 f_\mathrm{c}^{0.7}$).

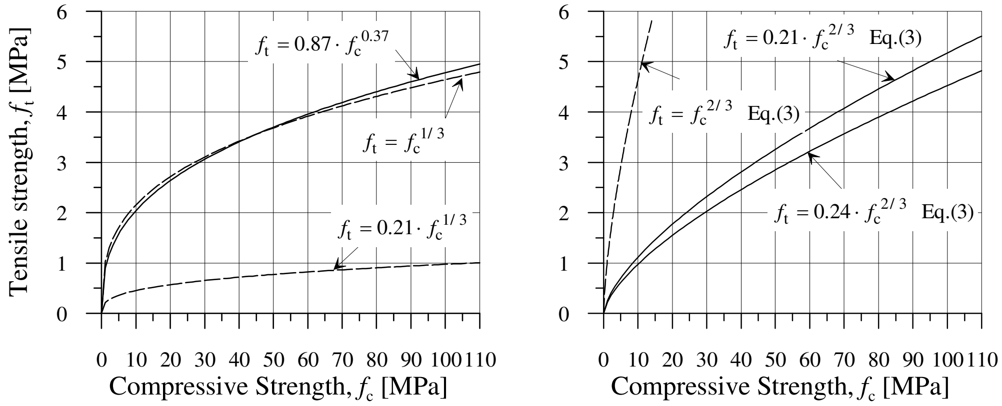
Also in Eurocode[22], the characteristic (5%) compressive cylinder strength, f_ck, is used to calculate the mean value of the axial tensile strength of concrete, f_ctm, according to:

$$f_\mathrm{ctm} = B \cdot f_\mathrm{ck}^{2/3} \qquad \text{for} \le \text{C50/60} \tag{4}$$

$$f_\mathrm{ctm} = 2.12 \cdot \ln\left(1 + \frac{f_\mathrm{cm}}{10}\right) \qquad \text{for} > \text{C50/60} \tag{5}$$

where B is 0.3, $f_\mathrm{cm} = f_\mathrm{ck} + 8$ and where f_ck is the compressive strength of cylinders. The notation C50/60 indicates that a cylinder strength of 50 MPa corresponds to a cube strength of 60 MPa.

In Figure 3 Eqs. (1) to (3) are shown. For Eq. (1) A is assumed to be 1.0 and 0.21 respectively in Figure 3a. If the different curves in the figure are compared the general difference between the compressive strength being raised to 2/3 or 1/3 is obvious. Eqs. (1) and (3), with $A = 1$ and $B = 0.21$, have approximately the same tensile strength at 110 MPa but the form of the curves are very different for the lower strengths. If the compressive strength is e.g. 40 MPa, Eq. (1) gives a tensile strength of approximately 3.5 MPa and Eq. (3) a tensile strength of approximately 2.5 MPa. This indicates the magnitude of the difference that could be obtained if the relationship used in an analysis does not represent the examined concrete well.



a) *b)*

Figure 3 Variation obtained when different correlations between compressive and tensile strength are used.

In Figure 4 the mean compressive and the mean uniaxial tensile strength for the eight bridges are plotted together with two fitted equations that are based on Eqs. (1) and (3). As can be expected both fitted equations can be plausible for this strength region. Note, the two equations are only intended to show the principal behaviour of the equations and nothing else.

In the figure, also Eurocode values are plotted for tensile strengths versus compressive cube strengths (It is here assumed that the mean value of the cube strength, here called $f_{\mathrm{cm,cube}}$, could be estimated in the same way as for cylinders, mean value = characteristic value+8 MPa, i.e. $f_{\mathrm{cm,cube}} = f_{\mathrm{ck,cube}}+8$. $f_{\mathrm{ck,cube}}$ and f_{ctm} from table 3.1 in section 3: Materials in Eurocode[22]). This curve gives higher tensile strength values than the uniaxial tensile tests. This indicates that the long time uniaxial tensile strength cannot be estimated from the Eurocode equations in a safe manner.

