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Strength and Structural Safety of Concrete Structures

Résistance et sécurité structurale des constructions en béton

Festigkeit und Sicherheit von Betonkonstruktionen

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SUMMARY
The structural safety of concrete structures, as far as the compressive and tensile strength is concerned, is partly depending on how the mixing of the concrete is performed and partly depending on how the concrete is handled with respect to compaction, curing etc. Thus the quality assurance just comprise both checking the concrete mix by testing standard cube specimens and checking if compaction, curing etc. have been performed satisfactorily by a final test of the concrete strength in the finished structure.

RESUME
La sécurité des structures en béton, en ce qui concerne la résistance à la compression et à la traction, dépend partiellement du malaxage correct et du maniement propre concernant le compactage, la cure etc. L'assurance de la qualité nécessite un prélèvement de béton aussi bien par essais sur des éprouvettes cubiques que le contrôle final du béton sur l'ouvrage.

ZUSAMMENFASSUNG
Die Sicherheit einer Betonkonstruktion, soweit sie auf die Druck- und Zugfestigkeit zurückzuführen ist, beruht zum Teil auf der korrekten Mischung des Betons und zum Teil auf der richtigen Verdichtung, Nachbehandlung usw. Die Qualitätssicherung muss folglich sowohl die Prüfung des Betons an genormten Prüfkörpern, als auch die Prüfung des Betons im Bauwerk betrachten, das letztere als Kontrolle, dass die Verdichtung, die Nachbehandlung usw., zufriedenstellend ausgeführt sind.

1. INTRODUCTION

An investigation has earlier been carried out by the Swedish National Road Administration in order to study the concrete strength of the slipformed piers of the Angered Bridge in Gothenburg. This investigation was presented by Ingvarsson[1] at the RILEM Symposium on Quality Control of Concrete Structures held in Stockholm 1979. In a more comprehensive manner this study was published as publication TB 133 [2] from the Swedish National Road Administration.

Investigations concerning the strength of concrete in finished structures have been carried out only in few cases at building sites with varying climatic conditions and so on. Beside those investigations by Lewandowski[3] and Petersons[4] the study carried out at the Angered Bridge is of special interest, since the mix proportions of the concrete were the same throughout the whole building period during which the piers were concreted. Furthermore, the same cement make and gravel-pits were used.

When slipform concreting the piers of the Angered Bridge 150 mm standard cube specimens were cast from the same concrete as the concreting layer, within which ø 100x100 mm cylinder specimens then were drilled out. Both the cylinders and the cube specimens were then tested so that a comparison could be made between the strength of the finished piers and the strength of the corresponding cube specimens. The observed ratios $t = f_{cc}/f_{ca}$ between the strength f_{cc} of the piers (drilled-out cylinders) and the strength f_{ca} of the corresponding standard cube specimens illustrate the effects of varying climatic conditions, compaction, curing and so on. The observed t-ratios at the Angered Bridge are shown in Fig.1. Based on the observed mean ratio, amounting to 0.80, and the corresponding standard deviation amounting to 0.10, the calculated normal probability density function is shown in Fig.1 in order to make a comparison possible. Apparently, the normal distribution seems adequate for the studied strength ratio $t = f_{cc}/f_{ca}$.

2. STRENGTH OF CONCRETE

If the ultimate compressive strength which can be utilized in a concrete structure is denoted f_{cu}, this can be expressed by the following equation

$$f_{cu} = \lambda \cdot f_{ca} \cdot t$$

where λ is a correlation coefficient between the compressive strength of the 150 mm standard cube specimens (f_{ca}) and the compressive strength of the corresponding ø 150x300 mm standard cylinder specimens. The latter strength is more accurate as far as the strength which can be utilized in compression is concerned. According to Swedish Standard (SS 13 72 07) the coefficient λ can be put to $1/1.35 = 0.74$.