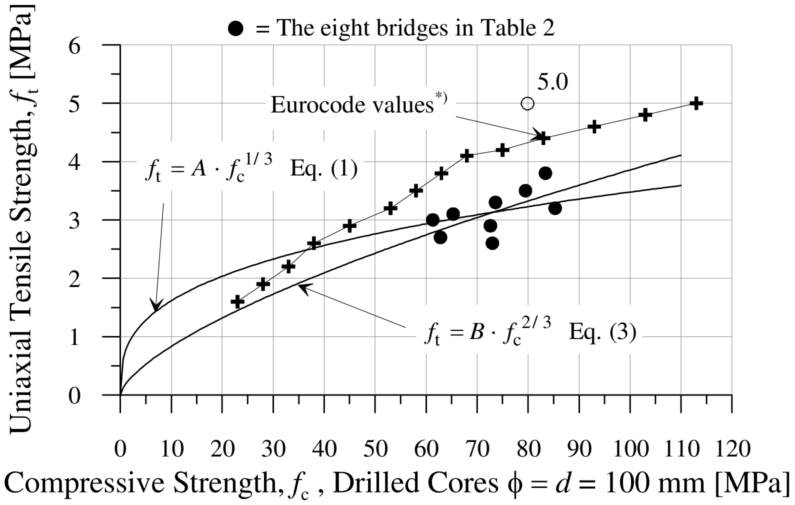


Figure 4 Compressive and uniaxial tensile strength for eight railway concrete bridges together with Eurocode values for cubes and two fitted equations. (A=0.75 and B=0.18 where the coefficients of determination, R-squared is 0.30 and 0.39, respectively, i.e. poor fits - the fitted equations are only used to show the principal behaviour of the two equations). $^{*)}$ *Eurocode values:* $f_{cm,cube}$ *(=* $f_{ck,cube}$*+8) and* f_{ctm} *from table 3.1 in section:3 Materials in Eurocode*[22].

If the tensile strength is investigated for an existing structure another interesting problem arises. Should the uniaxial tensile test or the splitting test be used? If the uniaxial tensile strength for the slab in Table 1 is compared to the axial tensile strength from splitting strength test (i.e. the splitting strength reduced to 80 % according to the Swedish recommendations, BBK94[1]) the difference is about 25 % (2.9 MPa compared to 0.8·4.9 = 3.9 MPa). One reason for the difference could be that the uniaxial tensile test is more sensitive to existing microcracks. This large difference in strength could be very crucial for e.g. a bridge in an assessment situation of the bearing capacity, but probably it is the national regulations that decide the choice between the methods.

The splitting strength from Table 1 could also be used to complement the comparison in Figure 4. The mean values are used for bridge no. 8, i.e the compressive strength (72.6+85.3)/2 = 79 MPa together with the splitting strength (4.9+6.2)/2 = 5.5 MPa multiplied with, let say 0.9 according to Eurocode[22], giving the axial tensile strength 5 MPa, see circle in Figure 4. The axial tensile strength is higher than the tensile strength that could be found in Eurocode[22], i.e. about

4.2 MPa for the compressive strength 79 MPa, see Figure 4. The splitting tests thus seem to give higher values than the uniaxial tensile tests and the tensile strengths given in Eurocode.

6 SUMMARY AND CONCLUSIONS

In a study of the concrete compressive strengths for twenty Swedish bridges built during 1931-1962, the mean increase in compressive strength is about 70% compared to the 28-day concrete strength (corresponding to a mean increase of 21 MPa with a high standard variation of 14 MPa). This increase could also be expected for bridges built during the 1940s and 1950s. An increase in concrete compressive strength can also be expected for bridges built during the 1960s but probably not as high.