The compressive strength f_{ca} of the standard cube specimens expresses the strength obtained at ideal curing conditions with respect to temperature and humidity. Therefore f_{ca}, so to speak, denotes a delivery check parameter concerning whether the actual grade of concrete is mixed in a proper manner or not. According to Bellander[5], for f_{ca} it can be stated that for each grade of concrete, the lower 10-percent fractile is 7 N/mm^2 lower than the average strength of the actual specified grade of concrete. The acceptance criteria of the former Swedish Concrete Code (B5-1973) were based on this fact. Thus for a grade K 40 concrete, a compressive strength of 47 N/mm^2 as an average was required. Considering the compressive strength as normal distributed, this requirement corresponds to an assumed standard deviation equal to $s(f_{ca}) = 7/1.28 = 5.5$ N/mm^2 which amounts to 12 % of the average compressive cube strength of a grade K 40 concrete, for which the mean value is equal to $m(f_{ca}) = 47$ N/mm^2.

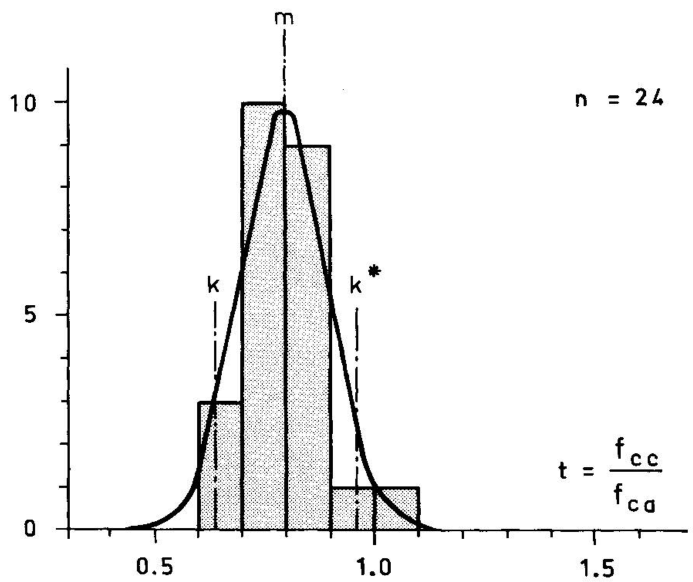

Fig.1 By Ingvarsson [1] and [2] observed ratio $t = f_{cc}/f_{ca}$ between strength in the finished structure (f_{cc}) and the strength of corresponding standard cube specimens (f_{ca}). n = number of observations. m = 0.80 (mean value). s = 0.10 (standard deviation). k = m - 1.65 s. k* = m + 1.65 s.

Except the compressive strength variation due to mixing etc., the actual ultimate compressive strength f_{cu} depends on a lot of site conditions, such as more or less skilful workmanship, compaction and curing as well as climatic conditions etc. These factors can be expressed by the ratio $t = f_{cc}/f_{ca}$ as stated above, which makes a statistical approach possible, based on the Angered Bridge investigation presented above. Assuming that the mean value for t being equal to m(t) = 0.80 and that the corresponding standard deviation being equal to s(t) = 0.10, which amounts to 12.5 % of the mean value, has a more general validity, makes a statistical approach to calculate the ultimate compressive strength f_{cu} in a finished concrete structure possible. Such an approach results in that the ultimate compressive strength $f_{cu} = 0.74 \cdot f_{ca} \cdot t$ in finished concrete structures can be calculated and expressed by the mean value $m(f_{cu}) = 27.8$ N/mm^2 and the corresponding standard deviation $s(f_{cu}) = 4.8$ N/mm^2 as far as Swedish Grade K 40 concrete is concerned. These parameters are shown in Fig.2 by the corresponding normal probability density function, together with the same function for the strength f_{ca} of the corresponding standard cube specimens (m = 47 N/mm^2, s = 5.5 N/mm^2).