The study of a typical reinforced railway concrete trough bridge, the Lautajokki Bridge, showed that the concrete compressive strength was approximately 15% higher in the longitudinal beam (85.3 MPa) than in the slab (72.6 MPa which is a statistically significant difference at the 95% confidence level).

The tensile strength for the Lautajokki Bridge showed a similar variation as the compressive strength, but the difference was lower (and not statistically verified). The mean uniaxial tensile strength was approximately 8.5% higher in the beam (3.2 MPa) than in the slab (2.9 MPa) and for the splitting test the same relationship was 20%. The ratio between the uniaxial and the splitting tensile strength were approximately 0.5 (beam) and 0.6 (slab) which are lower than what could be found in e.g. Eurocode[22], where the axial tensile strength is set to 90% of the splitting strength.

When conversion equations are used to determine the tensile strength with the help of the compressive strength, caution should be used. The experimental values obtained for uniaxial strength of old concrete are lower than what is given in Eurocode. Concrete age, aggregate size and strength here obviously have an influence. For the tested old concrete, the relation $f_t = A \cdot f_c^{1/3}$ with $A = 0.75\text{-}0.9$ gave a good correlation for high concrete strengths (60 to 85 MPa) while the relation $f_t = B \cdot f_c^{2/3}$ with $B = 0.21\text{-}0.24$ gave conservative values for strengths below 50 MPa.

Background material to the presented investigation can be found in Thun et al. [26].

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REFERENCES

1. BBK94 (1994, 1996). Swedish Recommendations for Concrete Structures. Volume 1 – Design, Volume 2 – Materials, Construction, Control. Svensk Byggtjänst, Stockholm 1994, 185 + 116 pp. ISBN 91-7332-686-0, 91-7332-687-9. Supplement 1996. pp. 57. ISBN 91-7147-274-6.
   BBK 79 (1979). Swedish Recommendations for Concrete Structures. Volume 1 – Design, Volume 2 – Materials, Construction, Control. Utgivna av Statens Betongkommitté hos AB Svens Byggtjänst, Stockholm 1979, 157 + 77 sid. ISBN 91-7332-046-3. In Swedish.

2. Rådman J. (1998). Development of Concrete Compressive Strength. A study of Swedish Bridges constructed During the 20th Century. Division of Structural Engineering. Luleå University of Technology. Master's Thesis, 1998:258 CIV. pp. 55.

3. Möller G., Petersons N. and Elfgren L. (1994). Asessement of In-Place Concrete Strength in Structures. (Bedömning av hållfasthet i färdig konstruktion). Betonghandbok – Material utgåva 2. Avsnitt 11. Stockholm: Svensk Byggtjänst. pp. 373. ISBN 91-7332-709-3. In Swedish.

4. prEN 13971 (2006). Assessment of in-situ compressive strength in structures and precast concrete components. Final draft. prEN 13791:2006:E. European Committee for Standardization, June 2006. pp. 28. Note that this is a draft version of the standard.

5. Betongprovning (2002). Betongprovning med svensk standard. 1 utg. Stockholm: SIS förl., 2002. (SIS handbok, 0347-2019; 5). pp. 283. ISBN 91-7162-553-4

6. Montgomery, D. C. (2001). Design and Analysis of Experiments, 5th Edition. John Wiley & Sons Inc. pp. 696. ISBN 0471316490

7. Coladarci T, Cobb C. D., Minium E. W., Clarke R. C. (2003). Fundamentals of Statistical Reasoning in Education. John Wiley 6 Sons Inc. October 2003. pp. 480. ISBN 0-471-06972-8

8. Bungey J.H. and Millard S.G. (1996). Testing of Concrete in Structures. Blackie Academic & Professional, an imprint of Chapman & Hall, London 1996. pp. 286. ISBN 0-7514-0241-9.

9. Bellander U. (1976). Concrete Strength in Finished Structure. Part 1, Destructive Testing Methods. (Hållfasthet i färdig konstruktion Del 1, Förstörande metoder. Rimliga kravnivåer). Cement och Betonginstitut Forskning 13:76, Stockholm 1976. In Swedish.