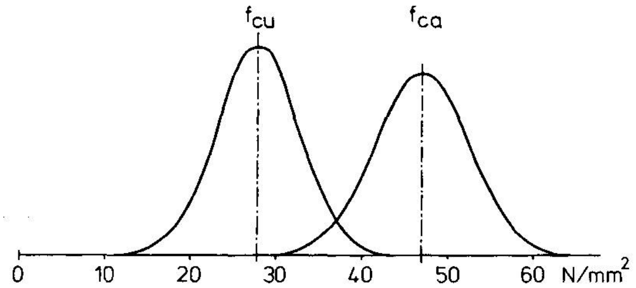

Fig.2 Compressive strength f_{cu} in a finished concrete structure of Swedish Grade K 40 concrete compared with the strength f_{ca} of the corresponding standard cube specimens.

3. STRUCTURAL SAFETY

In order to study the structural safety, the actual compressive strength f_{cd} used in design must be compared with the ultimate compressive strength f_{cu}. For Swedish Grade K 40 concrete, $f_{cd} = 19/\gamma$ N/mm^2, according to the new Swedish Concrete Code (BBK 79), where γ is a coefficient varying between 1.0 and 1.2 depending on the actual "safety class". This value of f_{cd} corresponds to the load factor equal to 1.0 for permanent loads and 1.3 for live loads. The actual structural safety can be expressed by the ratio S* defined as $S^* = f_{cu}/f_{cd}$. On basis of f_{cu} amounting to 27.8 N/mm^2 on an average, with a standard deviation of 4.8 N/mm^2, the structural safety corresponding to $m(S^*) = 1.46\gamma$ and $s(S^*) = 0.25\gamma$ can be observed to be valid for Swedish concrete structures, for which Grade K 40 concrete is specified. The normal probability density function for the structural safety S* when assuming $\gamma = 1.1$ is shown in Fig.3, from which it can be concluded that the probability for failure ($f_{cd} \geqslant f_{cu}$) is about 0.015.

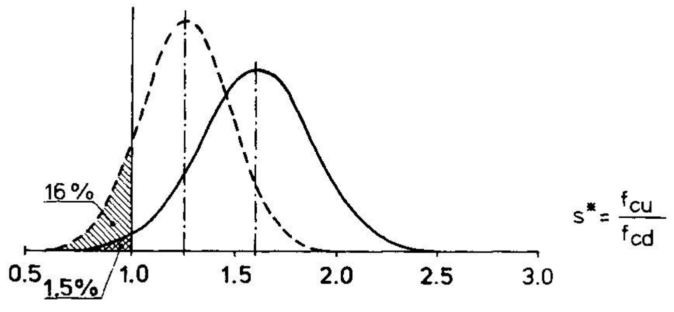

Fig.3 Structural safety $S^* = f_{cu}/f_{cd}$ when assuming $\gamma = 1.1$. The dashed curve shows the effect of delivering Grade K 30 concrete instead of specified Grade K 40 concrete.

4. CONCLUDING REMARKS

Regarding the risk for gross errors delivery of wrong grade of concrete seems predominant. If, for example, Grade K 30 concrete is delivered instead of Grade K 40 concrete, the ultimate compressive strength is reduced to 21.9 N/mm^2 instead of 27.8 N/mm^2 on an average. Thus the mean structural safety is reduced to 1.15γ from 1.46γ, which moves the probability density function to the left in Fig.3, so the probability for failure ($f_{cd} \geqslant f_{cu}$) is increased to about 0.16 from 0.015. In order to avoid such gross errors it seems adequate to take out and test standard cube specimens. However, these are not adequate for checking the strength of the finished structure as this depends on a lot more factors such as compaction, curing and climatic conditions. Therefore, it must moreover be recommended to carry out tests of the concrete strength in the finished structure, even though standard cube specimens are taken out and tested. For this purpose Bellander[6] has proposed acceptance criteria for concrete strength in finished structures, which have been adopted in the new Swedish Concrete Code (BBK 79).

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