10. Johansson S-E. (2005). Personal Communication. Cementa (Heidelberg Cement Group), Malmö, Sweden.

11. Lea F. M. (1970). The Chemistry of Cement and Concrete. 3 ed. London: Edward Arnold, 1970, pr. 1983. pp. 727. ISBN 0-7131-2277-3

12. Taylor G.D. (2002). Materials in Construction: Principles, Practice and Performance. 2 ed. Pearson Higher Edsucation. pp. 597. ISBN 0582369347

13. Neville, A. M. (1995). Properties of Concrete. 4 ed. Harlow: Longman Group. pp. 844. ISBN 0-582-23070-5

14. Washa, G. W. and Wendt, K. F. (1975). Fifty Year Properties of Concrete, ACI Journal, January 1975. pp. 20-28.

15. Washa, G. W., Saemann J. C., and Cramer S. M. (1989). Fifty-Year Properties of Concrete made in 1937. ACI Materials Journal, V.86, No.4, July 1989, pp. 367-371.

16. Walz K. (1976). Festigheitsentwicklung von Beton bis zum Alter von 30 and 50 Jahren. Betontechnische Berichte, 3, 1976. pp. 57-78.

17. Report 291 (2004). Reliability-Based Classification of the Load Carrying Capacity of Existing Bridges. Guideline Document. Report 291. October 2004. Road Directorate, Ministry of Transport, Denmark. pp. 48.

18. Paulsson B., Töyrä B., Elfgren L., Ohlsson U. and Danielsson G. (1996). Load Bearing Capacity of Concrete Bridges. Research and Development Project. (Forsknings- och utvecklingsprojekt avseende betongbroars bärighet. “30 ton på Malmbanan“). Rapport 3.3 Infrastruktur, Banverket, Borlänge 1996. pp. 51 + appendix. In Swedish.

19. Paulsson B., Töyrä B., Elfgren L., Ohlsson U. and Danielsson G. (1997). Increased Loads on Railway Bridges of Concrete. “Advanced Design of Concrete Structures“ (Ed. by K. Gylltoft et al.), Cimne, Barcelona, 1997. pp. 201-206. ISBN 84-87867-94-4.

20. Bartlett M. F. and MacGregor J. G. (1999). Variation of In-place Concrete Strength in Structures. ACI Materials Journal, V.96, No.2, March-April. 1999. pp. 261-270.

21. Nilsson M., Ohlsson U. and Elfgren L. (1999). Partial Coefficients for Concrete Strength for Railway Bridges along the railway line ”Malmbanan”. (Partialkoefficienter för hållfasthet i betongbroar längs Malmbanan). Division of Structural Engineering, Luleå University of Technology. Technical Report 1999:03. pp. 67. In Swedish.

22. Eurocode (2004). Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings. European Committee for Standardization, CEN. April 2004. EN 1992-1-1. pp. 225.
23. CEB-FIP (1993). Model Code 1990. Design Code, Comité Euro-International du Béton, Bulletin d’Information No 213/214, Thomas Telford, London 1993. pp. 437. ISBN 0-2777-1696-4.

24. Westerberg B. (2006). Personal communications. Tyréns AB, Stockholm, Sweden.

25. HPCS (2000). High Performance Concrete Structures - Design Examples. AB Svensk byggtjänst, Stockholm. 2000. pp. 157. ISBN 91-7332-930-4

26. Thun H., Ohlsson U. and Elfgren L. (1999). Concrete Strength in Railway Bridges along Malmbanan. Characteristic Compression and Tensile Strength for 20 bridges between Luleå and Gällivare. (Betonghållfasthet i järnvägsbroar på Malmbanan. Karakteristisk tryck- och draghållfasthet för 20 broar mellan Luleå och Gällivare). Technical Report 1999:02. pp.34. In Swedish.